DUE GLOBTEMPERATURE PROJECT

Technical Specification Document

WP1.2 – DEL-06

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Distribution

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1.0	ESA	No
2.0	ESA + consortium	No

Change log

Version	Comments
1.0	First version
2.0	Updates following UCM#2 and UCM#3 Modifications on the harmonised format which is now frozen

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0. Executive Summary

The ESA DUE GlobTemperature Technical Specification for land surface temperature (LST) provides the framework for the project. It scopes the user needs and thus the development of GlobTemperature output datasets, tools and documentation to firstly evaluate these outputs and then to deliver them to the user community.

A quantified set of Technical Specifications have been determined to both guide the Project, and to facilitate an assessment of its success. The process for deriving these specifications can be summarised. We took as input the set of User Requirements from the Requirements Baseline Document, and through analysis determined how the Project could meet each one and the most effective way of doing so. This brief overview of how these requirements could be achieved was expanded upon in more detail in Sections 4.2, 5, 6, and 8. From these detailed accounts it has been possible to quantify a set of Technical Requirements which together fulfil the User Requirements. Moreover, both the User Requirements and the subsequent Technical Specifications have been mapped onto the suite of GlobTemperature deliverables ensuring full traceability of how the requirements will be met by the Project.

The key points from the Technical Specifications are summarised followed by the tabulated full list:

- A single reference point for the physical nomenclature to describe land / ice and lake surface temperatures and the essential terminology for their retrieval, validation and exploitation
- A harmonised format for all GlobTemperature disseminated output datasets with common metadata and accompanying documentation. The process towards an internationally endorsed common format for future re-processing of non-GlobTemperature products is also being discussed within the International Land Surface Temperature and Emissivity Working Group (ILSTE-WG)
- To provide a user-friendly GlobTemperature Website and Data Portal in terms of registration, information, visualisation tools, and data access via FTP client, command line utilities, and interactive web browser
- Updated validation and intercomparison protocols to deliver robust and traceable validation and intercomparison for quality assessment of GlobTemperature products
- Mechanism to link to products archived externally, with information on metadata provided on the Data Portal
- Algorithm design, product specifications and routes to delivery to meet the broad range of user requirements on LST datasets
- The foundation of an international group of LST experts and users who can more effectively interact with each other and the wider user community, and are able to provide an independent source of advice and appraisal in LST science

- To provide multiple pathways to both deliver the GlobTemperature products to the users in a simple and effective manner, and also to keep the user community fully informed with all aspects of the Project and wider LST activities

Technical Specification Number	Description
GT-TS-1	Provide definitions of physical nomenclature available for public dissemination
GT-TS-2	Organise and chair an international committee to provide an independent source of advice and appraisal for GlobTemperature (and related projects), and to act as a forum for user / expert interaction
GT-TS-3	The basis for the GlobTemperature harmonised formats will be CF-compliant netCDF-4 with individual file sizes < 200 Mb
GT-TS-4	Ensure User Requirements are updated with feedback from the International LST & E Working Group (ILSTE-WG) and the User Consultation Meetings (UCMs)
GT-TS-5	Provide Level-2 single-sensor datasets in harmonised format
GT-TS-6	Provide Level-3 and Level-4 datasets in harmonised format to be disseminated as 10° x 10° tiles
GT-TS-7	Provide single-sensor GEO datasets at temporal resolutions of 1-hour or less
GT-TS-8	Provide links from the Data Portal to external data centres, including information on metadata, for datasets not directly disseminated by GlobTemperature
GT-TS-9	Primary (Tier-1) merged LST datasets to be gap-filled
GT-TS-10	Standard spatial resolution of Level-3 and -4 datasets to be 0.05° unless designated otherwise
GT-TS-11	Standard temporal resolution of primary (Tier-1) merged LST datasets to be 3-hourly
GT-TS-12	Secondary (Tier-2) merged LST datasets to not be gap-filled, with priority of 10-year datasets
GT-TS-13	Secondary (Tier-2) continental tiles to be gap-filled
GT-TS-14	Develop Climate Data Record of over 10-years for (A)ATSR in harmonised format with low bias, high precision, and high stability. Targets: 1.0 K, 1.0 K and 0.3 K respectively
GT-TS-15	Determine the optimal cloud clearing methods over land for LST retrieval
GT-TS-16	Provide input satellite datasets for GlobTemperature Matchup Database (GT_MDB) in harmonised format
GT-TS-17	Provide in situ matchup datasets for GlobTemperature Matchup Database (GT_MDB) in harmonised format

Technical Specification Number	Description
GT-TS-18	Provide validation and intercomparison matchup datasets derived according to a consistent protocol
GT-TS-19	Provide satellite vs. satellite matchup datasets for GlobTemperature Matchup Database (GT_MDB) in harmonised format
GT-TS-20	Inverstigate NRT merged LST demonstration product with standard timeliness of less than 24 hours (target 99% coverage); maximum timeliness to be no more than 48 hours; target to be 12 hours
GT-TS-21	Validate the LST uncertainty estimates provided in the harmonised datafiles
GT-TS-22	Ensure quality of GlobTemperature datasets through comprehensive validation, intercomparison, and user evaluation
GT-TS-23	Data Portal to provide visualisation tools and statistics for LST data, LST anomalies, validation information and intercomparison data
GT-TS-24	Provide information and documentation, including news and events, to the users via the GlobTemperature Website
GT-TS-25	Data portal to provide information page on metadata, and links to validation reports and Products User Guide (PUG) for each disseminated dataset
GT-TS-26	Ensure straightforward user access to the GlobTemperature Website and Data Portal with minimal required information for registration
GT-TS-27	Provide access to data archived and disseminated by GlobTemperature via FTP client, command line utilities, and interactive web browser
GT-TS-28	Develop platform independent tools for reading and sub-setting datasets provided in the harmonised formats, and cloud filtered time series extraction
GT-TS-29	Evaluate retrieval methods for optimisation of the LST products from Sentinel-3
GT-TS-30	All harmonised formats to adhere to common metadata compliant with CF conventions
GT-TS-31	As default datafiles to be disseminated with mandatory variables only. User functionality to be provided to allow selection of optional variables from auxiliary datafiles
GT-TS-32	Provide ancillary information as optional to users and be stored in auxiliary datafiles
GT-TS-33	Provide uncertainty information per pixel for Level-2 data and per grid cell for Level-3 data as mandatory
GT-TS-34	Provide cloud flags in Level-2 harmonised format and information on number of cloud affected pixels in Level-3 harmonised format

Technical Specification Number	Description
GT-TS-35	Where information is available provide full uncertainty breakdown for Level-2, -3 and -4 data in a consistent manner
GT-TS-36	Where available provide ancillary data in harmonised format datafiles: meteorological data, emissivity, land cover classification, fractional vegetation cover, NDVI and albedo
GT-TS-37	All datafiles in harmonised format to be compressed at highest level (9), with `float` variables scaled to `short` where designated and geolocation data stored to 4 decimal places
GT-TS-38	Provide flags on the data quality in the harmonised format datafiles
GT-TS-39	Standard temporal resolution of Level-3 datasets to be day / night
GT-TS-40	Provide high-latitude only (polar) datasets in equal-area projection
GT-TS-41	Provide all harmonised format datafiles according to a common file naming convention
GT-TS-42	Comply with minimum agreed period between releases of re-processed datasets
GT-TS-43	Update users on GlobTemperature Mailing List whenever new or re-processed data becomes available on the Data Portal
GT-TS-44	Provide multiple information pathways to ensure users are kept updated on GlobTemperature news and events: Website, email, newsletters, publications, conference / workshop presentations and posters
GT-TS-45	Maintain the GlobTemperature Mailing List through Project networking and Website / Data Portal registrations
GT-TS-46	Maintain statistics on Website / Data Portal access and downloads
GT-TS-47	Provide single-sensor datasets of minimum length 10-years with a target of 30-years where new observations have a target timeliness of 1 month
GT-TS-48	Provide a data repository for users to share tools within the community
GT-TS-49	Provide a Data Portal tool to screen data as a function of cloud cover prior to download

1. Introduction

The Technical Specification Document for the ESA DUE GlobTemperature project provides the framework for the project to follow in terms of the provision of user needs; the development of GlobTemperature output datasets, tools and documentation; the approach to assessing the success of the delivered output products through the mechanism of the User Case Studies; and the quality of these products through the application of a robust and traceable validation and intercomparison procedure. It will also consolidate a physical nomenclature to describe land surface temperature (LST).

More specifically, a summary of the user requirements and implications for LST; a determination and justification for the GlobTemperature product portfolio including a trade-off analysis, specifications of the products and web portal specifications; validation protocols and high level summaries of current results; and work plans for the user case studies. The backbone of the Technical Specification is to provide traceability from the User Requirements through to the delivered suite of GlobTemperature products.

This document will be iterated with the International Land Surface Temperature and Emissivity Working Group (ILSTE-WG) with feedback obtained following user consultation; with further releases therefore scheduled. Furthermore, it is expected that these aspects will directly contribute to all documents produced within the framework of GlobTemperature: the physical nomenclature (Section 2.1) will form part of the LST White paper (DEL-28) [AD-6]; the validation and intercomparison protocols (Section 5) will link such activities with the ILSTE-WG and with the LST White Paper [AD-6] - the protocols themselves appear both here (Section 5.1 and Appendix B – Detailed categorisation of the LST Validation Protocol) and in deliverables associated with the validation and intercomparison of the GlobTemperature products. The User Case Study work plans provide the framework for which to channel resources in evaluating the value of the GlobTemperature products to user applications (Section 7). This document will additionally provide high-level summaries for the evolving GlobTemperature presentation pack for internal and more importantly for external use.

The title of each main chapter is shown in Figure 1. An essential point is that the Technical Specifications Document has some important interactions which are also shown in the figure. It is of particular note that a summary of the Requirements Baseline Document [AD-3] is an input to this document, as is the validation and inter-comparison protocol. The algorithm trade-off analysis summary (Section 6.3) provides an overview of the work carried out on the identified candidate algorithms for GlobTemperature developments to provide recommendations for retrievals in GlobTemperature products; a full algorithm trade-off analysis is presented in [AD-5].

Physical nomenclature definitions (Section 2.1) will be iterated with the ILSTE-WG whose role will be also be defined. Definitions include, amongst others, the following key parameters in land surface temperature: LST; land surface air temperature (LSAT); skin temperature; soil temperature; radiometric temperature; thermodynamic temperature; angular anisotropy; emissivity; biome; fractional vegetation cover; land cover class; satellite zenith angle; solar zenith angle.

Finally, the document concludes with a set of targets for GlobTemperature which include data set availabilities, publications, users, and international meetings and conferences. This is a living document in that further versions will include updates to the Technical Specifications based on feedback obtained throughout the life cycle of the Project. Such feedback will be collated following meetings of the International LST & Emissivity Working Group (ILSTE-WG) and the User Consultation Meetings (UCMs) thus providing a mechanism over which the Project will evolve to meet the requirements of the user community. Section 8.5 provides in tabulated form the necessary traceability from the User Requirements [AD-3] to the list of enumerated Technical Specifications, and thence through to the GlobTemperature deliverables.

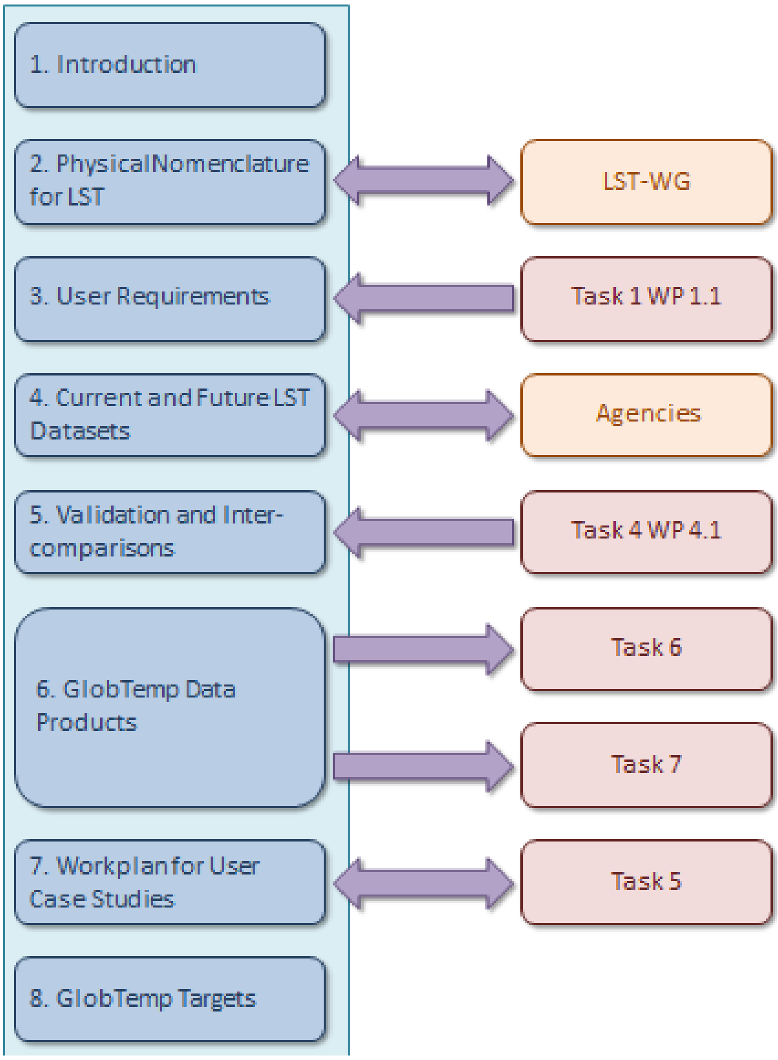

Figure 1: Content structure of the Technical Specification and interactions with each Project activity

1.1. Applicable documents

Table 1: List of applicable documents

Reference Number	Document	Reference
[AD-1]	GlobTemperature Project Management Plan	GlobTemp-WP8-DEL-01
[AD-2]	GlobTemperature Monthly Progress Reports	GlobTemp-WP8-DEL-02
[AD-3]	Requirements Baseline Document	GlobTemp-WP1-DEL-05
[AD-4]	GlobTemperature Newsletters	GlobTemp-DEL-07-Newsletter
[AD-5]	LST CDR Algorithm Trade-Off Analysis	GlobTemp-WP6-DEL-08
[AD-6]	LST White Paper	GlobTemp-WP2-DEL-28
[AD-7]	GlobTemperature User Consultation Meeting Reports	GlobTemp-WP2-DEL-20

1.2. Reference documents

Table 2: List of reference documents

Reference Number	Reference
[RD-1]	Joint Commitee for Guides in Metrology, *Evaluation of Measurement Data - Guide to the Expression of Uncertainty in Measurement.* 2008.
[RD-2]	Norman, J.M. and F. Becker, *Terminology in thermal infrared remote sensing of natural surfaces.* Agricultural and Forest Meteorology, 1995. **77**: p. 153-166.
[RD-3]	Pinheiro, A.C.T., J.L. Privette, and P. Guillevic, *Modeling the observed angular anisotropy of land surface temperature in a savanna.* IEEE Transactions on Geoscience and Remote Sensing, 2006. **44**: p. 1036-1047.
[RD-4]	Vinnikov, K.Y., et al., *Angular anisotropy of satellite observations of land surface temperature.* Geophysical Research Letters, 2012. **39**(23): p. L23802.
[RD-5]	Schneider, P., et al., *Land Surface Temperature Validation Protocol (Report to European Space Agency).* 2012(UL-NILU-ESA-LST-LVP).
[RD-6]	GES DISC, *Goddard Earth Sciences Data and Information Sevrices Center (http://disc.sci.gsfc.nasa.gov/).*
[RD-7]	Merchant, C.J., et al., *The surface temperatures of Earth: steps towards integrated understanding of variability and change.* Geosci. Instrum. Method. Data Syst., 2013. **2**(2):

Reference Number	Reference
	p. 305-321.
[RD-8]	Schaepman-Strub, G., et al., *Reflectance quantities in optical remote sensing—definitions and case studies.* Remote Sensing of Environment, 2006. **103**(1): p. 27-42.
[RD-9]	AMS, *American Meteorological Society Glossary of Meteorology [Available online at http://glossary.ametsoc.org/wiki/"term"].*
[RD-10]	Wan, Z. and J. Dozier, *A generalized split-window algorithm for retrieving land surface temperature from space.* IEEE Transactions on Geoscience and Remote Sensing, 1996. **34**: p. 892–905.
[RD-11]	CEOS, *Committee on Earth Observation Satellites (http://www.ceos.org/).*
[RD-12]	Pinheiro, A., C. Prigent, and W. Rossow, *International Workshop on the Retrieval and Use of Land Surface Temperature: Bridging the Gaps, http://rain.atmos.colostate.edu/GDAP/reports/NCDC-LSTWorkshopReport_final.pdf*, 2008.
[RD-13]	Ghent, D., *LST User Exploitation Document: A review of the applications of current satellite-derived Land Surface Temperature (LST) products and a synthesis of user requirements (Report to European Space Agency).* 2012.
[RD-14]	Remedios, J.J. and N. Humpage, *Sentinel Convoy for Land Applications: Workshop Report. University of Leicester. SCL-ULE-TN-01_V3.1.* 2012.
[RD-15]	GlobTemperature, *First User Consultation meeting http://www.globtemperature.info*, 2012.
[RD-16]	Ghent, D., et al., *Advancing the AATSR land surface temperature retrieval with higher resolution auxiliary datasets: Part B – validation.* in preparation.
[RD-17]	Coll, C., Z.M. Wan, and J.M. Galve, *Temperature-based and radiance-based validations of the V5 MODIS land surface temperature product.* Journal of Geophysical Research-Atmospheres, 2009. **114**.
[RD-18]	Gottsche, F.M., F.S. Olesen, and A. Bork-Unkelbach, *Validation of land surface temperature derived from MSG/SEVIRI with in situ measurements at Gobabeb, Namibia.* International Journal of Remote Sensing, 2013. **34**(9-10): p. 3069-3083.
[RD-19]	CF Conventions, *NetCDF CF Metadata Conventions (http://cfconventions.org/).*
[RD-20]	Llewellyn-Jones, D., et al., *AATSR: Global-change and surface-temperature measurements from Envisat.* Esa Bulletin-European Space Agency, 2001(105): p. 11-21.
[RD-21]	Soria, G. and J.A. Sobrino, *ENVISAT/AATSR derived land surface temperature over a heterogeneous region.* Remote Sensing of Environment, 2007. **111**(4): p. 409-422.
[RD-22]	Prata, F., *Land Surface Temperature Measurement from Space: AATSR Algorithm*

Reference Number	Reference
	Theoretical Basis Document. 2002.
[RD-23]	Coll, C., et al., *Ground measurements for the validation of land surface temperatures derived from AATSR and MODIS data.* Remote Sensing of Environment, 2005. **97**(3): p. 288-300.
[RD-24]	Noyes, E.J., *Technical Assistance for the Validation of AATSR Land Surface Temperature Products, Final Report - February 2006 (Report to European Space Agency).* 2006(ESA Contract Number: 19054/05/NL/FF).
[RD-25]	Ghent, D., et al., *Advancing the AATSR land surface temperature retrieval with higher resolution auxiliary datasets: Part A – product specification.* in preparation.
[RD-26]	Arino, O., et al., *GlobCover: ESA service for Global land cover from MERIS*. Igarss: 2007 Ieee International Geoscience and Remote Sensing Symposium, Vols 1-12: Sensing and Understanding Our Planet. 2007, New York: Ieee. 2412-2415.
[RD-27]	Baret, F., et al., *GEOV1: LAI and FAPAR essential climate variables and FCOVER global time series capitalizing over existing products. Part1: Principles of development and production.* Remote Sensing of Environment, 2013. **137**: p. 299-309.
[RD-28]	Veal, K.L., et al., *Final Report on progress towards a Surface Temperature Dataset for the Polar Regions from ATSR (Report to Department of Energy and Climate Change).* 2012.
[RD-29]	Istomina, L.G., et al., *The detection of cloud-free snow-covered areas using AATSR measurements.* Atmospheric Measurement Techniques, 2010. **3**: p. 1005-1017.
[RD-30]	Bulgin, C.E., et al., *Cloud Clearing Techniques over Land for Land Surface Temperature Retrieval from the Advanced Along Track Scanning Radiometer.* International Journal of Remote Sensing, 2014. **35**(10): p. 3594-3615.
[RD-31]	Marsham, J.H., *Lake Temperatures - thermal remote sensing and assimilation into a lake model.* PhD Thesis, The University of Edinburgh, 2003.
[RD-32]	MacCallum, S.N. and C.J. Merchant, *Surface water temperature observations of large lakes by optimal estimation.* Canadian Journal of Remote Sensing, 2012. **38**: p. 25-45.
[RD-33]	Saunders, R., et al., *RTTOV8 - Science and Validation Report.* U.K. Met. Office, NWP SAF, 2006.
[RD-34]	MacCallum, S.N. and C.J. Merchant, *ARC-Lake v2.0, 1991-2011 [Dataset]. University of Edinburgh, School of GeoSciences / European Space Agency.* 2013.
[RD-35]	Lehner, B. and P. Doll, *Development and validation of a global database of lakes, reservoirs and wetlands.* Journal of Hydrology, 2004. **296**(1_4): p. 1-22.
[RD-36]	Hook, S., et al., *Lake Surface Temperature.* Bulletin of the American Meteorological Society, 2011(93): p. S18-S19.

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[RD-37]	Aires, F., et al., *A new neural network approach including first-guess for retrieval of atmospheric water vapor, cloud liquid water path, surface temperature and emissivities over land from satellite microwave observations.* J. Geophys. Res., 2001. **106**(D14): p. 14887-14907.
[RD-38]	Prigent, C., F. Aires, and W.B. Rossow, *Land surface microwave emissivities over the globe for a decade.* Bulletin of the American Meteorological Society, 2007. **87**: p. 1573-1584.
[RD-39]	Rossow, W.B. and R.A. Schiffer, *Advances in Understanding Clouds from ISCCP.* Bull. Amer. Meteor. Soc., 1999. **71**: p. 2-20.
[RD-40]	Prigent, C., F. Aires, and W.B. Rossow, *Land surface skin temperatures from a combined analysis of microwave and infrared satellite observations for an all-weather evaluation of the differences between air and skin temperatures.* J. Geophys. Res., 2003. **108**: p. 4310-4321.
[RD-41]	Catherinot, J., et al., *Evaluation of "all weather" microwave-derived land surface temperatures with in situ CEOP measurements.* Journal of Geophysical Research-Atmospheres, 2011. **116**.
[RD-42]	Holmes, T.R.H., et al., *Land surface temperature from Ka band (37 GHz) passive microwave observations.* Journal of Geophysical Research: Atmospheres, 2009. **114**(D4): p. D04113.
[RD-43]	Moncet, J.L., et al., *Land surface microwave emissivities derived from AMSR-E and MODIS measurements with advanced quality control.* Journal of Geophysical Research-Atmospheres, 2011. **116**.
[RD-44]	Schmetz, J., et al., *An introduction to Meteosat Second generation (MSG).* Bulletin of the American Meteorological Society, 2002a. **83**: p. 977-992.
[RD-45]	Schmetz, J., et al., *Radiometric performance of SEVIRI.* Bulletin of the American Meteorological Society, 2002b. **83**: p. ES50-ES51.
[RD-46]	Trigo, I.F., et al., *The Satellite Application Facility on Land Surface Analysis.* Int. J. Remote Sens., 2011. **32**: p. 2725-2744.
[RD-47]	Freitas, S.C., et al., *Quantifying the Uncertainty of Land Surface Temperature Retrievals From SEVIRI/Meteosat.* IEEE Trans. Geosci. Remote Sens., 2010.
[RD-48]	Trigo, I.F., et al., *An assessment of remotely sensed land surface temperature.* J. Geophys. Res., 2008a. **113**(D17108).
[RD-49]	Peres, L.F. and C.C. DaCamara, *Emissivity Maps to Retrieve Land-Surface Temperature from MSG/SEVIRI.* IEEE Trans. Geosci. Remote Sens., 2005. **43**: p. 1834-1844.
[RD-50]	Trigo, I.F., et al., *An assessment of remotely sensed land surface temperature.* Journal of Geophysical Research-Atmospheres, 2008. **113**(D17).

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[RD-52]	Borbas, E.E., et al., *A Global infrared Land Surface Emissivity Database and its validation.* Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface, 11th, San Antonio, TX, 14-18 January 2007. American Meteorological Society, Boston, MA, 2007, Paper P2.7, 2007.
[RD-53]	Wan, Z., *New refinements and validation of the MODIS land surface temperature/emissivity products.* Remote Sensing of Environment, 2008. **112**: p. 59– 74.
[RD-54]	Baker, N., *Joint Polar Satellite System (JPSS) VIIRS Land Surface Temperature Algorithm Theoretical Basis Document (ATBD).* 2011.
[RD-55]	Freitas, S.C., et al., *Land surface temperature from multiple geostationary satellites.* International Journal of Remote Sensing, 2013. **34**(9-10): p. 3051-3068.
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[RD-59]	Dybkjaer, G., R. Tonboe, and J.L. Hoyer, *Arctic surface temperatures from Metop AVHRR compared to in situ ocean and land data.* Ocean Science, 2012. **8**: p. 959-970.
[RD-60]	LP DAAC, *Land Processes Distributed Active Archive Center (LP DAAC) (https://lpdaac.usgs.gov).*
[RD-61]	Hulley, G., S. Veraverbeke, and S. Hook, *Thermal-based techniques for land cover change detection using a new dynamic MODIS multispectral emissivity product (MOD21).* Remote Sensing of Environment, 2014. **140**(0): p. 755-765.
[RD-62]	CLASS, *NOAA Comprehensive Large Array-Data Stewardship System (CLASS) (http://www.class.ncdc.noaa.gov/).*
[RD-63]	Copernicus, *Global Land Service.*
[RD-64]	EUMETCast, *(http://www.eumetsat.int/home/main/dataaccess/eumetcast/index.htm).*
[RD-65]	S3_L2_ADF, *Sentinel-3 Level-2 Auxiliary Data File Project.*
[RD-66]	STSE, *SEN4LST Project,* http://due.esrin.esa.int/stse/projects/stse_project.php?id=140,

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[RD-67]	Wan, Z. and Z.L. Li, *Radiance-based validation of the V5 MODIS land-surface temperature product.* International Journal of Remote Sensing, 2008. **29**(17-18): p. 5373-5395.
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[RD-70]	Rebhan, H. and P. Goryl, *ESA Sentinel-3 Calibration and Validation Plan (S3-PL-ESA-SY-0265).* 2013.
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[RD-73]	Hulley, G.C. and S.J. Hook, *Intercomparison of versions 4, 4.1 and 5 of the MODIS Land Surface Temperature and Emissivity products and validation with laboratory measurements of sand samples from the Namib desert, Namibia.* Remote Sensing of Environment, 2009. **113**(6): p. 1313-1318.
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[RD-75]	Jimenez-Munoz, J.C., et al., *Temperature and Emissivity Separation From MSG/SEVIRI Data.* Geoscience and Remote Sensing, IEEE Transactions on, 2014. **52**(9): p. 5937-5951.
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[RD-77]	Cheng, J. and S. Liang, *Estimating the broadband longwave emissivity of global bare soil from the MODIS shortwave albedo product.* Journal of Geophysical Research: Atmospheres, 2014. **119**(2): p. 2013JD020689.
[RD-78]	Seemann, S.W., et al., *Development of a global infrared land surface emissivity database for application to clear sky sounding retrievals from multispectral satellite radiance measurements.* Journal of Applied Meteorology and Climatology, 2008. **47**(1): p. 108-123.
[RD-79]	Parkes, I.M., et al., *AATSR Validation Implementation Plan Part 1 - AATSR Validation Principles and Definitions (No. PO-PL-GAD-AT-005).* 2005.

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[RD-147]	GCOS, *Global Climate Observing System* http://www.wmo.int/pages/prog/gcos/index.php?name=news.
[RD-148]	GloboLakes, *Global Observatory of Lake Responses to Environmental Change* http://www.globolakes.ac.uk/.

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[RD-151]	EarthTemp Network, http://www.earthtemp.net/.
[RD-152]	GHRSST, *Group for High Resolution Sea Surface Temperature* https://www.ghrsst.org/.
[RD-153]	ESA DUE, *ESA Data User Elements Programme* http://due.esrin.esa.int/.
[RD-154]	ESA CCI, *ESA Climate Change Initiative Programme* http://www.esa-cci.org/.
[RD-155]	AVHRR Polar Pathfinder, *Advanced Very High Resolution Radiometer (AVHRR) Polar Pathfinder* http://nsidc.org/.
[RD-156]	MODIS Snow/Ice Project, *The MODIS Snow and Sea Ice Global Mapping Project* http://modis-snow-ice.gsfc.nasa.gov/.
[RD-157]	S3VT, *ESA Sentinel-3 Validation Team* http://congrexprojects.com/2013-events/13m56/introduction.
[RD-158]	IPCC, *Intergovernmental Panel on Climate Change* http://www.ipcc.ch/.
[RD-159]	WMO, *World Meteorological Organization* http://www.wmo.int/pages/index_en.html.
[RD-160]	GEWEX, *Global Energy and Water Exchanges Project* http://www.gewex.org/.
[RD-161]	GEOSS, *Global Earth Observation System of Systems* http://www.earthobservations.org/geoss.shtml.
[RD-162]	OSI-SAF, *EUMETSAT Ocean & Sea Ice Satellite Application Facility* http://www.osi-saf.org/.
[RD-163]	NOAA-NCDC, *National Oceanic and Atmospheric Administration - National Climatic Data Center* http://www.ncdc.noaa.gov/.
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1.3. Glossary

ADF--------------- Auxiliary Data File
AHS --------------- Airborne Hyperspectral Scanner
AIRS -------------- Atmospheric Infrared Sounder
ASCAT------------ Advanced Scatterometer
(A)ATSR---------- (Advanced) Along Track Scanning Radiometer
AMMA----------- African Monsoon Multidisciplinary Analysis
AMSR ------------ Advanced Microwave Scanning Radiometer
ARM-------------- Atmospheric Radiation Measurement
ASTER ------------ Advanced Spaceborne Thermal Emission and Reflection Radiometer
ASTER-GDEM--- ASTER Global Digital Elevation Map
ASTER-GED------ ASTER Global Emissivity Database
AVHRR ----------- Advanced Very High Resolution Radiometer
BBE--------------- Broadband Emissivities
BRDF------------- Bidirectional Reflectance Distribution Function
BSRN------------- Baseline Surface Radiation Network
BT---------------- Brightness Temperature
CAL/VAL --------- Calibration/Validation
CCI--------------- Climate Change Initiative
CCRR------------- Cloud Clearing Round Robin
CDF--------------- Cumulative Distribution Function
CDR--------------- Climate Data Record
CEDA------------- Centre for Environmental Data
CEMS------------- Climate, Environment and Monitoring from Space
CEOP ------------- Coordinated Energy and Water Cycle Observations Project
CEOS-LPV ------- Committee on Earth Observation Satellites – Land Product Validation
CF ---------------- Climate and Forecast Conventions
CICE--------------- Community Ice COde
CIMSS ------------ Cooperative Institute for Meteorological Satellite Studies

CLASS------------ Comprehensive Large Array-Data Stewardship System
DA--------------- Data Assimilation
DMI-------------- Danish Meteorological Institute
DMSP------------ Defense Meteorological Satellite Program
DUE--------------- Data user Element
ECMWF---------- European Centre for Medium Wave Forecasting
ECV --------------- Essential Climate Variable
EDR--------------- Environmental Data Record
EO----------------- Earth Observation
ESA --------------- European Space Agency
ET----------------- Evapotranspiration
EUMETSAT------ European Organisation for the Exploitation of Meteorological Satellites
EURO4M -------- European Reanalysis and Observations for Monitoring
FOV--------------- Field Of View
FTS---------------- Fourier Transform Spectrometer
FV----------------- Fractional Vegetation
GCM-------------- General Circulation Model
GCOM----------- Global Change Observation Mission
GCOS------------- Global Climate Observing System
GDAP------------- GEWEX Data and Assessments Panel
GEO--------------- Geostationary Earth Orbit
GEOSS------------ Global Earth Observation System of Systems
GEWEX----------- Global Energy and Water Cycle Experiment
GHRSST---------- Group for High Resolution Sea Surface Temperatures
GLASS------------ Global Land Atmosphere System Study
GLWD------------ Global Lakes and Wetlands Database
GMES------------- Global Monitoring for Environment and Security
GOES------------- Geostationary Operational Environmental Satellites
GSW-------------- Generalised Split Window
GT_BDB--------- GlobTemperature Benchmark Database
GT_MDB--------- GlobTemperature Matchup Database
HDF--------------- Hierarchical Data Format
HRV--------------- High Resolution Visible
HYCOM---------- HYbrid Coordinate Ocean Model
IASI--------------- Infrared Atmospheric Sounding Interferometer
ILSTE-WG------- International Land Surface Temperature & Emissivity Working Group
IPCC-------------- Intergovernmental Panel on Climate Change
IPF---------------- Instrument Processing Facility

IPMA------------- Instituto Português do Mar e da Atmosfera
ISCCP------------- International Satellite Cloud Climatology Project
IST ---------------- Ice Surface Temperature
JAXA-------------- Japan Aerospace Exploration Agency
JMA-------------- Japan Meteorological Agency
JPL---------------- Jet Propulsion Laboratory
KIT ---------------- Karlsruhe Institute of Technology
LEO --------------- Low Earth Orbit
LP DAAC--------- Land Processes Distributed Active Archive Center
LSA-SAF---------- Land Surface Analysis Satellite Application Facility
LSAT-------------- Land Surface Air Temperature
LSE---------------- Land Surface Emissivity
LST ---------------- Land Surface Temperature
LSWT------------- Lake Surface Water Temperature
MEaSUREs------ Making Earth System Data Records for Use in Research Environments
MERIS------------ MEdium Resolution Imaging Spectrometer
MIR --------------- Mid-Infrared
MODIS ----------- Moderate Resolution Imaging Spectrometer
MPR-------------- Monthly Progress Report
MSG-------------- Meteosat Second Generation
MTSAT----------- Multi-functional Transport Satellites
MW-------------- Mircowave
NAALSED-------- North American ASTER Land Surface Emissivity Database
NASA------------- National Aeronautics and Space Administration
NCEO------------ National Centre for Earth Observation
NCEP ------------- National Centers for Environmental Prediction
NCO-------------- netCDF Operator
NetCDF ---------- Network Common Data Format
NDVI-------------- Normalised Difference Vegetation Index
NOAA ------------ National Oceanic and Atmospheric Administration
NPP/VIIRS------- National Polar-Orbiting Partnership Visible/Infrared Imager Radiometer
NRT --------------- Near Real Time
NVAP------------- NASA Water Vapour Project
NWP-------------- Numerical Weather Prediction
OE----------------- Optimal Estimation
OSI-SAF ---------- Ocean and Sea-Ice Satellite Application Facility
OSTIA------------ Operational Sea Surface Temperature and Sea Ice Analysis
PDF--------------- Probability Density Function

PUG-------------- Product User Guide

PW--------------- Precipitable Water

QC---------------- Quality Control

ROI--------------- Region Of Interest

S3VT-------------- Sentinel-3 Validation Team

SEN4LST --------- Synergistic Use of the Sentinel Missions for Estimating and Monitoring Land Surface Temperature

SEVIRI ------------ Spinning Enhanced Visible and Infrared Imager

SLSTR------------- Sea and Land Surface Temperature Radiometer

SM---------------- Soil Moisture

SMAC------------- Simplified Method for Atmospheric Correction

SMAP------------- Soil Moisture Active –Passive

SMOS ------------ Soil Moisture Ocean Salinity

SSM/I------------- Special Sensor Microwave / Imager

SST--------------- Sea Surface Temperature

STSE -------------- Support to Science Element

SURFRAD-------- Surface Radiation Budget Network

SW--------------- Split Window

SWIR ------------- Short Wave Infrared

SZA-------------- Satellite Zenith Angle

TCWV------------ Total Column Water Vapour

TES-------------- Temperature and Emissivity Separation

TIR ---------------- Thermal Infrared

TISI--------------- Temperature Independent Spectral Indices

TOA-------------- Top-Of-Atmosphere

TOPC------------- GCOS Terrestrial Observation Panel for Climate

TVDI-------------- Temperature-Vegetation Dryness Index

UCM------------- User Consultation Meeting

UCS--------------- User Case Study

UTC--------------- Coordinated Universal Time

VI----------------- Vegetation Index

VIS ---------------- Visible

WGCV------------ Working Group on Calibration and Validation

WMO------------ World Meteorological Organisation

2. International Working Group and Standardization

A key aspect of GlobTemperature is to standardise terminology and data for ease of use by the user community. Section 2.1 details a first attempt at defining a common nomenclature for LST science. The governance of such standardisation is to be overseen by an international group of LST experts, users of LST, and representatives of the space agencies (Section 0). This group will provide an independent source of advice and appraisal for LST documentations and data.

2.1. Physical Nomenclature for LST

A variety of definitions exists for terms associated with the retrieval, validation and exploitation of land, lake and ice surface temperatures. No single resource exists which attempts to draw together all the applicable terms with community agreed definitions. Indeed, it is frequently the case that many of the terms defined here in

Table 3 are used interchangeably, in some cases inconsistently. The purpose of this chapter is provide a unifying resource of definitions for the broad range of terminology associated with surface temperatures of the land, inland waters, and sea-ice of the Earth. The objective is for developers and users alike to utilise this nomenclature as a reference independent of satellite / airborne / ground instrumentation and retrieval methodology.

As a baseline, the definitions are first collated from the growing source of literature on LST. For LST validation, for instance, several definitions are adopted from [RD-1], which is the standard for Metrology nomenclature. In order to achieve community acceptance of the nomenclature presented here, the definitions are to be iterated with International LST & E Working Group (ILSTE-WG); this being a representative sample of the view of the wider data provider, LST expert, and user communities. Furthermore, liaison with the Land Product Validation (LPV) sub-group of the Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV), both directly and through contacts within the ILSTE-WG aim to promote this nomenclature for inclusion in the first LPV "Best Practices Guide for LST", which is still to be defined.

While some of these terms may be more qualitative than the more precise mathematical terminology as presented in [RD-1], their use is now so embedded in the psyche of the LST data provider and user communities it is pertinent to provide a unified definition of these terms so as to ensure consistency within this field. Individuals who require a precise mathematical definition of thermal remote sensing properties, such as directional and hemispherical radiometric temperatures, or directional and hemispherical emissivities, are referred to [RD-2]. Rather the objective here is to provide a nomenclature that both LST experts and LST users can identify and adopt to facilitate improved communication (**addresses requirement REQ-28-TR**).

GT-TS-1*: Provide definitions of physical nomenclature available for public dissemination*

*Addresses user feedback **GT-UF-4**: Adopt a common LST terminology including a common protocol on validation and intercomparison disseminating these to the user community*

Table 3: Physical nomenclature; starred entries indicate terms that are defined only in the context in which they are used, i.e. in terms of a particular sensor wavelength and a given approximation to the radiative transfer equation.

Terminology	Definition	Comments
Absolute bias	A systematic error between a measurement and the true value [RD-1]	This is of theoretical importance only here, as the exact true value of LST cannot be known due to measurement error
Accuracy	Accuracy is defined as the degree of conformity of the measurement of a quantity and an accepted value or the “true” value [RD-1]	
Angular anisotropy	It is defined as a difference in a material's physical or mechanical properties when viewed along different directions or axes [RD-3, RD-4]	For LST this refers to the surface emissivity at the macroscopic scale; and that at each specific location, and at each specific time, the dependence of LST on Sun position and viewing geometry is absolutely unique
Biome	The term biome in LST science is a generic type of vegetation, a biome set being used to constitute a land cover classification for all land points	For some LST retrieval schemes coefficients may be categorised by biome
Brightness temperature (BT)	Brightness temperature is the signal observed at the satellite instrument, calibrated to radiance and converted to the equivalent temperature of a perfectly emitting surface. Effectively it is the directional temperature obtained by equating the measured radiance with the integral over wavelength of the Planck’s Black Body function times the sensor response. It is the temperature of a black body that would have the same radiance as the radiance actually observed with the radiometer [RD-2]	

Terminology	Definition	Comments
Calibration	Calibration is the process of quantitatively defining the system response to known, controlled system inputs [RD-5]	It may involve the subsequent implementation of correction factors from ground or in-flight calibration to transform the measured signals in a satellite instrument to calibrated radiances
Discrepancy	Discrepancy described the lack of similarity between two measurements, where this is outside some expected error bound [RD-5]	
Error	Result of a measurement minus a true value of the measurand [RD-1]	Note that in practice, at least for LST, a true value cannot be determined and therefore a conventional true value is used instead
Fractional Vegetation Cover (FV / FVC)	The ratio of the vertically projected area of vegetation on the ground to the total vegetation area	For satellite data In simplified terms this is the fraction of a specified area that is covered by green vegetation. For LST retrieval this parameter has often been used to infer emissivity given emissivities for the fully vegetated or low vegetation states
Ground Truth	In situ measurements of a measurand	However, this term is generally not used because in situ measurements are not actually 'truth'
Ice surface temperature (IST)*	The surface temperature of ice bodies including land ice, and sea-ice, measured in situ and estimated from satellites	
Intercomparison	The process of comparing two or more (LST) data sets to allow evaluation of their relative consistency [RD-5]	
Land surface air temperature (LSAT)	A measurement of the average kinetic energy of the air near the surface of the Earth. This is usually measured at 2m height at meteorological stations [RD-6, RD-7]	

Terminology	Definition	Comments
Land Surface emissivity (LSE)	Emissivity describes a material's ability to emit the thermal energy as a fraction of that which would be emitted from a perfectly emitting surface (a blackbody) [RD-5]	Emissivity is a function of wavelength
Land surface temperature (LST)*	Land Surface Temperature (LST) is the mean radiative skin temperature derived from thermal radiation of all objects comprising the surface, as measured by remote sensing ground-viewing or satellite instruments [RD-2, RD-5]	It is a basic determinant of the terrestrial thermal behaviour, as it controls the effective radiating temperature of the Earth's surface
Lake surface water temperature (LSWT)*	The skin temperature of lake bodies including inland seas, reservoirs measured in situ and estimated from satellites [RD-7]	
Measurand	A measurand is the particular quantity subject to measurement [RD-1]	
Precision	Precision is the closeness of agreement between independent measurements of a quantity under the same conditions [RD-1]	
Radiance	Measure of the quantity of radiation emitted from the surface. The spectral radiance is the radiant flux in a beam per unit wavelength and per unit area and solid angle of that beam [RD-8]	Radiance is the spectral radiance integrated over wavelength
Radiometric temperature	Derived from a radiative energy balance of a surface and is the best approximation to the thermodynamic temperature based on a measure of radiance [RD-2]	
Random error	Result of a measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions [RD-1]	

Terminology	Definition	Comments
Reference standard	Measurement standard designated for the calibration "in situ" of other (similar) measurement systems. Usually applied to instruments of a given kind or at a given location for which the reference standard has been agreed to be relevant [RD-5]	
Relative bias	A systematic error between measurements obtained from different data sources [RD-5]	
Relative error	The relative error is the error of measurement divided by a true value of the measurand [RD-5]	
Satellite azimuth angle	The length of the arc of the horizon (in degrees) intercepted between North and the direction of the satellite from the observation point measured clockwise from the reference direction [RD-9]	This is frequently referred to as the Viewing Azimuth Angle (VAA)
Satellite zenith angle	The angle between a straight line from a point on the earth's surface to the satellite and a line from the same point on the earth's surface that is perpendicular to the earth's surface at that point [RD-9]	This is frequently referred to as the Viewing Zenith Angle (VZA)
Skin temperature	The temperature of a layer of a medium of depth equal to the penetration depth of the electromagnetic radiation at the given wavelengths [RD-2]	Surface brightness and radiometric temperatures are the effective temperature that a radiometer would measure near the surface, including emissivity effects and reflected downwelling radiance
Soil temperature	The sub-surface temperature measured at a given depth [RD-9]	

Terminology	Definition	Comments
Solar azimuth angle	The length of the arc of the horizon (in degrees) intercepted between North and the direction of the sun from the observation point measured clockwise from the reference direction [RD-9]	
Solar zenith angle	The angle between a straight line from a point on the earth's surface to the sun and a line from the same point on the earth's surface that is perpendicular to the earth's surface at that point [RD-9]	
Split-Window (SW)	Refers to the use of adjacent infrared filtered bands (channels in an instrument) to correct for atmospheric effects based on differential absorption [RD-10]	
Systematic error	Mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions minus a true value of the measurand [RD-1]	
Thermodynamic temperature	Thermodynamic temperature is a macroscopic quantity that is an absolute measure of temperature. A statistical interpretation of the thermodynamic temperature is referred to as the kinetic temperature, and it is a macroscopic quantity defined on a microscopic scale in terms of the mean kinetic energy of solid particles [RD-2]	
Total column water vapour (TCWV)	Amount of water (depth of vertical column of unit-crossectional area) which would be obtained if all the water vapour in a specified column of the atmosphere were condensed to liquid [RD-6]	

Terminology	Definition	Comments
True value	A true value is the value consistent with the definition of a given particular quantity [RD-5]	
Uncertainty	A parameter associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand, that is the value of the particular quantity to be measured [RD-1]	
Validation	The process of assessing, by independent means, the quality of the data products [RD-11]	Primarily this is an assessment of the accuracy using equivalent in situ observations
Validation loop	The validation loop describes the iterative process between algorithm development and validation, where validation findings are investigated and reflected in algorithm changes with the final goal of improving the output product [RD-5]	

2.2. Interactions with the International LST Working Group

Exploitation of LST and emissivity data, while being addressed through GlobTemperature faces challenges, which are common to the international community working in this area:

- Users requiring better understanding of the nature of the data
- Users wishing to see signposts to high quality LST products from individual sensors
- Users wishing for data in consistent formats with better understanding of data uncertainties
- Users wishing to use combined data or to derive their own combined datasets
- Users wishing to be confident of a formal communication route to LST experts

GlobTemperature will provide a foundation for collaboration and international progress. To further advance these common themes, a new group has been founded with the support of GlobTemperature in its first three years. The International Land Surface Temperature and Emissivity Working Group (ILSTE-

WG) is becoming a truly international initiative providing a unifying, collaborative element in the LST community bringing together users with producers and providers of data.

The ILSTE-WG has been founded jointly by a number of LST experts: representatives of NASA-JPL and members of the ESA GlobTemperature Team (specifically U. Leicester in the UK and IPMA in Portugal). The ILSTE-WG Steering Committee has been formed with agency representatives and LST experts and the first meeting was held on 6th June 2014. The Steering Committee is responsible for agreeing the Terms of Reference of the Group, planning for the General Meetings, and providing the leadership. The structure of the ILSTE-WG is presented in Figure 2, which additionally notes early-identified projects, which would benefit from the oversight of the ILSTE-WG. Further projects have been added to list, such as the ECOSTRESS Project run by NASA-JPL.

General Meetings take place bi-annually alternating between Europe (initially during the GlobTemperature User Consultation Meetings) and North America (during a large conference such as AGU); with Steering Committee teleconferences taking place every three to six months.

Common threads have already been identified for which the ILSTE-WG is becoming the forum to recommend best practice:

- Improved engagement with the international community of LST and Emissivity users
- The process towards acceptance and compliance of a harmonised data format
- Sharing of information, documentation and data – such as ground validation datasets
- Agreeing the derivation and endorsement of standard protocols in the field of LST and Emissivity
- Requirements for future instruments

To address these themes a number of task-orientated groups are being considered. These would focus on such particular elements of LST and Emissivity work.

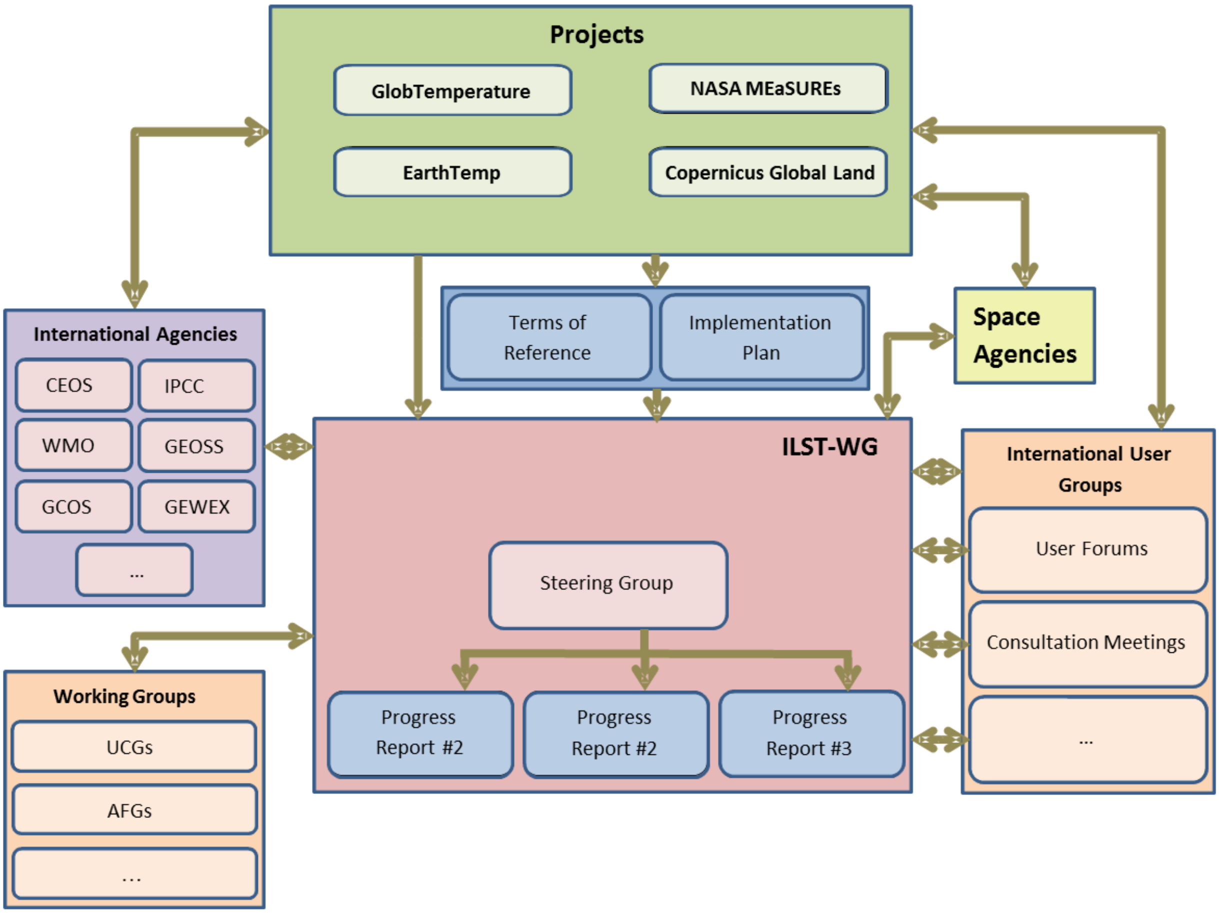


Figure 2: Schematic detailing the expected structure of the International LST & E Working Group (ILSTE-WG)

The first phase of the ILSTE-WG as initiated through GlobTemperature will have the following key functions:

- To 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

- To deliver a range of user-provider meetings and workshops, increasing links across the community.

- To support the alignment of LST best practice with the planned activities and data provision of operational agencies

- To agree standardised protocols for data formats and access to data, appropriate to key sectors of the LST user community.

- To support a dedicated validation group, supporting a consistent approach to data validation, in line with CEOS-LPV Best Practices, and linking individual validation projects.

- To provide an independent source of advice and appraisal, as requested, for GlobTemperature and other related projects such as the NASA MEaSUREs (Making Earth System Data Records for Use in Research Environments) Projects and the EarthTemp Network.
- To develop white papers on LST, setting out the state-of-the-art at regular intervals

With regards to the independent source of advice and appraisal for the GlobTemperature Project several deliverables have been identified whereby the ILSTE-WG could be used as a forum for review:

- DEL-04: GlobTemperature Web Portal
  - V1 [M12], v2 [M24], v3 [M36]
- DEL-05: Requirements Baseline Document
  - V1 [M12], v2 [M24], v3 [M36]
- DEL-06: Technical Specification Document
  - V1 [M06], v2 [M24]
- DEL-10: Technical Note – Definition of a common nomenclature for LST
  - [M12]
- DEL-12: Satellite LST Validation Report
  - V1 [M12], v2 [M24], v3 [M36]
- DEL-13: Satellite LST Intercomparison Report
  - V1 [M12], v2 [M24], v3 [M36]
- DEL-28: White Paper on Satellite LST
  - [M24]

Where feasible, individuals external to the GlobTemperature Project Team from the ILSTE-WG General membership are identified and approached to review specific deliverables (deliverable sections). In the interest of international buy-in and cooperation the ILSTE-WG will also be a focus for review on other related international LST projects. However, it must be stated that since the ILSTE-WG operates on a "best efforts" basis for most members the review of deliverables is entirely on the goodwill of international colleagues, and the maintenance and growth of the community takes priority. Current membership is outlined in Appendix A – International LST & E Working Group Membership.

GT-TS-2*: Organise and chair an international committee to provide an independent source of advice and appraisal for GlobTemperature (and related projects), and to act as a forum for user / expert interaction*

3. User Requirements

A primary purpose of the GlobTemperature Technical Specification is to document the strategy of delivering products which meet the requirements quantified following the User Requirements Survey. A key aspect here is traceability from these User Requirements through to the GlobTemperature outputs. In this section a brief overview of the User Requirements process is presented with the implementation detailed in Section 3.2.

3.1. Requirements Baseline Document summary

The Requirements Baseline Document version 0 (DEL-05) [AD-3] undertook the following forms of assessment of user requirements for LST: review of previous user requirements documents including the NASA white paper on LST and Emissivity Needs [RD-12], the LST User Exploitation document [RD-13] and the Sentinel Convoy for Land Applications report [RD-14]; an evaluation of user requirements from the questionnaires completed during the first User Consultation Meeting for GlobTemperature (UCM#1) [RD-15]; and the development, distribution and analysis of a new survey on user requirements completed by eighty respondents across the globe. From this assessment a comprehensive list of user requirements for best practice in LST data provision was compiled. The User Requirements defined from the results of the User Survey have been augmented with updates following mini-questionnaires carried out during breakout sessions The User Requirements defined from the results of the User Survey have been augmented with updates following mini-questionnaires carried out during breakout sessions.

Table 4).

The codes 'TR' and 'BR' in the requirement specification refer to 'threshold' and 'breakthrough' respectively; whereby threshold requirements indicate the limit beyond which data would be of no use for their application; and breakthrough requirements which indicate the level at which significant improvement to the given application would be achieved. Where questions did not permit different levels to be specified then requirements were considered to be at the threshold level.

It is pertinent here to briefly summarise the methodology for determining these requirements. To assess whether a GlobTemperature requirement could be quantified then three options were available. First, the responses were evaluated to see whether a 'hard' requirement could be issued on the basis of 75 % or more of participants agreeing on a particular option or where a particular specification would satisfy 75 % of respondents. If this type of requirement could not be constructed, an assessment was made as to whether a requirement based on a majority response could be issued. This type of requirement is appropriate where respondents could only select a single response from a range of options. Finally, if this type of requirement could not be issued, a decision could be made to construct a 'soft' requirement. This type of requirement was best suited to multiple choice questions where participants could select a range of options that they felt were applicable to their use of LST data. In this case, where 45 % or more of participants requested a particular option then a requirement was made for its provision.

If none of these types of requirement could be constructed then no requirement was issued. Once a requirement was identified then it was first checked against the outcomes of the first user consultation meeting (UCM#1) for agreement, differences or contradictions. Agreement and differences that are a natural refinement of the requirement were noted in the comments column of the requirements table. Where a contradiction occurred, the outcomes from both UCM#1 and the current survey were weighed to construct the final requirement, which was justified in the comments section of the requirements table along with a description of the discrepancy.

This process described related to threshold levels specified by respondents. Where the information was provided, the same process was reiterated with breakthrough level specifications. These were also included in the requirements table but are acknowledged as currently being more difficult to meet than the threshold requirements, primarily due to limitations in instrument capabilities rather than data production.

The User Requirements defined from the results of the User Survey have been augmented with updates following mini-questionnaires carried out during breakout sessions.

Table 4: GlobTemperature User Requirements V1 – updates are detailed in a separate table

Number	Requirement
REQ-1-TR	Provide LST data at a spatial resolution of 1 km or finer.
REQ-2-TR	Provide LST data at a temporal resolution of day/night (12 hours) or less.
REQ-3-TR	Provide a dataset of at least 10 years in length.
REQ-4-TR	Provide an LST uncertainty budget split into a number of different components eg. uncertainties from random and systematic effects.
REQ-5-TR	Provide LST data with a maximum bias of 1 K.
REQ-6-TR	Provide LST data with a precision of 1 K or better.
REQ-7-TR	Provide LST data with a stability of 0.3 K per decade or better.
REQ-8-TR	Provide cloud-screening information with LST data.
REQ-9-TR	Provide surface emissivity assumed in the LST retrieval as an ancillary data field.
REQ-10-TR	Provide LST data with individual file sizes of 200 MB or less.
REQ-11-TR	Provide access to LST data via FTP download.
REQ-12-TR	Provide LST data with timeliness for new observations of 24 hours.
REQ-13-TR	Provide the timeliness specified in REQ-12-TR for 99 % of observations.
REQ-14-TR	Provide dataset updates for reprocessing and algorithm development not more than once a month.

Number	Requirement
REQ-15-TR	Provide LST users with email alerts about data availability and reprocessing.
REQ-16-TR	Establish a single file specification covering all metadata requirements.
REQ-17-TR	Provide spatially averaged GEO, LEO or combined products in merged data at a resolution of 0.05 degrees or less.
REQ-18-TR	Provide temporally averaged GEO, LEO or combined products in merged data at a resolution of 3 hours or less.
REQ-19-TR	Provide a detailed description of externally linked datasets within a data portal.
REQ-20-TR	Provide links to product specification documents for LST products.
REQ-21-TR	Provide LST data with and without gap filling.
REQ-22-TR	Provide LST data in both swath and gridded format.
REQ-23-TR	Provide gridded LST products with both regular latitude-longitude and equal area projections.
REQ-24-TR	For averaged LST products timescales of day/night or 24 hours should be applied.
REQ-25-TR	Provide LST data at 0000, 0600, 1200, 1400 and 1800 local time.
REQ-26-TR	Provide LST data at an hourly resolution for UTC times.
REQ-27-TR	Provide LST data globally.
REQ-28-TR	Establish a common nomenclature for the expression of error and uncertainty terms and provide information on the definition of terms.
REQ-29-TR	Provide uncertainty information as confidence intervals, estimated root mean square total error or estimated mean and standard deviation of total error.
REQ-30-TR	Provide the 95 % confidence interval with confidence level information.
REQ-31-TR	Provide detailed flags for quality checks and statistics of data comparison with reference to in-situ validation data.
REQ-32-TR	Provide information on 2 m air temperature, aerosol affected pixels, the diurnal cycle and data adjustment.
REQ-33-TR	Provide land cover type, fraction of vegetation cover, albedo assumed in the retrieval and NDVI with LST data.
REQ-34-TR	Provide LST products in NetCDF format.
REQ-35-TR	Validate uncertainty estimates in LST data.
REQ-36-TR	Provide merged datasets globally.

Number	Requirement
REQ-37-TR	Provide descriptions of dataset length and coverage and a link to the main provider web page for data accessed via a portal.
REQ-38-TR	Provide dataset validation reports, detailed descriptions of file content and dissemination options and interactive map services for LST data.
REQ-39-TR	Provide tools for data reading and sub-setting, data extraction on different grids, data compositing, generation of match-up datasets, data visualisation tools, data inter-comparison tools, data processing tools, data analysis tools, trend analysis and tools for visualisation and evaluation of data uncertainties and quality.
REQ-40-TR	Provide LST data from single sensors, instrument series and merged products.
REQ-41-TR	Provide merged data both with and without gap filling.
REQ-1-BR	Provide LST data at a spatial resolution of < 1 km.
REQ-2-BR	Provide data at a temporal resolution of 3 hours or less.
REQ-3-BR	Provide LST data with a maximum bias of 0.1 K.
REQ-4-BR	Provide LST data with a precision of 0.1 K or better.
REQ-5-BR	Provide LST data with a stability of 0.1 K per decade or better.

3.2. User requirements for GlobTemperature products

The purpose of the Technical Specifications document is to formulate a strategy for the Project to follow in order for GlobTemperature to successfully deliver output products which meet at least the threshold requirement as stated in The User Requirements defined from the results of the User Survey have been augmented with updates following mini-questionnaires carried out during breakout sessions.

Table 4. A brief summary of the LST implementation is given in Table 5, with more detailed descriptions provided in the remainder of the document. In each sub-section where the implementation of a requirement is described then this is clearly indicated to provide additional traceability.

Table 5: GlobTemperature strategy to address User Requirements v1 – updates are detailed separately

Number	Technical Specification
REQ-1-TR	Single-sensor level-2 datasets for (A)ATSR, Metop-AVHRR and MODIS are to be provided in harmonised format
REQ-2-TR	Level-3 single-sensor datasets for (A)ATSR, Metop-AVHRR, and MODIS will be provided for day/night (12 hours) at standard temporal resolutions.
REQ-3-TR	Both the (A)ATSR single-sensor dataset and the (A)ATSR Climate Data Record will span over 10 years. In addition both MODIS single-sensor datasets for Terra and Aqua will also span over 10

Number	Technical Specification
	years.
REQ-4-TR	The proposed harmonised format distinguishes between the different components of the LST pixel uncertainty.
REQ-5-TR	Existing single-sensor datasets – AATSR [RD-16], MODIS [RD-17] and SEVIRI [RD-18] have been shown to produce LST data with a bias of ≤ 1 K. Each of these datasets will be disseminated via the GlobTemperature Data Portal in harmonised format. Furthermore, the objective of the (A)ATSR Climate Data Record is to reduce existing bias further.
REQ-6-TR	Existing single-sensor datasets – MODIS [RD-17] have been shown to produce LST data with a precision of ≤ 1 K. Both these datasets will be disseminated via the GlobTemperature Data Portal in harmonised format. Furthermore, the objective of the (A)ATSR Climate Data Record is to further improve precision.
REQ-7-TR	The (A)ATSR LST Climate Data Record aims to deliver a dataset with very high stability. Quantification of this currently remains unknown, although the 0.3 K is seen as a minimum goal (for SST the ARC product has a stability of better than 0.05 K per decade).
REQ-8-TR	The proposed harmonised format for Level-2 products specifies cloud-screening information as a mandatory component of the Quality Control flags.
REQ-9-TR	The proposed harmonised format identifies surface emissivity assumed in the LST retrieval as an ancillary data field. For single-sensor datasets which explicitly exploit surface emissivity in their retrieval, such as MODIS, this will be provided as mandatory information.
REQ-10-TR	The choice of netCDF-4 as the format preferred by the user community allows for high-level of internal compression of datafiles with no difference in read performance to uncompressed files. As such, all Level-2 and Level-3 will be able to be provided with individual file sizes less than 200 MB.
REQ-11-TR	Access to LST data will be provided via dedicated FTP download from temporary user workspaces. These temporary user workspaces will be created when users place bulk orders for data via the Data Portal, with files deleted after a period of two weeks.
REQ-12-TR	The GlobTemperature NRT Merged LST demonstration product processed at IPMA's operational chain, archived locally and made available via FTP through the GlobTemperature portal aims to provide timeliness for new data of less than 24 hours
REQ-13-TR	The aim for the demonstration NRT project is to provide the majority of data at the objective timeliness described in REQ-12-TR. The maximum timeliness for data being 2 days
REQ-14-TR	Once a dataset is released to the user community via the Data Portal any further evolution of the algorithm and re-processing will be subject to a minimum period of one month being enforced between releases. In reality it is not foreseen that progressive releases of the same dataset will occur at such a high frequency as once a month.
REQ-15-TR	All users on the GlobTemperature User Mailing List will be provided with email alerts about data

Number	Technical Specification
	availability and reprocessing. Users are currently being informed of upcoming events and new releases of components of the GlobTemperature Website / Data Portal and continuation of this to data availability and reprocessing is straightforward. The GlobTemperature User List is being maintained as new users are both identified externally and through registration via the GlobTemperature Website.
REQ-16-TR	Standard metadata are an important component of the harmonised format. Exact individual metadata will be iterated with the ILSTE-WG to ensure all metadata requirements are covered.
REQ-17-TR	The Tier-1 and Tier-2 Merged LST Products will provide spatially averaged GEO, LEO and combined products at 0.05°.
REQ-18-TR	The Tier-1 combined GEO/LEO product will provide temporally averaged merged data at a resolution of 3 hours.
REQ-19-TR	Each dataset disseminated or linked from the GlobTemperature Data Portal will also contain a dedicated page describing the product with a breakdown of the Metadata.
REQ-20-TR	Each dataset disseminated or linked from the GlobTemperature Data Portal will also contain downloadable .pdf links of Product User Guides (PUGs) which will contain detailed descriptions of the Products and how to extract and exploit the data in the accompanying datafiles.
REQ-21-TR	Tier-1 Merged LST Products will be gap-filled, and Tier-2 Merged LEO and Merged GEO LST Products will be provided without gap-filling.
REQ-22-TR	Single-sensor LST datasets will be provided as both level-2 (swath) and level-3 (gridded) products in the agreed harmonised format.
REQ-23-TR	For global gridded datasets equal-angle (regular latitude-longitude) is more suitable for global user applications and if user demand is sufficient will be provided at a broad set of resolutions defined in Section 6.5.5 to successfully meet the wide range of user requirements. For high latitude applications then equal area projections are more suitable and as such dedicated polar IST / LST datasets will be available in these projections.
REQ-24-TR	For the single sensor datasets Level-3 products will be averaged by day and night.
REQ-25-TR	The Tier-1 combined GEO/LEO product will provide temporally averaged merged data at a resolution of 3 hours (at 0000, 0300, 0600, 0900, 1200, 1500, 1800, 2100 UTC). The single-sensor GEO datasets will also provide data at hourly resolutions or better meeting the requirement of data at the requested times.
REQ-26-TR	The single-sensor GEO datasets will provide data at hourly resolutions or better.
REQ-27-TR	All single-sensor LEO datasets will be provided globally in the agreed harmonised format. In addition, GlobTemperature merged LST and the (A)ATSR Climate Data Record will also be provided globally.
REQ-28-TR	The common nomenclature detailed in Section 2.1 will be provided to the user community via the GlobTemperature Website. This includes definitions of all terms related to the retrieval and

Number	Technical Specification
	validation of LST, IST and LSWT including error and uncertainty terms. The common nomenclature is to be agreed with the ILSTE-WG.
REQ-29-TR	Uncertainty information is to be provided as mandatory in the harmonised format. For Level-2 datasets this amounts to total uncertainty on a pixel basis. In other words a single value per pixel that characterizes the dispersion of the values that could reasonably be attributed to the measurand. Optional uncertainty information allows the Data Provider to break this down into its component elements. For higher-level products, as well as total grid cell uncertainty, the uncertainty information can be optionally disaggregated into random, synoptically correlated, and sampling components.
REQ-30-TR	As stated for REQ-29-TR uncertainty information is to be provided as the value that characterizes the dispersion of the values that could reasonably be attributed to the measurand rather than as confidence levels.
REQ-31-TR	Mandatory consolidated cloud and confidence flags are to be provided in the quality control (QC) variable of the harmonised product. Optional detailed cloud and confidence flags from Level-1b source data can also be provided for additional quality checks. Statistics of data comparison with reference to in-situ validation data and for satellite-to-satellite comparisons will be provided in the Validation and Intercomparison Reports available via the GlobTemperature Website.
REQ-32-TR	Where the information is available, Level-2 single-sensor datasets in harmonised format will provide information on 2 m air temperature and aerosol affected pixels as a QC flag. Such information will be averaged to Level-3 if available. The GlobTemperature Merged LST Product will resolve the diurnal cycle. Where data adjustment is performed this will be provided in the harmonised format as attribute comments.
REQ-33-TR	Where available, land cover type, fraction of vegetation cover, albedo assumed in the retrieval and NDVI will be provided with LST data. All these fields are included in the harmonised format. AATSR for example includes land cover type, fraction of vegetation cover and NDVI as standard.
REQ-34-TR	The proposed harmonised format for all LST products is netCDF-4.
REQ-35-TR	The uncertainty estimates for all GlobTemperature LST output products will be validated in addition to the LST data following taking guidance from the SST approach.
REQ-36-TR	The GlobTemperature Merged LST Product will be provided as both global and regional datasets.
REQ-37-TR	All datasets disseminated via the GlobTemperature Data Portal will have a full list of metadata accompanying the dataset as a page of information on the Data Portal. This will include descriptions of dataset length and coverage and a link to the main provider web page.
REQ-38-TR	For each disseminated dataset in the harmonised format the GlobTemperature Data Portal will provide links to dataset validation reports, detailed descriptions of metadata – with links to download Product User Guides - and information on the dissemination options. For LST data both FTP download, and interactive map services will be provided for acquiring LST data.

Number	Technical Specification
REQ-39-TR	Python tools, which are platform independent, will be provided to read the LST data in their harmonised formats; such tools will allow for sub-setting. The visualisation suite on the Data Portal will allow users to view data composited on different timescales, maps and time-series of data intercomparisons from the matchup database, and LST and LST anomalies.
REQ-40-TR	GlobTemperature LST output products will include single-sensor datasets in harmonised format, datasets of the (A)ATSR instrument series (Climate Data Record), and Multi-Sensor Merged LST.
REQ-41-TR	Tier-1 Merged LST Products will be gap-filled, and Tier-2 Merged LST Products will be provided without gap-filling.
REQ-1-BR	The GlobTemperature Data Portal will link to an external data centre for VIIRS Land Surface Temperature Environmental Data Record which has a spatial resolution of ~0.75 km (Section 4.2.7). Very high spatial resolution data (< 100 m) is not planned for delivery within the framework of the GlobTemperature Project. However, the ASTER Global Emissivity Database (GED) contains climatology of mean LST at 100 m; a link to this this dataset will be provided from the GlobTemperature Data Portal (Section 4.2.12). Furthermore, post-Project support of the Data Portal allows for the possibility of high resolution data being made available via this single LST portal.
REQ-2-BR	The Tier-1 combined GEO/LEO product will provide temporally averaged merged data at a resolution of 3 hours.
REQ-3-BR	The (A)ATSR LST Climate Data Record aims to deliver a dataset with very low bias. Quantification of this currently remains unknown.
REQ-4-BR	The (A)ATSR LST Climate Data Record aims to deliver a dataset with very high precision. Quantification of this currently remains unknown.
REQ-5-BR	The (A)ATSR LST Climate Data Record aims to deliver a dataset with very high stability. Quantification of this currently remains unknown.

3.3. Feedback on data formats

Question thirty-eight of the User Requirements Survey, as detailed in the Requirements Baseline Document [AD-3], asked participants in which file format they would like LST data to be provided. Respondents were only able to select one option; however, some indicated via the 'other' box that more than one file format was acceptable and information was been included in the responses where provided. The favoured file format is CF-Compliant NetCDF with 33 of 68 respondents selecting this option. The next nearest choice was HDF-EOS (which is standard format of MODIS products) with 16 participants expressing a preference for this format (Figure 3).

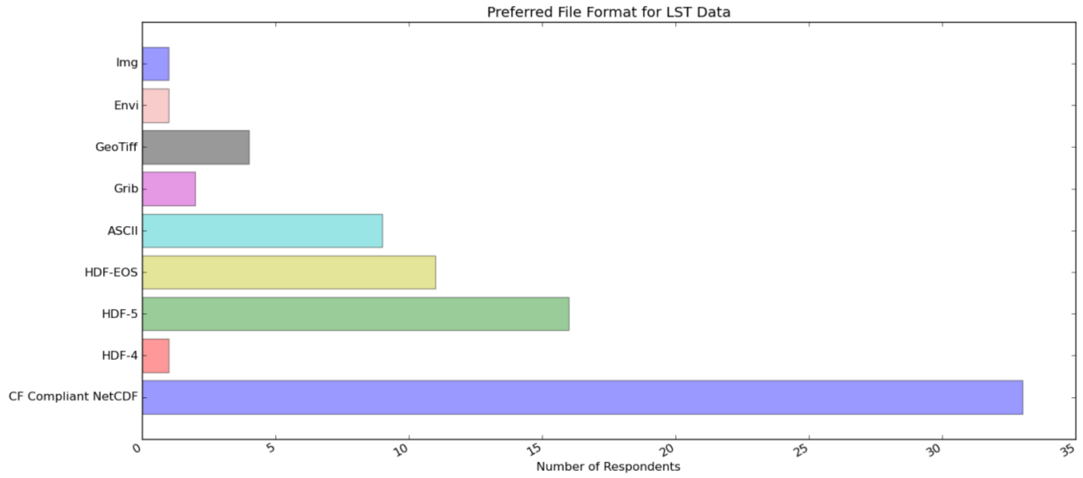


Figure 3: A summary of the preferred file formats for the provision of LST data. Information comes from question thirty-eight of the GlobTemperature User Requirements survey.

NetCDF format is a self-describing, portable, scalable, appendable, sharable, archivable, and machine-independent data format. It is supported by all major data analysis and visualisation packages, such as for example IDL, Matlab, R, BEAM, Panoply, etc., and programming interfaces exist for a wide variety of other programming languages.

As such, CF-compliant netCDF-4 is the proposed format for all GlobTemperature data products (**addresses requirement REQ-34-TR**). The exact description of the proposed format is presented in Section 6.5. To ensure data file sizes remain manageable it is further proposed that all GlobTemperature data products are internally compressed to the highest level (level 9) possible (**addresses requirement REQ-10-TR**). There is no detriment to the performance of reading these datafiles by implementing the highest-level of internal compression; the compression of the datafiles instead only impacts the initial writing of the datafiles and is thus borne internally by the Project rather than impacting the users.

GT-TS-3*: The basis for the GlobTemperature harmonised formats will be CF-compliant netCDF-4 with individual file sizes < 200 Mb*

The distinct features of Level-2, Level-3, Level-4 and databases for multi-sensor validation and intercomparison necessitate minor enhancement to these grouped harmonised formats, but all based on core variables and common metadata. Standard metadata are indeed an important component of the harmonised format (Section 6.5.3). A single file specification covering all metadata requirements will be implemented for GlobTemperature output datasets, with common naming conventions across Level-2, Level-3, Level-4 and the GlobTemperature Matchup Database (GT_MDB) for equivalent variables (**addresses requirement REQ-16-TR**). Exact individual metadata will be iterated with the ILSTE-WG to ensure all metadata requirements are covered. The CF (Climate and Forecast) metadata conventions are designed to promote the processing and sharing of files created in netCDF format. It has been adopted by a wide variety of national and international programs as the standard, including GHRSST in the domain of surface temperature. The conventions define metadata that provide a definitive description of what the data in each variable represents, and the spatial and temporal properties of the data. This enables users of data from different sources to decide which quantities are comparable, and facilitates building applications with powerful extraction, re-gridding, and display capabilities (http://cfconventions.org/) [RD-19].

The finalised form of the CF-compliant netCDF-4 harmonised format is to be iterated with the ILSTE-WG, with user feedback provided through the User Consultation Meetings.

GT-TS-4*: Ensure User Requirements are updated with feedback from the International LST & E Working Group (ILSTE-WG) and the User Consultation Meetings (UCMs)*

3.4. Evolution of Requirements Baseline Document and User Requirements for GlobTemperature Products

3.4.1. Quantitative User Requirements

The User Requirements (Table 4) defined from the results of the User Survey have been augmented with updates following mini-questionnaires carried out during breakout sessions thus satisfying the technical requirement **GT-TS-4**; these updates are recorded in Table 6.

Table 6: Updates to GlobTemperature User Requirements. Text highlighted indicate updates following both UCM#2 (blue) and UCM#3 (green)

Number	Requirement
REQ-3-TR	Provide a dataset of at least 30 years in length.
REQ-12a-TR*	Provide LST NRT data with timeliness for new observations of 12 hours.
REQ-12b-TR*	Provide LST long-term data record updates with a timeliness of 1 month for new observations.
REQ-14-TR	Provide dataset updates for reprocessing and algorithm development not more than quarterly.
REQ-32-TR	Provide information on 2 m air temperature, aerosol affected pixels, the diurnal cycle and data adjustment, total column water vapour, wind speed and humidity.
REQ-39-TR	Provide tools for data reading and sub-setting, data extraction on different grids, data compositing, generation of match-up datasets, data visualisation tools, data inter-comparison tools, data processing tools, data analysis tools, trend analysis and tools for visualisation and evaluation of data uncertainties and quality, time series extraction.
REQ-42-TR	Explore ways of sharing data reading and visualisation tools within the LST community.
REQ-43-TR	Provide a data download tool with the ability to screen data as a function of cloud cover prior to download.

Number	Requirement
REQ-44-TR	Provide tiled data for L3, L4 and geostationary satellite products at 10 x 10 degree resolution.
REQ-6-BR	Provide LST NRT data with timeliness for new observations of 6 hours.
REQ-7-BR	Provide LST long-term data record updates with a timeliness of 48 hours for new observations.

Table 7: GlobTemperature strategy to address updates to User Requirements; updates to the strategy are highlighted in red.

Number	Technical Specification
REQ-3-TR	Both the (A)ATSR single-sensor dataset and the (A)ATSR Climate Data Record will span over 10 years. In addition both MODIS single-sensor datasets for Terra and Aqua will also span over 10 years. The SST CCI Project is deriving intercalibrated L1b AVHRR GAC data spanning 30 years. Although outside the original framework of GlobTemperature, the project will investigate the potential exploitation of this L1b data stream to develop a future 30+ year LST data record.
REQ-12a-TR*	The GlobTemperature NRT Merged LST demonstration product processed at IPMA's operational chain, archived locally and made available via FTP through the GlobTemperature portal aims to provide timeliness for new data of less than 24 hours. The objective will be set to 12 hours, although final timeliness will be dictated by technical feasibility.
REQ-12b-TR*	The only long-term datasets (over 10 years) being derived in GlobTemperature are for (A)ATSR and MODIS. (A)ASTR is a historical data record so is not applicable to this requirement. The GlobTemperature "value-added" MODIS products will be developed with new observations aimed at timeliness within 1 month.
REQ-14-TR	Once a dataset is released to the user community via the Data Portal any further evolution of the algorithm and re-processing will be subject to a minimum period of quarterly being enforced between releases. In reality it is not foreseen that progressive releases of the same dataset will occur at such a high frequency as quarterly.
REQ-32-TR	Where the information is available, Level-2 single-sensor datasets in harmonised format will provide information on 2 m air temperature, total column water vapour, wind speed and humidity; with aerosol affected pixels as a QC flag. Such information will be averaged to Level-3 if available. The GlobTemperature Merged LST Product will resolve the diurnal cycle. Where data adjustment is performed this will be provided in the harmonised format as attribute comments.
REQ-39-TR	Python tools, which are platform independent, will be provided to read the LST data in their harmonised formats; such tools will allow for sub-setting. The visualisation suite on the Data Portal will allow users to view data composited on different timescales, maps and time-series of data intercomparisons from the matchup database, and LST and LST anomalies. For time series extraction a tool will be developed tool that allows cloud filtering to provide data as both a plot and csv data file. The aim will be to extract for a given pixel a time series covering

Number	Technical Specification
	an entire instrument mission; although this will require considerable processing thereby requiring the user to accept a waiting time on delivery.
REQ-42-TR	A repository will be set up to allow users to share data reader and visualisation tools within the community. A minimum set of required information will be requested of any user wanting to share their tools and the user must accept responsibility for ensuring the robustness, security and any licensing matters regarding the tools are satisfied. Maintenance of the tools do not lie within the remit of the GlobTemperature consortium.
REQ-43-TR	Cloud cover information provided within the QC flags of the GlobTemperature Products can be applied by the Data Portal facility prior to dissemination. This would though increase the waiting time for users to acquire the final data.
REQ-44-TR	All L3 and L4 data are provided as tiled datafiles with the nominal resolution chosen as 10° x 10°. The Geostationary data within the Merged product is also to be provided as tiled datafiles at this same resolution.
REQ-6-BR	The only GlobTemperature “operational” data product currently within scope is the NRT Merged Product demonstration. Since this requires data from multiple input data streams with considerable processing requirements such timeliness is not considered feasible. However, once data from Sentinel-3 becomes available a NRT GlobTemperature LST Product for Sentinel-3 would be feasible within the remit of a CCN.
REQ-7-BR	The production of “operational” “value-added” MODIS data with a timeliness of 48 hours for new observations would be feasible within the remit of a CCN

3.4.2. Qualitative User Feedback

Although much of the feedback obtained during UCMs are of a qualitative nature and thus not necessarily suitable for deriving User Requirements – which then drive Technical Specifications – such feedback is nevertheless pertinent to the direction of the Project; and indeed in the methods employed to deliver the most appropriate products to maximise exploitation. As such, where possible the response to this user feedback has been enumerated as GT-UFs and addressed throughout the Technical Specifications. A summary of the key user feedback is now presented:

UCM#2

- There is an urgent need to better understand/characterise the relationships between i) observations of “all-sky” land surface air temperature (LSAT) and “clear-sky” thermal infrared (TIR) LST; and ii) TIR retrieved LST and microwave (MW) retrieved LST ensure including the “clear-sky” bias.
- Clear interest in global long-term datasets of LST - the desire being for 30-year datasets – with both “all-sky” and “clear-sky” products.

- Many users are interested in high spatial resolution (< 1km) LST data, and even (< 100m) particularly in urban and ET applications.

- The importance of mission continuity was expressed and the subsequent continuity in the provision of LST products (example includes Landsat-8 and Sentinel-3).

- A common LST terminology is needed, which includes a common protocol on validation and independent comparisons between datasets. This needs to be communicated to the user community.

- Need for consistent and accurate LST products, with unified formats (NetCDF and GIS-friendly GeoTiff) and metadata, product lists and dissemination schedules; with the provision of as much ancillary information as possible through the option of being able to customise the dataset files.

- For higher-level products there is a requirement for information to be preserved from the Level-2 products on the quality of the input data, and time of observations of the input data for example.

- Current cloud screening was frequently viewed as not sufficient to meet application needs; with some regions particularly problematic - high latitude being one of them.

- Provision of "user-friendly" uncertainties in the output LST products to enable appropriate selection of datasets in applications, with information on their derivation and consistency between datasets. Ideally this should be at a per-pixel level. Metadata and/or documentation describing the uncertainty metrics, how the uncertainty value is calculated and how the data is processed.

- Key requirements were extraction tools to subset datafiles with all information retained through the extraction process, and simple visualisation tools / Quick Looks to examine data at different resolutions, to format the selection and visualise data in different projections, with a filter for cloud cover. While some users are more likely to adapt their existing tools, others would require the data provider to provide tools.

- Much consensus in principle on the concept of users sharing extraction / visualisation tools within the LST community, although copyright issues prevent some users from sharing their tools; such a concept would require ensuring shared tools were error free.

UCM#3

- High accuracy LST data for urban studies is in high demand, at both medium and high spatial resolutions. It should be noted, that this weighting towards this request may partially be a result of the large numbers of urban participants following on from the EarthTemp meeting.

- There were numerous studies which highlighted the need for high quality LST data from polar-orbiting satellites with near daily global coverage spanning multiple years. In this regards the MODIS LST, NOAA-AVHRR GAC LST, and Metop-AVHRR LST data should be prioritised.

- Only some of the GlobTemperature datasets and very few external datasets provide sufficient information on uncertainties; this needs to be addressed.

- Emissivity is requested as information in auxiliary datafiles, although it is recognised that this may be more challenging when embedded in the coefficients for some retrievals

- With reference to the (A)ATSR CDR users would like to know the number of data points/pixels used in averages as well as the times of the observations. Scan times could be put inserted into the auxiliary data file with the number of cloudy pixels

- Cloud detection is still a major problem to users, and a renewed effort on cloud clearing for existing and new products is recommended. Cloud screening algorithms applied should be documented. Furthermore, filtering for cloud at the point of data download is seen as extremely relevant and was a tool that would be widely used.

- Increasing the provision of microwave data since only 1–year of SSM/I data is currently available from the Data Portal, and a suggestion is that this could be formatted more consistently with the other LST datasets available.

- Increased sharing of expertise and experiences regarding best validation protocols and calibration procedures is recommended.

- Enhancement of the QC information: such as a comprehensive description of the flags and how to use them; and quality flags of value 1-5 to give consistency with sea surface temperature products. Overall quality should be moved up in the QC since more important than the day/night flag, with a bit tool/decoder to produce a mask on the QC inserted into the extraction tool.

- Some users found the delivery of many Level-2 and -3 files difficult to handle. It is suggested that daily files with global coverage would be useful with the possibility to download all the data as single zip-files. Improved folder structure can decrease download time such as one folder per year if there is only one file per day.

- Level-3 sub-setting - the tile remains the common unit, although global are also desirable. Enable tiles to be aggregated into a single file when multiple are selected from an ROI selection. It was acknowledged that there is a time penalty in aggregation - that seems to be okay to prevent users from having to do it.

- Data extraction should be user selectable (both in terms of area and the requested data fields), and able to work at a single pixel scale with some visualisation capability

- An extraction tool where a user can supply a list of validation location lat/lons and behind the scenes the data is extracted for all of the available sensors over the available time period

- Provision for users to send a disk and have an entire archive uploaded and posted back.

4. Current and Future LST Datasets

4.1. Current LST datasets

We first describe the LST datasets currently being produced by the various space agencies. For each satellite sensor dataset a description of the satellite sensor is provided followed by a summary of the LST dataset algorithm.

4.1.1. (Advanced) Along Track Scanning Radiometers (A)ATSR

This series consists of three instruments (ATSR-1, ATSR-2 and AATSR (Advanced Along-Track Scanning Radiometer) on board the European Space Agency (ESA) sun-synchronous, polar orbiting satellites ERS-1 launched in July 1991, ERS-2 launched in April 1995, and Envisat launched in March 2002, respectively. All these instruments have used similar orbits and equator crossing times ensuring a high level of consistency - thus providing approximately 20 years of data. Continuation of this data will be sustained with the launch of the Sea and Land Surface Temperature Radiometer (SLSTR) on board Sentinel-3. AATSR has good radiometric accuracy of less than 0.1 K, which is achieved using Stirling Cycle coolers to maintain the infrared detectors in an optimal thermal environment. On board calibration was performed by utilising two blackbodies which were scanned once each scan cycle. For LST retrieval the quoted target accuracy is 2.5 K during the day, and 1 K at night [RD-20]. For ATSR-1 the radiometric accuracy gradually deteriorated over the lifetime of the instrument as the detector temperatures increased, whereas for ATSR-2 good radiometric accuracy of less than 0.1 K was achieved over its lifetime. However, no data were acquired from ATSR-2 between December 1995 and June 1996 due to the scan mirror anomaly; and the ERS-2 gyro failure in January 2001 affected the satellite's ability to maintain its normal stellar yaw-steering mode.

A distinguishing feature of the ATSRs was the dual-angle (DA) capability (nadir and forward at an angle of ~55° to nadir). However, only the nadir view is utilised in the standard ESA LST retrieval - this being a split-window (SW) algorithm in which 1 km LST is retrieved based on the infrared channels at 11 and 12µm, whereby regression coefficients depend on fraction of vegetation cover, precipitable water, and land cover classes. With a swath width of 512km, AATSR is able to provide approximately 3-day global LST coverage with a repeat cycle of 35 days. Potential exploitation of the DA view for LST has received little attention; although [RD-21] did assess both SW and DA over topographically flat and homogeneous rice fields and found DA algorithms to be less accurate.

The (A)ATSR LST algorithm uses a nadir-only split-window algorithm [RD-22]:

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

where the retrieval coefficients $a_{f,i,pw}$, $b_{f,i}$ and $c_{f,i}$ are dependent on the biome (*i*), fractional vegetation cover (*f*), precipitable water (*pw*), satellite zenith view angle ($p(\vartheta)$), and the time of day (day or night); the terms *f* and *pw* are seasonally dependent whereas the biome (*i*) is invariant.

In the case of the ESA standard (A)ATSR Level-2 LST (ESA_V3) product there are 13 land biome classes and one lake class at a spatial resolution of 0.5°. The SiB/ISLSCP fractional vegetation cover product and the precipitable water auxiliary data from the NASA Water Vapour Project (NVAP) climatology also have a spatial resolution of 0.5°. These latter two are composed of separate global datasets for each month of the year. Issues relating to the auxiliary biome and fractional vegetation data utilised by the product were identified from validation, with the conclusion being that the resolution of these data were not high enough for their intended purpose [RD-23, RD-24].

As such substantial development under the ESA Long Term Land Surface Temperature Validation Project led by the University of Leicester has produced a significantly improved product (UOL_LST_2P) for AATSR [RD-16, RD-25]. The ESA_V3 auxiliary datasets have been superseded with near 1 km data. The new biome auxiliary data is a variant of the Globcover classification [RD-26], with the original 1/360° spatial resolution product having been re-gridded to 1/120°. In addition, the original Globcover bare soil class has been divided into six separate classes, taking the total number of land and inland water classes to 27. To incorporate these changes the Globcover nomenclature has been replaced, with the new classification system known as the ATSR LST Biome version-2 (ALB-2).

In addition to the 27 land and inland water classes an additional biome class (ALB-2 class 0) is included for completeness and represents the ocean and large lakes – this corresponds to where the AATSR land-sea mask identifies a pixel as sea – whereby SST is retrieved rather than LST. Inland and coastal water (ALB-2 class 26) represents the remaining water - classified as land by the land-sea mask. Although the biome classification is invariant - being based on the 2006 Globcover product - on any given orbit every pixel including class 0 is assessed for snow and ice cover. Where snow or ice is identified the pixel is reclassified as permanent ice (ALB-2 class 27) and LST is retrieved by applying the associated coefficients.

Fractional vegetation cover is taken now from the Geoland-2 FCOVER dataset, which is available globally at the desired near 1-km resolution of 1/112° every 10-days from 1999 and acquired from a moving temporal window of approximately 30-day composites of observations [RD-27]. The values of FCOVER are computed from leaf area index and other canopy structural variables available in the CYCLOPES (Carbon cYcle and Change in Land Observational Products from an Ensemble of Satellites) product using a neural network trained from the 1-D radiative transfer models SAIL and PROSPECT. The 10-day AATSR fractional vegetation cover auxiliary dataset is created from the FCOVER dataset with missing values gap-filled from climatology.

Precipitable water is derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis. Each auxiliary data file is derived from 6-hourly monthly climatology corresponding to the 4 synoptic times - 00UTC, 06UTC, 12UTC and 18UTC - covering the 10-year period 2002 – 2011 inclusive.

The standard ESA LST retrieval algorithm was implemented in version 5.58 of the AATSR Instrument Processing Facility (IPF) in March 2004, and in 2008 the archive was re-processed to include version 6.01 of the IPF. These standard products have been consistently processed to Level-2 LST utilising this same algorithm. UOL_LST_2P has been reprocessed from the L1b data following the ATSR 3rd reprocessing.

For IST, prior knowledge of the surface type is required in order to allow selection of the most suitable retrieval algorithm. The (A)ATSR IST dataset [RD-28] applies LST coefficients to retrievals over snow and ice. These coefficients have been regressed from radiative transfer modelling of permanent snow and ice surfaces utilising associated atmospheric profile and emissivity data. Where a surface is identified as transient snow/ice or sea-ice these IST coefficients are applied instead of the respective LST or SST coefficients.

The variability of surface type dictates a requirement for a dynamic mask that demarcates snow/ice-covered areas from snow/ice-free areas in addition to the usual requirements for a land-sea mask. Furthermore, it is the differentiation of ice from cloud over both land and water using the data available from the instrument channels that can be the most challenging feature of IST retrieval. For determination of the snow mask third-party ice extent data from OSTIA is used for sea-ice extent and over the land [RD-29] is used for daytime retrievals and IMS data for land-ice extent at night; the cloud mask is then an application of the UOL_V3 cloud clearing algorithm, which has been shown to perform well [RD-30].

Lake surface water temperature (LSWT) retrievals from ATSRs have been developed under the ESA project, ARC-Lake. Earlier work [RD-31] established that LSWT retrieval using standard ATSR SST retrieval coefficients is prone, for some lakes, to retrieval biases of 0.5K. Rather than specifying lake-specific retrieval coefficients and cloud clearing methods, which becomes less practical when considering all lakes resolvable by ATSR (> 1000), ARC-Lake uses optimal estimation (OE) retrieval and probabilistic (Bayesian) cloud screening techniques. This methodology is generic (i.e. applicable to all lakes) as variations in physical properties such as elevation, salinity, and atmospheric conditions are accounted for through the forward modelling of observed radiances.

The ARC-Lake LSWT algorithm [RD-32] uses the radiative transfer model, RTTOV8.7 [RD-33], driven by the NWP profile for the state of the atmosphere from ECMWF, to simulate top-of-atmosphere brightness temperatures for ATSR. Prior surface temperature fields (on a 1/120° grid) for the forward modelling are derived iteratively from ATSR observations using empirical orthogonal function techniques to fill in gaps in the observations (e.g. clouds). LSWT retrievals are performed at the ATSR level-1b pixel resolution using (where possible) dual-view 3-channel for night-time and dual-view 2-channel retrievals for day-time, before being averaged onto a 0.05° grid.

Currently, day and night-time ARC-Lake v2.0 LSWT products are available for 258 of Earth's largest lakes (mostly of area exceeding 500 km^2) from 1991 to 2011 [RD-34]. Lake locations have been defined using a land/water mask derived from a combination of a 1/120° global gridded binary mask (NAVOCEANO) and polygon data from the Global Lakes and Wetlands Database (GLWD) [RD-35]. Improvements in coverage and LSWT retrieval biases from ARC-Lake, compared to LSWTs from operational SST retrievals has been demonstrated as has the potential use of ARC-Lake LSWTs in climate applications [RD-36]. Ongoing work

(Globolakes: www.globolakes.ac.uk) is building on ARC-Lake but extending this dataset to smaller lakes, of order 100 km^2, providing a 20 year temperature record for approximately 1000 lakes.

4.1.2. Advanced Very High Resolution Radiometers (AVHRR)

The Advanced Very High Resolution Radiometer (AVHRR/3) is an across track scanner that senses the Earth's outgoing radiation from horizon to horizon: scan range of ±55.37º and a swath width of about ±1447 km. It provides global observations in the visible and infrared bands detailed in Table 8. These measurements are available twice a day (higher frequency may be achieved over the Polar Regions), at 1.1 km resolution at the sub-satellite point.

Although AVHRR/3 is a six-channel radiometer, only five channels are transmitted to the ground at any given time, since channels 3a and 3b do not operate simultaneously. For Metop satellites, channel 3a is operated during the daytime portion of the orbit and channel 3b during the night-time portion.

Table 8: Characteristics of the Advanced Very High Resolution Radiometer (AVHRR/3) onboard Metop

Channel	Central wavelength $\lambda_{central}$ (µm)	Radiometric Noise
1	0.630	S/N 9 at 0.5% albedo
2	0.865	S/N 9 at 0.5% albedo
3a	1.610	S/N 20 at 0.5% albedo
3b	3.740	0.12K at 300K
4	10.800	0.125K at 250K
5	12.000	0.12K at 250K

The LSA SAF adopted a procedure for LST retrieval from AVHRR split-window channels similar to that described above for SEVIRI data, but taking into account AVHRR response functions. Again emissivity estimates are based on the so-called Vegetation Cover Method and atmospheric correction takes into account hourly forecasts obtained from the operational global ECMWF model.

The AVHRR/Metop LST is first generated on a pixel-by-pixel basis. A daily composite is then generated from the former, where LST is re-projected onto a regular (0.01°) grid to form two regular fields (65ºS – 65ºN) with local daytime and night-time passages, respectively. Such processing of daily composites is not operational yet at the LSA SAF system; the respective operational readiness review is planned for the 1st quarter of 2015.

4.1.3. Special Sensor Microwave / Imager (SSM/I)

The Special Sensor Microwave / Imager (SSM/I) sensors have been on board the Defense Meteorological Satellite Program (DMSP) polar satellites since 1987. They observe the Earth twice daily at 19.35, 22.235, 37.0, and 85.5 GHz with both vertical and horizontal polarizations, with the exception of 22 GHz, which is for vertical polarization only. The observing incident angle is close to 53°, and the elliptical fields of view decrease in size proportionally with frequency, from 43 x 69 to 13 x 15 km^2. The local times of their descending and ascending modes are early morning and late afternoon respectively. There are up to 4 SSM/I instruments in space at the same time (with similar overpassing times).

A methodology has been developed to estimate the LST, along with atmospheric water vapour, cloud liquid water, and surface emissivities over land, from passive microwave imagers [RD-37]. It is based on a neural network inversion, trained on a large data set of simulated radiances, using real atmospheric and surface information over the globe. It makes use of a first guess information about emissivity (pre-calculated directly from the satellite observations, [RD-38]), and coincident surface skin temperature (derived under clear sky condition from IR observations, through the ISCCP program, [RD-39]). The method has been applied to the Special Sensor Microwave/Imager measurements, and LST have been estimated with a spatial resolution of 0.25°x0.25°, at least twice daily, depending on the number of SSM/I instruments in space. The theoretical RMS error of the LST over the globe is 1.3K in clear-sky conditions and 1.6K in cloudy conditions. In the absence of routine in situ surface skin measurements, retrieved LST values have been evaluated by comparison to the surface air temperature LSAT measured by the meteorological station network [RD-40]. The LST-LSAT difference shows all the expected variations with solar flux, soil characteristics, and cloudiness. After suppression of the variability associated to the diurnal solar flux variations, the LST and LSAT data sets show very good agreement in their synoptic variations, even for cloudy cases, with no bias and a global rms difference of 2.9 K. This value is an upper limit of the retrieval rms because it includes errors in the in situ data as well as errors related to imperfect time and space collocations between the satellite and in situ measurements. Results have also been evaluated over snow and ice surfaces and the results were consistent with surface air temperature [RD-40]. More recently, the microwave LST have been evaluated through a careful comparison with in situ measurements from the Coordinated Energy and water cycle Observations Project (CEOP) for 12 stations in different environments over a full annual cycle [RD-41]. Figure 4 illustrates some comparison results, separated by environment types and cloud coverage. Under clear sky conditions, the quality of our microwave neural network retrieval (TsMW1) is equivalent to the infrared ISCCP products, for most in situ stations, with errors ~3 K as compared to in situ measurements. The performance of the microwave algorithm is similar under clear and cloudy conditions, confirming the potential of the microwaves under clouds. We showed that the LST accuracy does not depend upon the surface emissivity, as the variability of this parameter is accounted for in the processing.

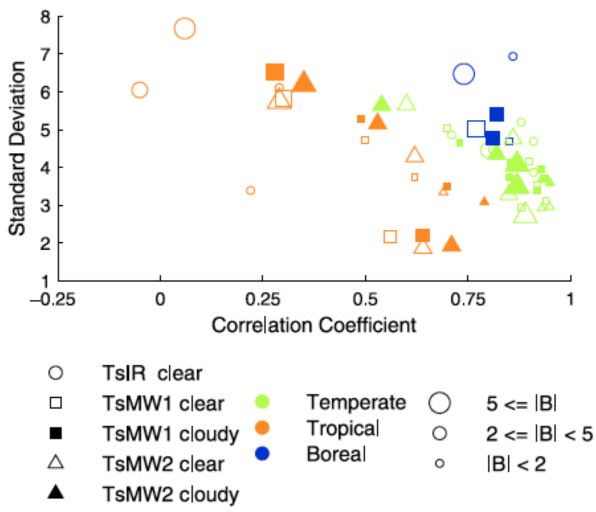


Figure 4: Scatterplot of the standard deviation of the difference between CEOP and satellite Ts versus the correlation coefficient between the two variables, for each selected stations. Symbols (circles, squares, and triangles) indicate the considered satellite product. Empty symbols indicate clear sky conditions and filled symbols indicate cloudy conditions. The color of the symbols is representative of the station environment. The size of each symbol gives an idea of the bias (in absolute value). TsIR is for the ISCCP estimate, TsMW1 is for our retrieval, and TsMW2 stands for the retrieval from [RD-42].

4.1.4. Advanced Microwave Scanning Radiometer (AMSR)

The Advanced Microwave Scanning Radiometer (AMSR) has similar characteristics to SSM/I, with the addition of low frequencies. AMSR was developed by the Japan Aerospace Exploration Agency (JAXA) with close cooperation of U.S. and Japanese scientists. It was launched on board the Earth Observation Satellite Aqua, in May 2002 (AMSR-E). It failed in October 2011. AMSR-2, the AMSR-E follow-up, was launched on board the Japanese Global Change Observation Mission (GCOM) on May 2012. Its characteristics are similar to AMSR-E.

AMSR measures horizontally and vertically polarized radiances at 6.9, 10.65, 18.7, 23.8, 36.5, and 89.0 GHz. It scans conically at a nominal 55° with a swath width of 1600 km. Spatial resolution of the individual measurements varies from 5 km at 89 GHz to ~50 km at 6.9 and 10.65 GHz. Inversion procedure for the LST has been applied to AMSR-E, similar to SSM/I. Results have been described in [RD-43]. It could also be applied to AMSR-2. Note that the overpassing time of AMSR is around midnight and midday (1h30 and 13h30 local time for AMSR-E).

4.1.5. Spinning Enhanced Visible and InfraRed Imager (SEVIRI)

The Spinning Enhanced Visible and Infrared Imager (SEVIRI) is the main sensor onboard Meteosat Second Generation (MSG), a series of 4 geostationary satellites to be operated by EUMETSAT. SEVIRI was designed to observe an earth disk with view zenith angles (SZA) ranging from 0^{o} to 80^{o}, with a temporal sampling of 15 minutes. SEVIRI spectral characteristics and accuracy, with 12 channels covering the visible to the infrared [RD-44, RD-45] are unique among sensors onboard geostationary platforms. The High Resolution Visible (HRV, Table 9) channel provides measurements with a 1km sampling distance at the sub-satellite point (SSP); for the remaining channels the spatial resolution is reduced to 3km at SSP. The nominal SSP is located at 0º longitude and therefore the MSG disk covers Africa, most of Europe and part of South America.

Level 1.5 data are disseminated to users after being rectified to 0^o longitude, which means the satellite viewing geometry varies slightly with the acquisition time (satellite zenith angles typically differ by less than 0.25^o between consecutive observations).

Table 9: Characteristics of the Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard Meteosat Second Generation

Channel	Central wavelength $\lambda_{central}$ (µm)	Dynamic Range	Radiometric Noise
VIS0.6	0.635	533 Wm-2sr-1λm-1	S/N 10 at 1% albedo
VIS0.8	0.81	357 Wm-2sr-1λm-1	S/N 7 at 1% albedo
NIR1.6	1.64	75 Wm-2sr-1λm-1	S/N 3 at 1% albedo
IR3.9	3.92	335 K	0.35K at 300K
WV6.2	6.25	300 K	0.75K at 250K
WV7.3	7.35	300 K	0.75K at 250K
IR8.7	8.70	300 K	0.28K at 300K
IR9.7	9.66	310 K	1.50K at 255K
IR10.8	10.80	335 K	0.25K at 300K
IR12.0	12.00	335 K	0.37K at 300K
IR13.4	13.40	300 K	1.80K at 270K
HRV	Broadband (about 0.4 – 1.1)	460 Wm-2sr-1λm-1	S/N 1.2 at 0.3% albedo

The EUMETSAT Satellite Applications Facility on Land Surface Analysis (LSA SAF; [RD-46]; http://landsaf.meteo.pt) produces an LST product based on SEVIRI data. LST fields are available every 15 minutes, in near real time and off-line, covering the MSG disk centred at 0º longitude and with a spatial resolution of about 3km at the sub-satellite point. LST is obtained by correcting top-of-atmosphere (TOA) radiances for surface emissivity, atmospheric attenuation along the path and reflection of downward radiation. The LST algorithm follows closely the generalized split window proposed by [RD-10] for AVHRR and MODIS, but adapted to SEVIRI response functions [RD-47, RD-48]. The algorithm coefficients were calibrated for classes of viewing angle and total column water vapour (available from ECMWF as operational hourly forecasts). The split-window algorithm requires values of channel emissivity at the surface, which are estimated as a weighted average of that of bare ground and vegetation elements within each pixel [RD-49, RD-50]. The fraction of vegetation cover, also generated on a daily basis from SEVIRI/MSG data by LSA SAF (e.g., [RD-46, RD-51]) is used as weight. This method produces emissivity values that are generally in line with those retrieved independently for other sensors [RD-52].

The uncertainty of LST values is also estimated and distributed. This depends on a number of factors [RD-47]: (i) the retrieval conditions in terms of atmospheric water content and viewing geometry, since the total optical path will strongly influence the performance of the generalized split-window algorithm; (ii) input uncertainties, including sensor noise, errors in the estimation of surface emissivity and in atmospheric total water vapour obtained from ECMWF forecasts; and (iii) errors in the cloud mask used to identify clear sky pixels. For most regions within the MSG disk these values are below 2K and pixels with error bars higher than 4K, generally near the edge of the MSG disk, are masked out.

Validation of SEVIRI LST relies on comparisons with other satellite products (e.g., MODIS) and with in-situ measurements. The latter generally reveal root mean differences between 1K and less than 2.5 K [RD-47, RD-50], depending on the surface (better agreement is generally found for sites located in homogeneous surfaces).

The LSA SAF initiated the production of SEVIRI LST in February 2005. The first retrievals covered the European area and were later extended to the whole disk in July 2005. Since then, the algorithm and input data were improved and therefore the LSA SAF team is planning a re-processing exercise to cover the full period of SEVIRI measurements (2003 onwards) with a single and most recent SEVIRI algorithm; the review to release the re-processed LST dataset is foreseen for the end of 2014.

4.1.6. MODerate resolution Imaging Spectroradiometer (MODIS)

MODIS instruments are part of the payload of two sun-synchronous, near-polar orbiting satellites Terra (EOS AM-1) launched on 18 December 1999 and Aqua (EOS PM-1) launched on 4 May 2002, respectively. Each instrument provides a pair of observations each day acquiring data in 36 spectral bands: for Terra-MODIS at approximately 10:30am (local solar time) in its descending mode; and at approximately 10:30pm (local solar time) in its ascending mode; for Aqua-MODIS at approximately 1:30pm (local solar time) in its ascending mode; and at approximately 1:30am (local solar time) in its descending mode. The large swath width of these instruments, 2330km, enables these satellites to view almost the entire surface of the Earth every day. The spatial resolution of the thermal bands is 1 km; with both land surface temperature and land surface emissivity being core products from these instruments.

1 km level-2 swath MODIS LST products – MOD11_L2 and MYD11_L2 – are acquired from the MODIS instruments on board the Terra and Aqua satellites respectively. MOD11_L2 data is available from 5th March 2000 and MYD11_L2 data is available from 4th July 2002. The generalized split-window (SW) algorithm [RD-10], similar to the split-window method used for AVHRR data, is used to estimate LST as a linear function of clear-sky TOA brightness temperatures from bands 31 and 32 centred on 11µm and 12µm respectively, with land surface emissivity being estimated from land cover types, with a linear correction being made to account for the satellite viewing angle. Specifically, the physics based day/night LST algorithm is used to simultaneously retrieve surface band emissivities and temperatures

from a pair of daytime and night-time MODIS observations in bands 20, 22, 23, 29, and 31-33 over all types of land cover. MODIS LST data is accompanied by quality control flags, which include an indication of the presence of clouds. Previous collections of the LST products have suffered from cloud-contamination; the latest operational version - collection 5 - though includes refinements to account for surface elevation in the cloud masking algorithm; the resultant accuracy is reported as better than 1.0 K [RD-53].

4.1.7. Visible Infrared Imaging Radiometer Suite (VIIRS)

VIIRS is one of five instruments on board the sun-synchronous near-polar orbiting satellite Suomi NPP which was launched in October 2011 with an expected operational lifetime taking it into 2017. Observations correspond to approximately 13:30 (local solar time) in its ascending mode, and with a swath width of 3040 km it achieves global coverage every day with a repeat cycle of approximately 16 days. It has a spatial resolution of ~375 m at nadir in the Imagery Bands and ~750 m at nadir in the Moderate Bands through a system of pixel aggregation techniques. VIIRS controls pixel growth towards the edge of scan such that the pixel sizes are comparable to nadir. The aim of NPP VIIRS is to extend and improve upon the heritage of AVHRR and MODIS while providing a bridge between MODIS and the operational JPSS VIIRS. Land surface temperature is one of several products being produced from VIIRS.

VIIRS LST algorithms use brightness temperatures measured by VIIRS IR channels processed through physical regression methods to retrieve skin LSTs. The baseline LST algorithm is a two-band, thermal split window algorithm based on a single equation for each land cover type, with an additional dual split window algorithm based on four thermal BTs (two middle infrared and two thermal infrared) bands that can be used when conditions are optimal, i.e. the measurements are unaffected by sun glint, with different algorithms for day and night. The algorithms used in the VIIRS LST product do not require emissivity information, only knowledge of the land surface type - for which there are separate coefficients. The algorithms require that the input BT values have a measurement accuracy of 2.4 K and a measurement precision of 0.5 K, the latter of which may not be met for some land types [RD-54].

4.1.8. Geostationary Operational Environmental Satellite (GOES)

The Geostationary Operational Environmental Satellites (GOES) Imager consists of a five channel radiometer covering visible and infrared bands of the spectrum (Table 10). NOAA/NESDIS operates two GOES satellites: GOES-W positioned over 135W and GOES-E over 75W. The temporal sampling over the disk is not homogeneous: images over North America are available at least hourly, while South America is covered every 3 hours.

Table 10: Characteristics of the GOES Imager

Channel	Nominal wavelength	Resolution at nadir	GOES series	System accuracy
1 (VIS)	0.65 μm	1 km	All	5% of max scene irradiance
2 (MIR)	3.9 μm	4 km	All	≤ 1 K
3 (WV)	6.7 μm	8 km	GOES-8 to GOES-11	
	6.5 μm	4 km	From GOES-12 onwards	
4 (TIR)	10.7	4 km	All	
5 (TIR)	12.0	4 km	GOES-8 to GOES-11	

IPMA have generated LST from GOES imager data for the period between 2010 and 2012, within the framework of FP7 GMES project Geoland2. From Jan 2013 onwards, IPMA is producing GOES LST in near real time, as part of Copernicus Global Land Initial Operations Service.

The algorithm used for GOES LST takes into account the information in the available channels and considers two different formulations used for night-time and daytime, respectively: (i) two-channel algorithms, which derive LST from one window channel in the thermal infrared – around 11 µm – and another in the middle infrared – around 3.9 µm (T_{TIR1} and T_{MIR}, respectively); this is used for night-time conditions, when T_{MIR} is not contaminated by solar radiation reflected by the surface; (ii) mono-channel method that corrects the TOA brightness temperature of a single channel, T_{TIR1}, for atmospheric attenuation and surface emissivity; this algorithm is used for daytime conditions. LST is estimated as a linear function of T_{TIR1} and T_{MIR} (night) or of T_{TIR1} (day), using regression coefficients estimated for different classes of water vapour in the atmosphere, view angle and land cover types [RD-55].

GOES LST is estimated hourly on a pixel-pixel basis, together with an error bar which takes into account the algorithm expected uncertainty and propagation of input errors.

4.1.9. Multi-functional Transport Satellites (MTSAT)

The Multi-functional Transport Satellites (MTSAT) series of geostationary satellites is operated by the Japan Meteorological Agency (JMA). The imager onboard MTSAT is very similar to that of GOES, with 1 visible (VIS) band and 4 in the infrared: (i) middle infra-red (MIR); (ii) water vapour (WV); and (iii) two split-window channels in the thermal infrared (TIR1 and TIR2). MTSAT is centred at 140 East, providing hourly coverage of most of Asia and Australia. The VIS data are available with a 1 km pixel sampling distance at nadir and 4 km for infrared channels.

IPMA have generated LST from MTSAT imager data for the period between 2010 and 2012, within the framework of FP7 GMES project Geoland2. From Jan 2013 onwards, IPMA is producing MTSAT LST in near real time, as part of Copernicus Global Land Initial Operations Service.

Although the sensor onboard MTSAT has two channels in the thermal infrared atmospheric window (split-window channels), only one of these is relayed via EUMETCast. Therefore, the algorithm implemented by IPMA to produce MTSAT LST is very similar to that described above for GOES. The coefficients of the regressions used were calibrated for MTSAT imager response functions [RD-55].

4.1.10. Infrared Atmospheric Sounding Interferometer (IASI)

The Infrared Atmospheric Sounding Interferometer (IASI) is a nadir viewing instrument flying operationally on MetOp satellites. IASI is composed of a Fourier Transform Spectrometer (FTS) with a spectral sampling of 0.25 cm^{-1}, and a spectral range of 645 to 2760 cm^{-1}. The IASI instrument utilises a step by step scanning mirror to achieve a swath width of 2200 km, and twice daily global coverage (>99 %). The optical axis of the scanning mirror moves from -48.3^{o} to $+48.3^{o}$ with respect to nadir. As IASI moves forward in its orbit a scan line is made of 30 Effective Fields of View (EFOV). Each EFOV consists of a matrix of 2 x 2 IFOVs (Instantaneous Field of View), each with a diameter of 0.84± (11 mrad ≤d≤14:65 mrad) and with centres located at 15.3 mrad (0.88^{o}) from the instrument optical axis. On the ground, the EFOV is 50 km by 50 km at nadir, and the distance between two EFOV is approximately 50 km. Each cell of the 2 x 2 matrix corresponds to a circular pixel of 12 km diameter at the sub-satellite point, and at the edge of the scan the across-track and along-track sizes of the individual pixel are 39km and 20 km respectively, with each of the 4 simultaneously imaged pixels utilising its own detector. There are currently two IASI instruments flying operationally, onboard MetOp-A and MetOp-B. A third instrument will be launched in 2017.

IASI LST products are available at 12 km spatial resolution at the sub-satellite point, increasing to 39 km and 20 km at the swath edge in the across- and along-track directions, respectively. The IASI Level 2 Product Processing Facility (PPF) is located at EUMETSAT headquarters in Darmstadt, producing operational products from MetOp (currently MetOp-A and MetOp-B). There also in eight decentralised satellite application facilities hosted by EUMETSAT member states. The level 2 processing combines IASI data with concurrent measurements of the AVHRR, AMSU-A and MHS, which are flown together on MetOp, to aid cloud detection and the initialisation of the geophysical–parameters retrieval although IASI stand-alone processing is possible if other measurements are not available [RD-56]. Version 5 of the PPF has a modular structure with IASI and auxiliary data first collocated in a pre-processing step. After configuration of the retrieval algorithm with coefficients and thresholds adapted to the time and location of the measurements, cloudiness is determined, followed by the geophysical parameters, including LST from cloud-free scenes. The LST (and land surface emissivity) are currently taken from statistical retrievals [RD-57]. A collection of statistical methods are applied first, which include EOF linear and ANN non-linear regressions. For the EOF analysis, principal component scores of the IASI radiances are computed and then input into the linear regression [RD-58].

4.2. Plans for GlobTemperature LST products

GlobTemperature LST products include both single-sensor datasets, the multi-sensor merged LST datasets, and the (A)ATSR Climate Data Record. All datasets are to be disseminated to the users via the GlobTemperature Data Portal (or linked to external sites in the case of some operational datasets produced by other space agencies) in harmonised format. Single-sensor LST datasets will be provided as both level-2 (swath) and level-3 (gridded) products in the agreed harmonised format, as will level-4 (merged) products whereby the optimum dissemination of higher level products is via 10° x 10° tiles (**addresses requirements REQ-22-TR, REG-40-TR and REQ-44-TR**).

GT-TS-5: *Provide Level-2 single-sensor datasets in harmonised format*

GT-TS-6: *Provide Level-3 and Level-4 datasets in harmonised format to be disseminated as 10° x 10° tiles*

The objective of data provision in GlobTemperature is to provide a one-stop-shop for all LST, IST, and LSWT data products. Thus third-party datasets will also be available via the Data Portal. Since non-GlobTemperature funded international collaborators may be unlikely to be able to provide datasets in the agreed GlobTemperature harmonised format, the Data Portal will not restrict access to only datasets in harmonised formats. For such third-party datasets the Data Portal will provide a link to the external data centre and will include a descriptive page on the product metadata. Although these datasets may be in non-harmonised format this is outweighed by the benefit to the user community of having a single point of access to all the major European and non-European LST, IST and LSWT datasets.

4.2.1. (Advanced) Along Track Scanning Radiometers (A)ATSR

For the single-sensor LST dataset from the ATSR (ATSR-1, ATSR-2, and AATSR) series, this will be provided via the GlobTemperature Data Portal in the harmonised format (Section 6.5.1 and Section 6.5.2). The algorithm (Section 6.2) utilised for the enhanced UOL_LST_2P product (the product itself is available on both the ESA archive and the CEDA archive in the UK) will be employed here for the GlobTemperature single-sensor (A)ATSR LST Product.

The harmonised format is slightly different, in terms of additional mandatory variables, from the format for UOL_LST_2P (although UOL_LST_2P was the baseline for the proposed harmonised format) since it is user-driven following the User Requirements Survey. As such, level-1b data available on the CEDA archive (ftp.ceda.ac.uk) following the 3rd ATSR re-processing will be processed to LST data in the harmonised format on the UK CEMS facility exploiting its new 20 Tb GlobTemperature workspace. The level-2 harmonised format will use the latest probabilistic cloud clearing detection algorithm (UOL_V3) to generate a cloud masks which will be stored as a component of the Quality Control flag. A further particular inclusion in the GlobTemperature (A)ATSR LST single-sensor dataset is the uncertainty budget breakdown (**addresses requirement REQ-4-TR**); an example is illustrated in Figure 5.

Version 2.0 of the GlobTemperature (A)ATSR LST product assigns these individual components to a 3-component model which categories the uncertainty in terms of: i) uncertainties from random effects; ii) uncertainties from locally correlated effects; and iii) uncertainties from large-scale systematic effects.

Such a categorisation is applicable across sensors and product levels. This is the approach, which will be implemented, where feasible, in new GlobTemperature products, and updated versions of existing GlobTemperature products. Thus a consistent approach to providing uncertainty information is the objective. A full description will be provided in the Product User Guide (PUG).

GT-TS-35*: Where information is available provide full uncertainty breakdown for Level-2, -3 and -4 data in a consistent manner*

Addresses user feedback ***GT-UF-8****: Provide "user-friendly" uncertainties in the output LST products at a per-pixel level with sufficient metadata information*

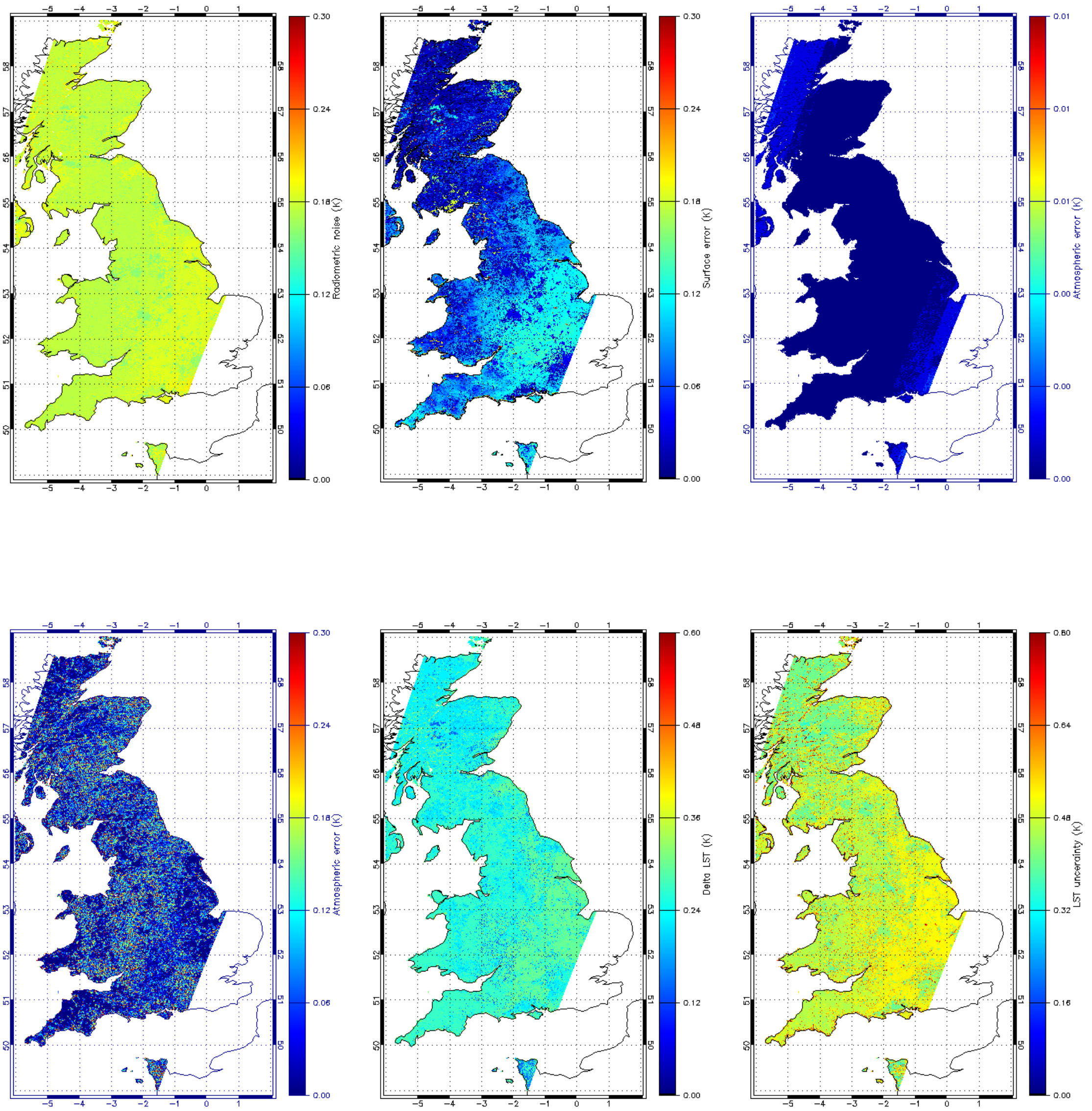


Figure 5: Example pixel-level LST uncertainty budget: radiometric noise (top row – 1st column); surface component (top row – 2nd column); atmospheric component (top row – 3rd column); geolocation uncertainty (top row – 4th column); model fitting uncertainty (bottom row – 1st column); and total pixel uncertainty (bottom row – 3rd column)

The same algorithm and procedure will be applied to Level-1b data from each of the ATSR instruments independently, albeit with instrument specific response functions, retrieval coefficients and tuning parameters. The homogenisation of the brightness temperatures for the instrument series will be carried out in the development of the (A)ATSR Climate Data Record (Section 4.2.14).

Level-3 datasets will be produced from these Level-2 datasets and be made available via the Data Portal. Furthermore, tools embedded within the Data Portal will permit easier ad hoc visualisation of the ATSR data by the users from these Level-3 datasets.

For ATSR the Arc-Lake product offers an optimum solution for Lake Surface Water Temperature (LSWT). Since this product is available at level-2, having been derived from the ATSR level-1b data at this pixel resolution, where available this product will supersede the level-2 retrievals described above for UOL_LST_2P. Arc-Lake is derived (where possible) from dual-view 3-channel retrievals for night-time and dual-view 2-channel retrievals for day-time. For any lake pixels where Arc-Lake is not available, the UOL_LST_2P retrievals for the inland water biome are to be used. The locations where Arc-Lake retrievals are derived are defined using the ARC-Lake land/water mask. The Arc-Lake dataset will continually be extended within the framework of the Globolakes Project for additional smaller lakes thus extending the LSWT data available. At each new LSWT release of GloboLakes the (A)ATSR GlobTemperature single-sensor dataset will be re-processed. For Level-3 products the (A)ATSR LSWT data will be combined into a single dataset before being averaged onto a regular grid to quantify retrieval uncertainty and apply retrieval methods to other sensors. ARC-Lake v2.0 data products are available from the Edinburgh DataShare repository [RD-34].

For IST, the latest developments at ULeic in (A)ATSR IST retrievals over land and sea will be exploited and will supersede the UOL_LST_2P LST data in the GlobTemperature product. This includes the application of alternative retrieval coefficients for sea-ice (this being classified as an additional biome) and the exploitation of additional auxiliary data for snow/ice masking. The cloud masking over snow/ice remains the ULeic probabilistic cloud clearing detection algorithm (UOL_V3). Thus, the GlobTemperature single-sensor (A)ATSR LST product will encompass the optimum solutions for LST, LSWT and IST covering all land, lake, and sea-ice domains.

(A)ATSR is ESA data.

Unrestricted use for ArcLake data (part of contractor's background IP).

4.2.2. Advanced Very High Resolution Radiometers (AVHRR)

The single-sensor Metop-AVHRR LST product in harmonised format will apply as a baseline the LSA SAF split-window algorithm for SEVIRI adapted for the AVHRR response functions. Emissivity estimates will be based on the Vegetation Cover Method, as with SEVIRI, while the atmospheric correction is based on ECMWF hourly forecasts of total column water vapour. The LSA SAF processing chain is not yet operational; and once operational the data is then to be additionally processed into the GlobTemperature harmonised format for dissemination via the GlobTemperature Data Portal. Near real time AVHRR/Metop level 1b data, i.e. geo-located radiances and respective navigation information, are available via EUMETCast (http://www.eumetsat.int/home/main/dataaccess/eumetcast/index.htm). Off line data are archived at EUMETSAT UMARF and at IPMA.

In the case that the LSA SAF processing chain takes longer to commission than the expected then the option exists to process the GlobTemperature single-sensor Metop-AVHRR LST dataset on the UK CEMS facility exploiting the core processing nodes and the dedicated GlobTemperature workspace. The full Level-1b data are archived on the CEDA archive with direct read access from these core processing nodes.

Level-3 datasets will be produced from these Level-2 datasets and be made available via the Data Portal permitting swift user specified visualisation through embedded tools. The derivation of the Level-3 products will follow the same mechanics as for (A)ATSR ensuring consistency across products in the GlobTemperature suite.

Background Intellectual Property Rights are applicable.

The LSA-002 product is considered "essential" in accordance with the WMO Resolution 40 (Cg-XII). This means that access to these SAF products is granted to all users without a licence, without charge and without conditions on use, as stated in the Basic Principles of EUMETSAT Data Policy (http://www.eumetsat.int/website/wcm/idc/idcplg?IdcService=GET_FILE&dDocName=PDF_LEG_DATA_POLICY&RevisionSelectionMethod=LatestReleased&Rendition=Web.

For Metop-AVHRR IST, the Level-3 dataset derived by DMI [RD-59] will form a stand-alone IST dataset in harmonised format. This consists of daily or 12 hourly merged and interpolated fields of IST produced using an optimal interpolation scheme developed for SST. The algorithm uses spatially varying and empirically determined error covariances. Associated with each of the grid points is an error estimate, based upon the availability of the data. The spatial resolution of the IST grid is 5 km and covering the Arctic Sea ice (Northward of 58° N).

Metop/AVHRR IST observations can be used without restrictions. DMI only have IPRs on the processing software that has been used to generate the data, but as long as they are not used for commercial purposes the data is available to the project without restriction.

4.2.3. Special Sensor Microwave / Imager (SSM/I)

The SSM/I-derived LST for 2003 will be provided to the GlobTemperature project. It includes both clear and cloudy skies. The LST are calculated at the SSM/I overpassing times (close to 6am and 6pm). It is on an equal area of 0.25° at the equator. It has been thoroughly evaluated by comparison with infrared estimates and with in situ measurements. The methodology has been described in [RD-41]. The data can be projected on another grid and a specific format if necessary.

The SSM/I brightness temperature source data are publicly available, with no restriction to their use. The resultant LST data will be produced exclusively for the GlobTemperature Project under the ESA defined conditions of use of the GlobTemperature output datasets.

4.2.4. Advanced Microwave Scanning Radiometer (AMSR-E)

The initial neural network inversion [RD-37] requires a large range of ancillary observations that are difficult to collect on near-real time. It was first developed to estimate the atmospheric parameters over land from microwave, and since the atmospheric signal is small as compared to the surface contribution caution was necessary. Based on the experience we have now with the retrieval of land surface parameters from microwave, the algorithm is to be revisited, limiting the number of ancillary inputs while maintaining the LST accuracy.

Work from [RD-42] showed that simpler algorithms have some potential, even using a single frequency channel from SSM/I. [RD-42] used the brightness temperatures (Tbs) at 37 GHz in vertical polarization only to estimate LST. This algorithm has been shown to yield realistic estimates of LST, for a large range of surfaces. It is based on the assumption that microwave surface emissivities are stable in space and time, and it shows limitations especially for surfaces with low emissivities. Our objective within GlobTemperature is to develop a LST retrieval algorithm, easily and broadly applicable to past and current microwave imagers. The algorithm will be based on measurements provided by microwave conical scanners, from 19 to 90 GHz. It will possibly require pre-calculated atlases of land surface emissivities, at the same frequencies.

Within the framework of GlobTemperature, three-years of LST will be produced from AMSR-E observations (2008-2010), on an equal area grid of 0.25° at the equator, for clear and cloudy conditions, at the overpassing time of AMSR-E (1:30AM and 13:30 PM). The results will be carefully compared to existing IR estimates under clear sky conditions, and to available in situ measurements.

The AMSR-E brightness temperature source data are publicly available, with no restriction to their use. The resultant LST data will be produced exclusively for the GlobTemperature Project under the ESA defined conditions of use of the GlobTemperature output datasets.

4.2.5. Spinning Enhanced Visible and InfraRed Imager (SEVIRI)

The single-sensor LST dataset from SEVIRI/MSG series, generated by the LSA SAF processing, will be provided via the GlobTemperature Data Portal in the harmonised format (Section 6.5.1). SEVIRI LST is generated using a generalized split-window algorithm (Section 6.2) with explicit correction for surface emissivity based on the vegetation cover method [RD-47, RD-50]. The atmospheric correction takes into account the differential absorption in the two split-window channels, adjusted to the view angle and water vapour in the atmosphere (as provided by ECMWF hourly forecasts). The SEVIRI LST dataset is currently available from 2005 to present. The LSA SAF will re-process the full SEVIRI archive (2004 – to present) maintaining a fixed algorithm (corresponding to that currently in operations) and using level 1.5 SEVIRI data re-processed at EUMETSAT.

The harmonised format, in terms of additional mandatory variables, projection and metadata is user-driven following the User Requirements Survey. The original level-2 SEVIRI data generated within the LSA SAF will be re-written following the harmonised format. Furthermore, tools embedded within the Data Portal will permit easier ad hoc visualisation of the SEVIRI LST data by the users.

Background Intellectual Property Rights are applicable.

The LSA-002 product is considered "essential" in accordance with the WMO Resolution 40 (Cg-XII). This means that access to these SAF products is granted to all users without a licence, without charge and without conditions on use, as stated in the Basic Principles of EUMETSAT Data Policy (http://www.eumetsat.int/website/wcm/idc/idcplg?IdcService=GET_FILE&dDocName=PDF_LEG_DATA_POLICY&RevisionSelectionMethod=LatestReleased&Rendition=Web).

SEVIRI data in the GlobTemperature harmonised format will be provided at a temporal resolution of 1 hour or better (**addresses requirements REQ-25-TR and REQ-26-TR).**

GT-TS-7: *Provide single-sensor GEO datasets at temporal resolutions of 1-hour or less*

4.2.6. MODerate resolution Imaging Spectroradiometer (MODIS)

There are two identified routes to dissemination of MODIS LST data:

- Direct dissemination of "value-added" MODIS product
- Link to external Data Portal

MODIS "value added" product (MOGSV / MYGSV)

The operational MODIS LST products (MOD11 / MYD11) for Terra / Aqua respectively are available from the Land Processes Distributed Active Archive Center (LP DAAC) [RD-60]. Many users are familiar with these operational products. In GlobTemperature the dissemination of this data is to be improved upon via direct dissemination of a "value-added" product (MOGSV / MYGSV). This will be an entirely new data product independent of the MOD11 / MYD11 data streams. In addition to a new LST field, the product also includes additional information on the satellite viewing geometry, full resolution geolocation information for Level-2 datasets; plus distinct emissivity information and the capture of additional cloud and aerosol detection metrics for Level-3 datasets. A key feature of the product is the provision of a full uncertainty budget from first principles consistent with the approach for (A)ASTR.

The operational Level-2 MODIS LST (MOD11_L2 / MYD11_L2) datafiles provide geolocation at tie-points every 5 pixels x 5 pixels. For users requiring 1 km swath data they currently have two choices available for geolocation: i) to interpolate between tie-points; ii) to extract full resolution information from the MOD03 / MYD03 products. This situation can be improved upon in GlobTemperature with the provision of Level-2 data in harmonised format. Full resolution geolocation and satellite viewing angles will be extracted directly from the corresponding MOD03 / MYD03 products and output with LST data from the MOD11_L2 / MYD11_L2 products.

In order to deliver uncertainty information from first principles consistent with other GlobTemperature products, such as (A)ATSR, it is necessary to derive new LST data from Level-1b radiances (MOD021KM / MYD021KM). This involves the generation of new coefficients for the chosen algorithm, in this case existing the split-window algorithm used operationally for MODIS. These new coefficients however enhance the retrieval across-track through increased classification into viewing angle and water vapour classes with subsequent bias-correction. Emissivity information is acquired from the Cooperative Institute for Meteorological Satellite Studies (CIMSS) and spatial / temporal interpolation of emissivity, water vapour, and retrieval coefficients is carried out. The uncertainty information adheres to a 3-component model, which identifies: i) uncertainty from random effects; ii) uncertainty from locally correlated effects; and iii) uncertainty from large-scale systematic effects.

GT-TS-35*: Where information is available provide full uncertainty breakdown for Level-2, -3 and -4 data in a consistent manner*

MODIS operational Level-3 products do not contain any information on uncertainty, nor do they contain Quality Control information on the full range of cloud detection flags (a notable absence is masking from thin cirrus). Taking the GlobTemperature LST data in harmonised format this information is to be incorporated into the GlobTemperature MODIS Level-3 "value-added" products, allowing for easier inter-comparability with other GlobTemperature higher-level products.

MODIS data and products acquired through the LP DAAC have no restrictions on subsequent use, sale, or redistribution (https://lpdaac.usgs.gov/products/modis_policies. Level-1 data will be acquired from http://e4ftl01.cr.usgs.gov/MOLT/ (Terra) and http://e4ftl01.cr.usgs.gov/MOLA/ (Aqua) for subsequent harmonisation in GlobTemperature format for dissemination.

The MOGSV / MYGSV data products are to be produced from beginning of mission to current month, thereby delivering single-sensor datasets of length greater than 10-years; with furthermore the provision of the latest MODIS observations with a timeliness of 1-month (**addresses requirements REQ-3-TR and REQ-12b-TR)**. The new MODIS products are to be processed from Collection 6 input data.

GT-TS-47*: Provide single-sensor datasets of minimum length 10-years with a target of 30-years where new observations have a target timeliness of 1 month*

MODIS enhanced product (MOD21 / MYD21)

From 2014 onwards a new MODIS LST and Land Surface Emissivity (LSE) product (MOD21 / MYD21) retrieved up to four times per day will be available [RD-61]. This product is being generated by international collaborators at NASA-JPL and applies a physics based approach originally designed for ASTER LST retrievals but adapted to MODIS data - the Temperature Emissivity Separation (TES) algorithm. The method retrieves LST and LSE in MODIS bands 29, 31 and 32.

Currently, users will be directed to the development dataset available from the NASA-JPL site: http://emissivity.jpl.nasa.gov/mod21. An email contact address will be provided to allow users to contact the data providers directly for the most up-to-date information on the status of the product. In this phase of access a significant amount of MOD21 data will be processed for validation and testing purposes. Once MOD21 has been officially released then the GlobTemperature Data Portal will instead link to the LP DAAC https://lpdaac.usgs.gov/products/community_products_table site [RD-60].

Dissemination via link to external data centre. User exploitation is then to comply with the individual conditions of use regarding distribution and acknowledgement.

A Web Page on the GlobTemperature Data Portal will provide accompanying details for the dataset (**addresses requirement REQ-37-TR**).

GT-TS-8*: Provide links from the Data Portal to external data centres, including information on metadata, for datasets not directly disseminated by GlobTemperature*

4.2.7. Visible Infrared Imaging Radiometer Suite (VIIRS)

Individual band data and the LST Environmental Data Record (EDR) product is available to be downloaded from the NOAA Comprehensive Large Array-Data Stewardship System (CLASS) (http://www.class.ncdc.noaa.gov/saa/products/search?datatype_family=VIIRS) [RD-62]. The GlobTemperature Data Portal will provide a link to this external data centre.

Dissemination via link to external data centre. User exploitation is then to comply with the individual conditions of use regarding distribution and acknowledgement.

A Web Page on the GlobTemperature Data Portal will provide accompanying details for the dataset (**addresses requirement REQ-37-TR**).

GT-TS-8*: Provide links from the Data Portal to external data centres, including information on metadata, for datasets not directly disseminated by GlobTemperature*

4.2.8. Geostationary Operational Environmental Satellite (GOES)

The single-sensor LST dataset from the imager on the GOES-East series of satellites, generated by IPMA within the Copernicus – Global Land service, will be provided via the GlobTemperature Data Portal in the harmonised format (Section 6.5.1). GOES LST is generated using a two-channel algorithm based on thermal (TIR) and middle (MIR) infra-red observations for night-time slots and a single TIR channel for daytime [RD-55]. The current version of the algorithm makes an implicit correction for surface emissivity based on a land cover classification, while the atmospheric correction takes into account the view angle and water vapour in the atmosphere (as provided by ECMWF hourly forecasts). GOES-East LST is currently available from 2010 to present.

The harmonised format, in terms of additional mandatory variables, projection and metadata is user-driven following the User Requirements Survey. The original level-2 GOES data generated within the Copernicus – Global Land Service [RD-63] will be re-written following the harmonised format. Furthermore, tools embedded within the Data Portal will permit easier ad hoc visualisation of the GOES LST data by the users.

Background Intellectual Property Rights are applicable; these data are subject to GMES/Copernicus data policy, which promotes full and open access to information produced by GMES/Copernicus services.

GOES data in the GlobTemperature harmonised format will be provided at a temporal resolution of 1 hour or better (**addresses requirements REQ-25-TR and REQ-26-TR).**

GT-TS-7*: Provide single-sensor GEO datasets at temporal resolutions of 1-hour or less*

4.2.9. Multi-functional Transport Satellites (MTSAT)

The single-sensor LST dataset from the imager on the MTSAT series of satellites, generated by IPMA within the Copernicus – Global Land service, will be provided via the GlobTemperature Data Portal in the harmonised format (Section 6.5.1). Given limitations on the availability of the full MTSAT channels, LST was generated using an algorithm to that applied to GOES-East data, i.e., based on MIR and TIR observations for night-time retrievals and on a single TIR channel for daytime, up to 2013. Once two split-window channels in the TIR region became available in near real time, LST continued to be generated using a split-window algorithm similar to that implemented for SEVIRI [RD-55]. The processing of MTSAT LST at IPMA started in Jan 2010. A re-processing of the full archive at IPMA, from 2010 onwards, is foreseen. Nevertheless the limitations in terms of channel availability will remain during the processing period.

The harmonised format, in terms of additional mandatory variables, projection and metadata is user-driven following the User Requirements Survey. The original level-2 MTSAT data generated within the Copernicus – Global Land Service will be re-written following the harmonised format. Furthermore, tools embedded within the Data Portal will permit easier ad hoc visualisation of the MTSAT LST data by the users.

Background Intellectual Property Rights are applicable; these data are subject to GMES/Copernicus data policy, which promotes full and open access to information produced by GMES/Copernicus services.

MTSAT data in the GlobTemperature harmonised format will be provided at a temporal resolution of 1 hour or better (**addresses requirements REQ-25-TR and REQ-26-TR).**

GT-TS-7*: Provide single-sensor GEO datasets at temporal resolutions of 1-hour or less*

4.2.10. Infrared Atmospheric Sounding Interferometer (IASI)

Near real time Metop-IASI level-1b data, i.e. geo-located radiances and respective navigation information, are available via EUMETCast (http://www.eumetsat.int/home/main/dataaccess/eumetcast/index.htm) [RD-64]. Off line data are archived at EUMETSAT UMARF and at NEODC.

Level-2 LST from IASI will be generated utilising work carried out on radiance inter-calibration of AATSR and IASI. The spectral response functions (spectral filters) of the AATSR instrument for each of the 11 and 12µm channels can be used in conjunction with the IASI radiance spectra to create quasi-AATSR brightness temperatures for IASI. This process uses the integral of the IASI data with each spectral response function, with use of spectral-filter integrated Planck functions to generate the equivalent brightness temperature values. IASI emissivities will be convolved to the AATSR spectral responses exploiting work being carried out at the Met Office on developing a global emissivity dataset from IASI; and the Generalised Split-Window (GSW) then applied to retrieve LST. The product will be output in harmonised format, with Level-3 averaged data additionally produced.

EUMETSAT radiances are available from http://eoportal.eumetsat.int/. Access to these data is granted to all users without charge, and against the signature of a licence agreement; they may not be redistributed without transformation (http://www.eumetsat.int/website/home/AboutUs/LegalInformation/DataPolicy/index.html).

4.2.11. Sea and Land Surface Temperature Radiometer (SLSTR)

The ATSR series is scheduled to continue with the Sea and Land Surface Temperature Radiometer (SLSTR) - which is based on the principles of AATSR - on board the Sentinel satellites 3-A and 3-B which comprise an element of the Global Monitoring for Environment and Security (GMES) / Copernicus programme, which responds to the requirements for an operational and near-real-time monitoring of the Earth surface over a period of 15 to 20 years. These are currently projected for launch in early-2016 (3-A) and 18 months later (3-B). SLSTR is designed to retrieve global sea-surface temperatures to an accuracy of better than 0.3 K and global land surface temperature to an accuracy of less than 1 K. Like AATSR a dual view capability is maintained with SLSTR - the nadir swath being 1420 km, and the backward view being 750 km. This will support a maximum revisit time of 4 days in dual view and 1 day in single view. There are nine spectral channels including two additional bands optimised for fire monitoring and improved cloud detection. The spatial resolution of SLSTR is 500m in the visible and shortwave infrared channels and 1 km in the thermal infrared channels.

The baseline retrieval for the operational ESA SLSTR LST product (SL_2_LST) is that which is described for the UOL_LST_2P retrieval for AATSR (Section 4.2.1). In other words it consists of a split-window algorithm with classes of coefficients for each biome-diurnal (day/night) combination. The coefficients will be applied through the use of Auxiliary Data Files (ADFs) [RD-65] including a biome map;

climatological fractional vegetation; and water vapour climatology; the cloud flagging is to be taken from the level-1b cloud detection scheme.

Providing Sentinel 3-A launches on schedule and depending on the length of the commissioning phase, then the single-sensor dataset will be added to the GlobTemperature suite in the agreed harmonised format. A further plan is review both the existing SL_L2_LST algorithm and any proposed synergy LST algorithms from the SEN4LST Project [RD-66]. A trade-off analysis will be performed for these and other potential algorithms with the selected algorithm processed to a Prototype GlobTemperature SLSTR LST algorithm. Due to the delays in the launch schedule a feasible plan would be to process GlobTemperature LST data from Sentinel-3 via the framework of a CCN.

SLSTR is ESA data.

4.2.12. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Emissivity Database (GED)

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Emissivity Database (GED) uses all ASTER scenes acquired from 2000 to 2008 inclusive to calculate mean seasonal emissivity climatology. This dataset is currently available for Africa, Australia, and Eurasia, with South America expected to be completed by end of 2014. For North America, the North American ASTER Land Surface Emissivity Database (NAALSED) v3.0 is available which provides a mean seasonal emissivity dataset for summer (Jul-Aug-Sep) and winter (Jan-Feb-Mar) time periods using data from 2000 to 2012 inclusive.

ASTER-GED and NAALSED are produced in 1 x 1 degree tiles at ~100 m and ~1 km spatial resolutions. Products include emissivity (5 ASTER TIR bands), surface temperature, NDVI, land-water map, geolocation information, observation count, and the resampled ATSER Global Digital Elevation Map (ASTER-GDEM). For GlobTemperature a link to the external data archive - LP DAAC (https://lpdaac.usgs.gov/products/community_products_table) [RD-60] will be provided where users can use either reverb or Earth Explorer to acquire the data.

Dissemination via link to external data centre. User exploitation is then to comply with the individual conditions of use regarding distribution and acknowledgement.

A Web Page on the GlobTemperature Data Portal will provide accompanying details for the dataset (**addresses requirement REQ-37-TR**).

***GT-TS-8**: Provide links from the Data Portal to external data centres, including information on metadata, for datasets not directly disseminated by GlobTemperature*

4.2.13. GlobTemperature Merged LST Product

The first step is to produce a daily merged LEO infra-red data set without any gap filling, with correction factors derived. The process is based on AATSR and MODIS data initially, with AATSR as the reference sensor for the system; AVHRR data will be added when available.

The second step is to use the daily merged infra-red LEO data to derive correction factors for the GEO sensors, in comparison to expectations from the validation and intercomparison, once microwave data is available. This can also be compared at this point for clear-sky data to achieve harmonisation of the sensors.

Once the GEO data are merged, LEO data and GEO data can be merged; in areas not covered by GEO observations the following stage of the merging process is based on LEO-only data. The methodology can be summarised as follows and illustrated schematically in Figure 6:

1. Comparison of LEO with GEO datasets:
    - LST validation and intercomparison studies to provide information on inter-instrument biases as a function of physical parameters
    - Matchups collocated in space and time for AATSR vs. SEVIRI, AATSR vs. GOES, MODIS vs. SEVIRI and MODIS vs. GOES
    - Add available knowledge of instrument calibration
    - Analyse consistency of LEO matchups for different viewing geometries, emissivities and land cover types
2. Correction factors:
    - Use validation and calibration information to establish correction factors for the sensors relative to the chosen LEO reference sensor (AATSR). Estimate regression coefficients to correct inconsistencies among LST datasets
    - Supplement this information with tests of algorithm consistency by applying the SEVIRI algorithm to LEO sensors to improve knowledge of the correction factors
    - Continue to revise correction coefficients, through the use of improved validation information and AVHRR/Metop LST product
3. Microwave versus infra-red data:
    - Establish relative biases between the data sets by comparisons of clear-sky data
    - Upscaling required in both the comparisons and the delineation of the clear-sky bias (by comparing the AMSR-E data to MODIS Aqua - same local time)

- Form estimates of the clear-sky bias uncertainty for years in which no microwave data are available (ERA-Interim data)

4. Uncertainty propagation:

   - A detailed error budget is required per pixel
   - Correlations by biome will be examined

5. Production (accompanying information):

   - A quality dataset with an indication of the reliability of estimates based on the number of LST original values to form the LST for a specific grid cell
   - Error-bars obtained from the uncertainties of original datasets being merged and the propagation of the errors from pixel scale to the grid scale
   - The provision of products with (Tier-1) and without (Tier-2) gap-filling (**addresses requirements REQ-21-TR and REQ-41-TR**).

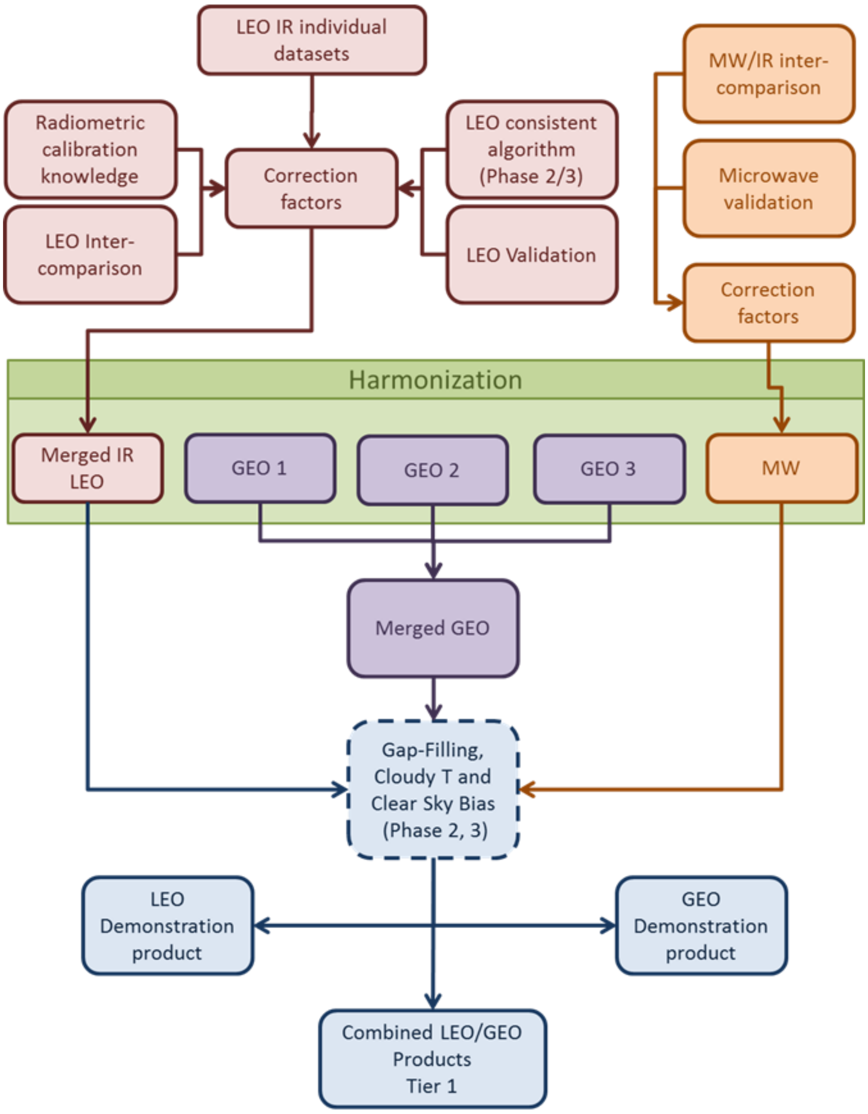


Figure 6: Schematic representation of the Production System for the Merged Product

The primary products (Tier 1 products) will be:

- A combined GEO/LEO product from 2010 onwards (at least 2010-2015). This product will be gap-filled, with estimated clear-sky biases, and also under-cloud LST where possible (**addresses requirements REQ-27-TR and REQ-36-TR**).

- A merged LEO product for 2003 (2003-2009) which will also feed into the merged GEO/LEO product. This product will be gap-filled with estimated clear-sky biases and also under-cloud LST where possible.

The expected spatial / temporal output grid of these Tier 1 products are 0.05° / 10-day composites with 8 output times (3 hourly diurnal time resolution) for GEO (**addresses requirement REQ-25-TR**) and 4 output times (6 hourly diurnal time resolution) for LEO data (**addresses requirements REQ-17-TR, REQ-18-TR and REQ-2-BR**).

***GT-TS-9**: Primary (Tier-1) merged LST datasets to be gap-filled*

***GT-TS-10**: Standard spatial resolution of Level-3 and -4 datasets to be 0.05° unless designated otherwise*

***GT-TS-11**: Standard temporal resolution of primary (Tier-1) merged LST datasets to be 3-hourly*

*Addresses user feedback **GT-UF-2**: Improve quantification on the relationship between observations of TIR retrieved LST and microwave (MW) retrieved LST including the "clear-sky" bias*

These datasets will be supplemented by demonstration products (Tier 2 products):

- Continental tiles of gap-filled GEO-only data for selected regions from 2003-2009.
- Merged GEO-only products (2010 onwards); these will not be gap-filled.
- Merged LEO-only products (2003 onwards) on a daily basis; these will not be gap-filled.

The expected spatial / temporal output grid of these Tier 1 products are 0.05° / 10-day composites for continental tiles and daily output for the GEO-only / LEO-only products (**addresses requirement REQ-17-TR**).

***GT-TS-10**: Standard spatial resolution of Level-3 and -4 datasets to be 0.05° unless designated otherwise*

***GT-TS-12**: Secondary (Tier-2) merged LST datasets to not be gap-filled, with priority of 10-year datasets*

***GT-TS-13**: Secondary (Tier-2) continental tiles to be gap-filled*

As with all GlobTemperature output products, the merged products will be delivered according to the agreed GlobTemperature harmonised format (**addresses requirement REQ-40-TR**). The exact specifications of the primary merged product will be iterated with the ILSTE-WG, and modified as a result of tests of the prototype.

4.2.14. GlobTemperature ATSR Climate Data Record

A Climate Data Record (CDR) requires SI traceability and needs to deliver the following:

- low bias
- realistic uncertainties
- full sensitivity to variability in LST
- independence of in situ data
- excellent stability / homogeneity

Current state-of-the-art in single-sensor LST datasets can now begin to address the objectives for climate quality:

- low bias:
    - High accuracy of LST data – validation shows majority of biases < 1.0 K (eg [RD-17, RD-67])
- realistic uncertainties:
    - Full pixel uncertainty budgets with explicit random, pseudo-random and systematic components [RD-25]
    - Validation of uncertainty budgets following a consistent approach to SST
- full sensitivity to variability in LST:
    - Previous assessments have confronted this [RD-68]
- independence of in situ data:
    - Accurate and highly stable in situ instruments with documented calibration at dedicated sites
    - Standardised protocols being employed in coordination with CEOS-LPV
- excellent stability / homogeneity
    - Assessment being carried out within the AATSR CDR Algorithm Trade-off Analysis (DEL-08) [AD-5]

The first critical step then is to understand the differences between the individual instruments. Both ATSR-2 and AATSR were both stable instruments; ATSR-1 was affected by elevated operating temperature, 3.7µm channel failure, plus elevated stratospheric aerosols following the Mount Pinatubo eruption. For SST inter-satellite differences have been shown to be ~0.1 K. As for SST, adjusting the resultant LSTs will not determine the cause of inter-instrument bias; homogenisation is more effective for BTs.

For generation of retrieval coefficients one needs to account for (known) differences in satellite calibration, in terms of spectral response for example. Since the ATSR's are well-calibrated instruments corrections derived from cross-calibration are to be applied to the simulations in the coefficient generation process. The full steps to construction of first a prototype (and then a full) Climate Data Record (CDR) of LST for the ATSR series of instruments can be summarised as follows:

1. Homogenisation of BTs

    - Reference the BTs of all the sensors and both split-window channels to be consistent with the calibration of AATSR to remove radiometric bias between instruments

- Use LST overlap analysis data to harmonise the temporal differences between the instruments. With co-located matchups between sensors one exploits common atmospheres and surface emissivities so prior errors cancel (to first order):

    i. A three-way analysis will be conducted from the start of the AATSR archive until the end of the ATSR-2 archive (AATSR, ATSR-2 and Terra-MODIS)

    ii. From the end of the ATSR-2 archive a two-way analysis will continue between AATSR and Terra-MODIS until the end of the AATSR archive

    iii. A statistical model of δLST will be generated from double differences (for example: ($AATSR_{sim}$ – $AATSR_{obs}$) – ($ATSR\text{-}2_{sim}$ – $ATSR2_{obs}$)) and applied so as to adjust to a common Local Equator Crossing Time (LECT). Discontinuities between instrument records should as a result be negligible

- Verify the overlap analysis in terms of relative bias between AATSR and Terra-MODIS is consistent over the ocean

2. Candidate algorithms

- Any candidate algorithm must be adaptable to (A)ATSR and SLSTR, but also to MODIS and AVHRR, with a consistent uncertainty budget extracted for each

- Creation of a "benchmark" dataset of atmospheric profiles, corresponding skin temperatures and surface emissivities for deriving retrieval coefficients

- Determine the optimum retrieval algorithm across sensors from validation and intercomparison

3. Uncertainty analysis

- Derive uncertainties with a full breakdown of the individual components:

- Exploit SST experience to propagate to global time series (for example uncertainties on SST global mean anomaly are around 0.014 K for ATSR-2 and 0.011 K for AATSR [RD-69])

4. Processing (A)ATSR LST CDR:

- Process monthly averaged products at 0.05° for day and night on UK-CEMS

- Only the highest quality clear-sky pixels to be used in the spatial and temporal averaging process

- Further optimisation of cloud detection to minimise the risk of cloud contamination in the dataset:

   i. For the prototype and first full CDR the UOL_V3 probabilistic approach is to be adopted as the best overall performing algorithm from a recent AATSR cloud clearing study over land [RD-30]

   ii. Re-processing of the CDR is to adopt the best performing cloud detection algorithm from the GlobTemperature (A)ATSR Cloud Clearing Round Robin (CCRR) exercise, which will be documented

- The LST product shall be distributed along with:

   i. quality dataset

   ii. propagated uncertainties

- Validation of Prototype CDR as part of the activities within the framework of the Validation and Intercomparison Work Package

- Examine the sensitivity to LST variation, which is a criterion for CDR assessment, and is to be realised through simulations

- Stability assessment of the CDR for trends, by examining de-seasonalised discrepancy with respect to a long-term reference site. The most suitable reference site is identified as Lake Tahoe (Section 5.2.5) which has provided continuous high-quality measurements since 1999.

This activity will deliver long-term data record from an instrument series (**addresses requirements REQ-3-TR and REQ-40-TR**). If the data record can be shown to be of climate quality then this dataset will by definition exhibit low bias, high precision, and high stability (**addresses requirements REQ-5-TR, REQ-6-TR and REQ-7-TR**). The adoption of better cloud clearing detection as delivered through the CCRR will further enhance the quality of the LST data.

GT-TS-14*: Develop Climate Data Record of over 10-years for (A)ATSR in harmonised format with low bias, high precision, and high stability. Targets: 1.0 K, 1.0 K and 0.3 K respectively*

GT-TS-15*: Determine the optimal cloud clearing methods over land for LST retrieval*

Addresses user feedback ***GT-UF-7****: Improve cloud screening, where feasible, in development of new products and updates to existing products with documented algorithms*

Currently LST is not classified by GCOS as an Essential Climate Variable (ECV); an objective of this deliverable is for LST to be re-assessed in the light of prospective advances in understanding.

4.2.15. GlobTemperature Matchup Database (GT_MDB)

The GlobTemperature Matchup Database (GT_MDB) encompasses datafiles for both in situ validation and multi-sensor intercomparisons. Their individual requirements mean datafiles generated within the GT_MDB follow set variants of a single harmonised format with common core features (Section 6.5.3).

For in situ validation satellite data providers are to deliver gridded LST subsets in harmonised format centred on the validation station for comparison with the station measurements.

***GT-TS-16**: Provide input satellite datasets for GlobTemperature Matchup Database (GT_MDB) in harmonised format*

The size of these subsets are determined by the characterisation of the surface for each individual stations, and may range from 5 x 5 pixels up to 50 x 50 pixels to ensure a sufficient coverage to capture the variability of the land around the validation site. The spatial resolution will be consistent with the `geospatial_lat_resolution` and `geospatial_lon_resolution` specified in the equivalent GlobTemperature Level-2, Level-3 or -4 datasets in equal-angle grids. All orbits overpassing a given site will be extracted as subsets for matching in the GT_MDB.

Similarly the validation scientist will deliver in situ measurements and thence datafiles of satellite matchups vs. in situ data in harmonised formats to the GT_MDB.

***GT-TS-17**: Provide in situ matchup datasets for GlobTemperature Matchup Database (GT_MDB) in harmonised format*

For intercomparisons the common proposed spatial resolution for re-gridding is 0.05º x 0.05º (compatible with both the merged LST products and the CDR). For some intercomparisons though other resolutions may be required (as detailed in Section 5.3). Both the mechanisms of intercomparison and the parameters for subsequent analysis may influence the results. The differences between weighted polygon averages for example and nearest neighbour binning may be significant; as may the temporal matching – nearest observation within a given time thresholds verses temporal interpolation. Also one needs to identify the importance of analysis with respect to different parameters: viewing geometry, orography, emissivity, and land cover classification for example. It is therefore important that all intercomparisons are carried out under a common framework.

***GT-TS-18**: Provide validation and intercomparison matchup datasets derived according to a consistent protocol*

To enable the matchup protocol to be advanced from the baseline protocol of [RD-5] an internal GlobTemperature Multi-sensor Intercomparison matchup Database has been constructed to facilitate testing of different matchup techniques:

- Options for spatial matching:
    - i. Nearest neighbour
    - ii. Polygon weighting

- Options for temporal matching
  - i. Nearest observation within Project defined threshold
  - ii. Temporal interpolation between bracketing observations (pertinent for GEO matchups)
- Creates datafiles of orbit / granule matchups on selected grid (nominally 0.05° x 0.05°) identified within 10° x 10° tiles
- Multi-sensor to support for example (A)ATSR, MODIS, SEVIRI, AVHRR, GOES and MTSAT
- Forms the basis for higher level matchup datasets and analysis

The baseline protocol for the matchup process is described in Section 5.1.3. This will be updated as the different mechanisms are better understood. It is then critical that the protocol is adhered to so as to give confidence to the user that each GlobTemperature output product has undergone a standardised evaluation. An agreed process for intercomparison is particularly important since such a process is to be carried out by different individuals within the GlobTemperature Project Team, and it is important that results are consistent and comparable. Specifically, intercomparisons of satellite observations coincident with in situ validation sites are to be carried out by KIT under the framework of the Validation and Intercomparison Work Package; while global satellite vs. satellite intercomparisons to generate empirical corrections for developing the suite of Merged LST Products will be split between ULeic and IPMA. All Satellite vs. Satellite matchups will be provided in the harmonised format for inclusion in the GT_MDB.

GT-TS-19*: Provide satellite vs. satellite matchup datasets for GlobTemperature Matchup Database (GT_MDB) in harmonised format*

Once the protocol is finalised then the use of open source solutions for data extraction will also be considered (a recommended solution is GDAL (www.gdal.org)). Parallel comparisons will be carried out between the GT_MDB developed tools and GDAL for consistency. ACRI-ST have developed several generic tools based on GDAL libraries allowing the generation of maps from sensor data dedicated to the comparison of satellite sensors. Such a solution will support the user requirement for transparency in product evaluation (**addresses requirements REQ-31-TR and REQ-39-TR**).

4.2.16. GlobTemperature Merged LST NRT Demonstration

The project team will implement a processing chain to generate in near real time the merged LST products.

- In a first stage, the team will target the generation of GEO-based LST, merging inter-calibrated LST from SEVIRI, GOES and MTSAT platforms: 3-hourly, clear sky LST, in harmonised GlobTemperature format.

- In a second stage, the product above shall be completed with NRT polar-orbiter LST products (AVHRR/Metop), maintaining the temporal frequency, but extending the area coverage towards the poles.

Being a demonstrational service, the LST merged product will be generated at IPMA's operational chain, archived locally and made available via FTP and through the GlobTemperature portal. For the majority of observations the objective is to provide users with data within 24 hours of acquisition with the target being within 12 hours (**addresses requirements REQ-12a-TR and REQ-13-TR**); the maximum timeliness being 2 days. The merged LST product (GEO-only and later GEO+LEO) shall be available in the GlobTemperature harmonised format, disseminated together with an error budget estimated on a pixel-by-pixel basis.

GT-TS-20*: Provide NRT merged LST demonstration product with standard timeliness of less than 24 hours (target 99% coverage); maximum timeliness to be no more than 48 hours; target to be 12 hours*

4.3. Summary of GlobTemperature datasets

The order of dataset dissemination is governed by the guaranteed access to source datasets and both the need, and the complexity, of performing the conversion of datasets at the local facilities of the partners. Therefore, some staging of data is needed, and the solution to this has been built on the UK-CEMS facility with 20 Tb of dedicated storage on the "globtemperature" workspace and access to central processing facilities to simplify the development of output datasets through code and data sharing. Furthermore, while most data will be archived directly on the main GlobTemperature archive at ACRI-ST other data will be hosted on the CEDA archive or on the LandSAF archive with direct dissemination from these archives via the GlobTemperature Data Portal.

The LST, IST and LSWT products to be produced within the framework of GlobTemperature, or externally linked to via the GlobTemperature Data Portal are summarised in Table 11, with the strategy for archiving and dissemination described in Table 12.

Table 11: Summary details of each GlobTemperature LST product

LST dataset	Satellite	Launch	Overpass time (descending node)	Comments
ATSR-1 ATSR-2 AATSR	ERS-1 ERS-2 Envisat	July 1991 April 1995 Mar. 2002	~10:30 ~10:30 ~10:00	L2 and L3 products developed in harmonised format, with data processing on UK-CEMS. ARC-Lake v2.0 data products are available from the L2 and L3 development. Integration into (A)ATSR CDR and

LST dataset	Satellite	Launch	Overpass time (descending node)	Comments
				Merged LST
AMSR-E	Aqua	May 2002	~01:30	L2 development in harmonised format by Estellus as single-sensor dataset for three years (2008 – 2010) and for integration into Merged LST Product No data available after October 2011 following failure of instrument
GOES	GOES	GOES 14: Jun. 2009 GOES 15: Mar. 2010	Geostationary orbit	L2 and L3 products developed in harmonised format with data processing through LandSAF
Metop- AVHRR	MetOp-A MetOp-B	Oct. 2006 Sept. 2012	~09:30	L2 and L3 products developed in harmonised format with data processing through LandSAF <u>or</u> UK-CEMS depending on operational capability of LandSAF within GlobTemperature deliverable timescales
GlobTemperature MODIS MOGSV / MYGSV	Terra Aqua	Dec. 1999 May 2002	~10:30 ~01:30	L2 and L3 products developed in harmonised format, with data processing on UK-CEMS from Collection 6 M?D021KM radiances, M?D03 geolocation data, M?D35 cloud data
MTSAT	MTSAT	Feb. 2006	Geostationary orbit	L2 and L3 products developed in harmonised format with data processing through LandSAF for 2010 onwards
SEVIRI	MSG	MSG-2: Dec. 2005 MSG-3: Jul.	Geostationary orbit	L2 and L3 products developed in harmonised format with data processing

LST dataset	Satellite	Launch	Overpass time (descending node)	Comments
		2012		through LandSAF
SLSTR	Sentinel-3	Expected: mid-2015	~10:00	Development of prototype L2 product with data processing direct on UK-CEMS if SLSTR data is available by mid-2016
SSM/I	DMSP	F15 – Dec. 1999	~06:00	L2 development in harmonised format by Estellus as single-sensor dataset for 2003 and for integration into Merged LST Product
MODIS (MOD21)	Terra Aqua	Dec. 1999 May 2002	~10:30 ~01:30	Link to external dataset currently in development at NASA-JPL. Operational data will be hosted on LP DAAC
VIIRS (standard EDR)	Suomi-NPP	Oct. 2011	~01:30	Link to external dataset
(A)ATSR CDR	ERS-1 ERS-2 Envisat	July 1991 April 1995 Mar. 2002	~10:30 ~10:30 ~10:00	Development of product on UK-CEMS in harmonised for at
Metop-AVHRR IST	MetOp-A MetOp-B	Oct. 2006 Sept. 2012	~09:30	DMI's IST L3 product through User Case Study
Matchup DB	N/A	N/A	N/A	All in situ matchups and intercomparison matchups to be archived together in GT_MDB harmonised formats
Merged LST	Multi-sensor	Multi-sensor	Multi-sensor	Data processing on UK-CEMS / LandSAF. L4 product in harmonised format

Table 12: Access and Archiving strategy for each GlobTemperature LST Product

Product	GlobTemperature Access and Archiving
(A)ATSR	Direct GlobTemperature disseminations (hosted on main archive)
AMSR-E	Direct GlobTemperature disseminations (hosted on main archive)
ArcLake	Direct GlobTemperature disseminations (hosted on Edinburgh DataShare)
GOES	Direct GlobTemperature disseminations (hosted on LandSAF)
Metop- AVHRR	Direct GlobTemperature disseminations (hosted on LandSAF)
GlobTemperature MODIS	Direct GlobTemperature disseminations (hosted on CEDA archive)
MTSAT	Direct GlobTemperature disseminations (hosted on LandSAF)
SEVIRI	Direct GlobTemperature disseminations (hosted on LandSAF)
SLSTR	Direct GlobTemperature disseminations (hosted on CEDA archive)
SSM/I	Direct GlobTemperature disseminations (hosted on main archive)
(A)ATSR CDR	Development of product on CEMS system (hosting on both main archive and CEMS)
Metop-AVHRR IST	DMI's IST through User Case Study
Matchup DB	All in situ matchups and intercomparison output datasets in harmonised formats (hosted on main archive)
Merged LST	Development of product on CEMS / LandSAF, archiving on main GlobTemperature archive
MODIS MOD21 / MYD21	External Link initially to NASA-JPL site then through LP DAAC once operational (through support of PI: Simon Hook)
VIIRS (standard EDR)	External Link to NOAA site (through support of PI: Simon Hook)
ASTER Global Emissivity Database	External Link to LP DAAC (through support of PI: Simon Hook)

5. Validation and Intercomparison

The validation and intercomparison protocols will link Task 4 of the Project with the ILSTE-WG and with the LST White Paper [AD-6]. The approach GlobTemperature will take is to follow, as a baseline, the LST Validation Protocol [RD-5] developed for the ESA Long-term Land Surface Temperature Validation Project (as applied in [RD-68]). This protocol is quickly gaining recognition within the LST community and has also been incorporated into the ESA Sentinel-3 Cal-Val Plan [RD-70] for LST Validation.

5.1. Protocol summary

There is a wide variety of approaches to LST validation. The different types of approaches are structured here within four different categories. The four categories are as follows:

5.1.1. Category A: Comparison of satellite LST with in situ measurements

This is the traditional and most conclusive approach to validating LST. It involves a direct comparison of satellite-derived LST with collocated and simultaneously acquired LST from ground-based radiometers. It is often more intensive than other approaches as a result of finding suitable sites, operating validation stations and obtaining the required ancillary information from additional measurements.

The protocol for the in-situ measurements will conform as closely as possible to the following:

- The measurements must be continuous and frequent enough to allow a close temporal matching between satellite overpasses and in-situ data, i.e. in-situ data need to be available every 1-3 minutes, which will also allow daytime and night-time validation. Furthermore, ancillary data relating to the near surface atmosphere, e.g. air temperature and humidity, and land surface emissivity data should be collected. Ideally, the validation site is to be uniform at scales of several kilometres and covers at least 3x3 satellite pixels. Although cloud-free campaigns with low aerosol content provide “ideal” conditions, validation should also be performed under difficult conditions and the in-situ measurements have to be continuously available and represent the whole bandwidth of possible atmospheres.

- The in-situ instruments, e.g. radiometers or FTIR spectrometers, should be calibrated to as near an accuracy of ±0.1 K as possible given the restrictions of the instrument and be traceable to a NIST blackbody.

- At sites where directional radiances are measured, also directional sky radiance at 53° from zenith [RD-71] has to be measured simultaneously with a duplicate radiometer. Measuring the down-welling sky radiance allows correcting for reflected radiance contained in the radiance measured over the target.

- At sites equipped with hemispherical broadband radiance sensors, up-welling and down-welling radiance measurements need to be simultaneously available in order to allow correction of reflected down-welling radiance. In practise, this requires identical up-looking and down-looking sensors, e.g. as usually found in radiance balance sensors.

- Where available, sun photometer measurements of aerosol optical depth are desirable; the temporal and spatial considerations are the same as for atmospheric profile data (see section 'Category B: Radiance-based validation').

- LST retrieval from satellite measurements and the derivation of in-situ LST from directional radiance measurements require knowledge of directional spectral (8-14 µm) land surface emissivity (LSE) for the respective target areas. In-situ emissivities need to be determined with appropriate spatial and temporal sampling to be representative of LSE.

- Provided that no fast, significant change at the surface occurs, e.g. due to rainfall, forest fires etc., estimates of in-situ LSE every 10 to 30 days suffice. However, in case of changes in surface moisture LSE may need to be retrieved several times per day.

- Over bare soils the uncertainty of current LSE products is the largest [RD-72, RD-73] and, therefore, for arid and semi-arid sites in-situ emissivity data are highly desirable. In-situ measurements and laboratory measurements were performed for two of KIT's validation sites [RD-74, RD-75], but generally such measurements are not available. Depending on the surface type, the accuracy of in-situ LSE is usually between ±0.005 and ±0.015.

- From 2014 onwards a new MODIS LSE product (MOD21) retrieved up to four times per day will be available, which was shown to provide reliable LSE estimates at 1km spatial resolution with an uncertainty of 0.015 [RD-61]. Where no in-situ emissivity data are available, the use of in-situ emissivities derived from MOD21 LSE is recommended.

- For a vegetated target, measurements of the density and height of the vegetation might prove useful. The fractional tree crown cover at the validation sites should be estimated and the emissivities of the relevant end-members should be acquired from literature.

- Obtaining in-situ LST from broadband radiance measurements, e.g. as available from SURFRAD and BSRN sites, requires knowledge of the associated broadband emissivities (BBE). The standard approach to obtain BBE is via regression relationships with multi-spectral emissivities, e.g. MODIS or ASTER LSE. The regressions can directly be based on satellite emissivities [RD-76] or on spectral emissivities obtained from matching satellite-retrieved LSE with laboratory spectra [RD-77, RD-78].

- All-sky cameras are desirable to provide an objective measure of cloudiness during the daytime. At night an upward viewing pyrgeometer can improve cloud-screening.

5.1.2. Category B: Radiance-based validation

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

Radiance-based validation offers a useful alternative to validation with in situ LST as it does not require in-situ measurements concurrent with the satellite overpass [RD-67]. The technique starts with an initial input satellite-retrieved LST value for which it simulates TOA BTs with a radiative transfer model; as inputs the model requires the - assumed to be known – LSE and (nearly) concurrent atmospheric profiles of air temperature, water vapour, and - if available - aerosols. Perturbations are then applied to the input LST value until the simulated TOA BTs bracket the BT observed by the satellite: the R-based LST (LST_R) is determined by interpolating between the bracketing LST. The difference, δLST, between the initial input LST and LST_R is the LST uncertainty.

Radiance-based validation requires accurate knowledge about the vertical structure of the atmosphere, in particular about the vertical profiles of air temperature and water vapour, and LSE has to be known. For selecting locations where R-based validation is to be carried out, a key criterion is the spatial homogeneity and temporal stability of the surface in terms of emissivity. As for the atmospheric profiles, the most appropriate data for global analyses of LST products are outputs from global circulation models (GCM), in particular from atmospheric reanalyses interpolated to the time of the satellite observation. Therefore, vertical profiles of air temperature and water vapour should be obtained from GCMs within a specified time around the satellite measurements and within a specified radius of the target area.

To assess whether the atmospheric profiles used in the radiative transfer simulations sufficiently represent the true atmospheric conditions observed during satellite retrievals the discrepancy $\delta(T_{11} - T_{12})$, which is the difference between the observed BT difference $(T_{11} - T_{12})_{obs}$ and the simulated BT difference $(T_{11} - T_{12})_{sim}$, can be examined. When the result of this 'double-differencing test', which was first implemented by [RD-67], is close to zero, then the atmospheric profiles can be assumed to be representative of the real conditions. However, the accuracy of radiance-based validation still crucially depends on the accuracy of the input LSE, which must be known.

5.1.3. Category C: Inter-comparison between LST products

A wide variety of airborne and space borne instruments collect thermal infrared data and many provide operational LST products. An inter-comparison of LST products from different satellite instruments is highly valuable for assessing relative algorithm performance and supplements in-situ and radiance-based validation by providing important information about the spatial distribution of LST deviations. Intercomparisons facilitate the evaluation of the LST products relative consistency, which is highly important for users needing to judge the relative merit of several products. Intercomparisons are also mandatory when combining several products into a 'best available product'. However, product intercomparisons on their own are not sufficient for comprehensive validation since the various products could be 'consistent' but nonetheless biased with respect to reference data, i.e. in-situ LST.

For each intercomparison the following methodology is to be followed as close as possible:

- Only the highest quality cloud-free pixels are to be considered.
- In order to satisfactorily intercompare datasets, spatial variability within the IFOV of each satellite needs to be accounted for. This is achieved by re-gridding the data onto a common spatial grid by averaging all geo-referenced, cloud free pixels weighted by their respective fractional area overlap with the corresponding common grid cell.
- The high temporal variability of LST ensures that intercomparison of different LST products is a challenging prospect. In order to minimise the impact on the intercomparison results, LST differences due to deviating observation times have to be minimised. This can be achieved by limiting the data to close temporal matchups; or – for intercomparisons between LEO and GEO datasets - by interpolating the GEO measurements that temporally bracket the LEO overpass time.
- Separate monthly composites of LST differences should be generated for daytime and night-time observations, where observations are categorised as “day” or “night” based on their respective solar zenith angles.

5.1.4. Category D: Time series analysis

Analysing time series of satellite data over temporally stable targets allows identification of potential calibration drift or other issues with the instrument or the input data that manifest themselves over time. Furthermore, problems associated with cloud contamination 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.

Time series provided at small spatial scales are subject to less spatial averaging and therefore provide more specific information with respect to temporal validation than time series of a merged global product. While the latter is interesting independently, merged data sets tend to include a variety of instrumental issues and geophysical signals which are difficult to separate, and they are therefore less useful for validation purposes.

A precision assessment reflects the repeatability of a product. This step is very important when analysing long time series or comparing different regions. Ideally, such an assessment should be based on a comparison with reference (in-situ) data with well-defined small uncertainties. However, due to the limited amount of such high quality reference data, precision is usually assessed by analysing the variability of LST products over surfaces known to be homogeneous and stable. In case such surfaces are not available, e.g. if there is a heterogeneous and dynamic vegetation cover in the target area, precision may also be quantified by evaluating the ‘smoothness’ of the time series of some geostatistical metric, e.g. variograms generally show significant variability (nugget) for pixels separated by very short distances. The evaluation should also consider the frequency of valid data with additional details on data QA (such as the application of gap filling techniques). Histograms of the data can be used to check if the distributions are plausible.

5.1.5. Sub-categorisation

It should be noted that, while exhibiting certain similarities, these categories do not directly translate to the hierarchical validation classes as suggested previously for SST validation [RD-79] and by CEOS. While a Category A validation will generally be more complex and resource-demanding than a Category D validation, the categories given here can be quite complementary and a comprehensive LST validation will ideally entail elements from all four of them.

Based on the complexity of the methodology and the expected accuracy of the validation, the four validation categories are further subdivided into several classes. For each category a set of quality criteria is established. A Class 1 validation must fulfil all these criteria. For each subsequent class, one of the listed criteria can be relaxed. Table 13 shows an overview of the categories and their classes, with the detailed categorisation described in Appendix B – Detailed categorisation of the LST Validation Protocol.

Table 13: Schematic overview of LST validation categories and complexity levels reproduced from [RD-5]

<table>
<tr><th></th><th colspan="4">Category</th></tr>
<tr><th></th><th>A
In situ</th><th>B
Radiance-based</th><th>C
Inter-comparison</th><th>D
Time series</th></tr>
<tr><td rowspan="8">Highest accuracy
Accuracy Class
Lowest accuracy</td><td>A1</td><td rowspan="3">B1</td><td rowspan="3">C1</td><td rowspan="2">D1</td></tr>
<tr><td rowspan="2">A2</td></tr>
<tr><td rowspan="2">D2</td></tr>
<tr><td>A3</td><td rowspan="2">B2</td><td rowspan="2">C2</td></tr>
<tr><td>A4</td><td rowspan="2">D3</td></tr>
<tr><td rowspan="2">A5</td><td rowspan="3">B3</td><td rowspan="3">C3</td></tr>
<tr><td rowspan="2">D4</td></tr>
<tr><td>A6</td></tr>
</table>

Furthermore, the LST uncertainties themselves need to be validated to provide further confidence to users of LST datasets. The protocol for this involves mapping the standard deviation of the satellite LST vs. in situ LST against the satellite uncertainty estimate and examining whether the uncertainty estimate falls within the predicted bounds (**addresses requirement REQ-35-TR**).

GT-TS-17*: Provide validation and intercomparison matchup datasets derived according to a consistent protocol*

GT-TS-21*: Validate the LST uncertainty estimates provided in the harmonised datafiles*

Addresses user feedback ***GT-UF-13****: Share information and expertise on best validation / calibration protocols*

5.2. Primary in situ Validation Sites

Only few active validation sites dedicated to long-term LST validation exist, namely KIT's four validation sites in Portugal and Africa and the site operated by the University of Valencia in Spain [RD-23]. However, the latter operates on a campaign basis and usually provides some measurements during the summer months. In order to increase the number of primary in-situ validation sites for the purpose of GlobTemperature, additional sites were selected based on a) their long-term operational availability and b) their category according to [RD-5]. An overview of potentially useful validation sites is given in Table 10.8 of [RD-80]. Many of these sites are temporary in nature (e.g. mobile ARM sites) and, therefore, provide only a limited number of data points for past satellite sensor generations.

Converting narrow band directional radiance measurements to LST

The ideal instrument for validating satellite-derived LST is a narrow band, narrow FOV radiometer with the same spectral characteristics and view direction as the overpassing satellite sensor. In practise this is unfeasible, but many satellite sensors observe the surface close to nadir (or such measurements can be selected) and, therefore, can be validated with in-situ LST from well-chosen sufficiently isotropic sites, e.g. sites covered by grass or sand [RD-81, RD-82]. KIT's validation stations and some ARM sites are equipped with narrowband infrared (IR) Heitronics KT-15 radiometers (self-calibrating, chopped radiometers, Heitronics Infrarot Messtechnik GmbH, Wiesbaden, Germany). The KT-15 measures IR radiance between 9.6 and 11.5µm and expresses the results as BTs with an absolute accuracy of ±0.3 K over a wide temperature range [RD-83]. For radiometers measuring in the atmospheric window and for a small distance between the sensor and the surface (a few 10m), atmospheric attenuation of the surface-leaving IR radiance can be neglected. However, the measurements contain radiance emitted by the surface (i.e. the target signal) as well as reflected downwelling TIR radiance originating from the atmosphere. Therefore, the radiance measured by the surface observing KT-15 is given by:

$$R_{KT-sfc} = \varepsilon B(T_{sfc}) + (1-\varepsilon) L_{down}$$

Where T_{sfc} is LST, ε is the channel-specific emissivity of the surface, B is the Planck function at the KT-15's centre wavelength (10.55µm), and $L_{down} = B(T_{sky})$ is the downwelling longwave radiance convolved with the KT-15's response function [RD-18]. Depending on surface emissivity and on downwelling longwave radiance (e.g. a cold clear sky vs. a warm humid atmosphere), the reflection term in the above equation can cause differences of several degrees Celsius [RD-84]. L_{down} is measured by an additional sky-facing radiometer. LST is obtained from KT-15 radiances by solving the above equation for $B(T_{sfc})$ and then solving the Planck function for T_{sfc} at the KT-15's centre wavelength.

<u>Converting broadband hemispherical radiance measurements to LST</u>

SURFRAD [RD-85] and other stations provide upwelling and downwelling broadband hemispherical IR radiances which are related to BT via the Stefan–Boltzmann law. Together with broadband emissivity (BBE), which can be obtained from regression relationships between BBE and MODIS multi-spectral LSE [RD-23, RD-76], LST can be obtained from the simplified radiative transfer equation at the land surface [RD-86, RD-87]. For meaningful comparisons with satellite-retrieved LST the land surface has to be near isotropic, since the in-situ sensors integrate over the entire lower hemisphere, whereas the satellite sensor is strongly directional (e.g. near nadir). In order to avoid influence of the atmosphere on the broadband measurements (3-50µm), the distance between the in-situ sensor and the target has to be small, since the sensors also measure outside the atmospheric window.

5.2.1. KIT Validation Stations

Key sources for ground-based validation data will be KIT's well established LST validation sites (Figure 7) in Evora (Portugal), Dahra (Senegal, subtropics), Gobabeb (Namibia, Namib desert) and at farms RMZ/Heimat (Namibia, Kalahari); according to the [RD-5] specifications, these are - for the solid land surface - currently the only available class A2 ground based validation stations worldwide.

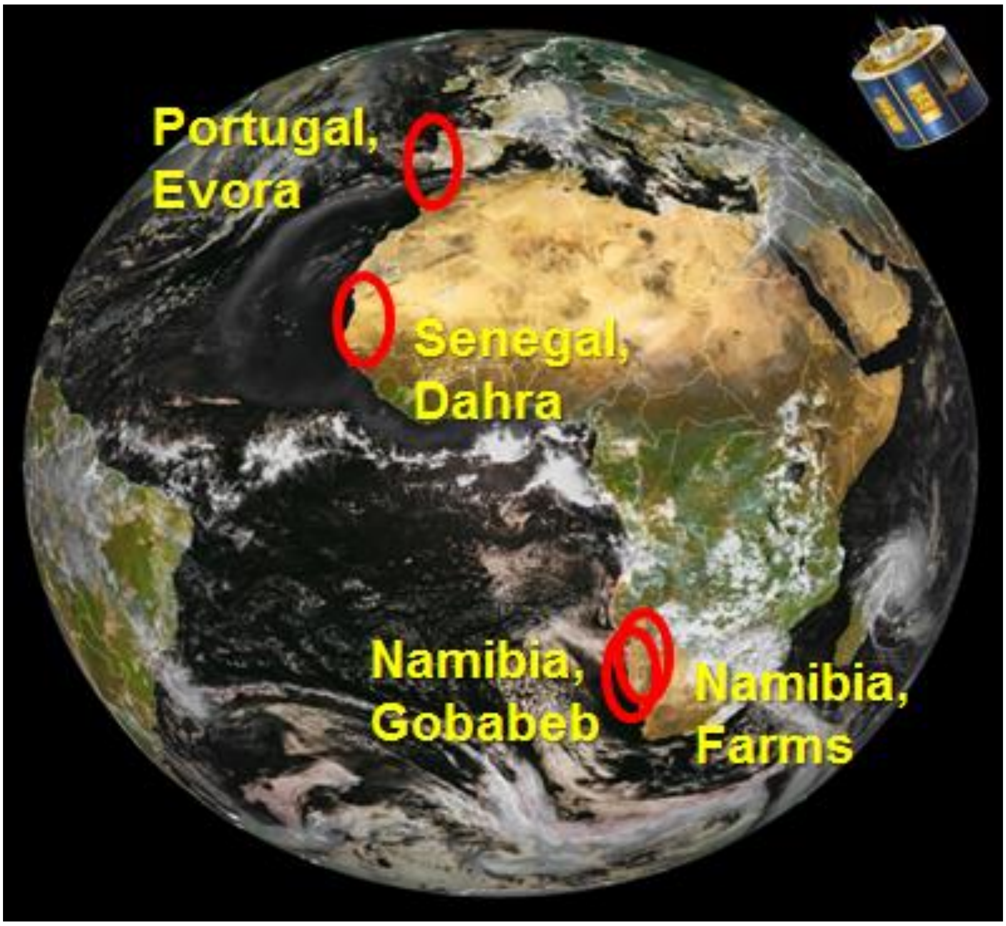


Figure 7: Locations of Karlsruhe Institute of Technology (KIT) validation stations

The core instruments of KIT's validation stations are Heitronics KT-15.85 IIP infrared radiometers. Relevant end-members are observed under a view angle of 30°; using this view angle instead of the nadir view is justified by the fact that the angular emissivity variation of sand, grass, and gravel is negligible up to view angles of at least 30° [RD-81, RD-82]. From 25m height the KT-15's full view angle of 8.5° results in a FOV of about 14 m^2. An additional KT-15 faces the sky at 53° with respect to zenith and measures the channel-specific downwelling longwave radiance, which is used to correct for the reflected component in the down-looking measurements.

Table 14: KIT stations (LST from narrow band, directional radiance measurements with KT15.85 IIP)

Code	Name	Latitude	Longitude	Elevation	Data period	Comment
EVO	Evora, Portugal	38.540244	-8.003368	230 m	Oct 2007 - now	gap Jan 2013 - Jun 2013
DAH_T	Dahra tree mast, Senegal	15.402336	-15.432744	90 m	Jul 2009 - now	more continuous after Jul 2010
GBB_W	Gobabeb wind tower, Namibia	-23.550956	15.05138	406 m	Jan 2008 - now	most continuous data set
KAL_R	Rust mijn Ziel (RMZ) Farm, Kalahari, Namibia	-23.010532	18.352897	1450 m	Apr 2009 - Feb 2011	**initial** Kalahari bush station
KAL_H	Farm Heimat, Kalahari, Namibia	-22.932827	17.992137	1380 m	Feb 2011 - now	**current** Kalahari bush station

In addition to the dedicated LST sites in Table 14, in-situ LST obtained from non-dedicated, continuously operating SURFRAD stations [RD-85] and ARM (Atmospheric Radiation Measurements) stations [RD-88] will be used for product validation within the GlobTemperature project (Figure 8). SURFRAD stations were successfully utilised to validate MODIS LST [RD-76, RD-86] and GOES-R LST [RD-87, RD-89]. In-situ LST from ARM sites were applied to validate AATSR LST [RD-16]. The long-term maintenance of the SURFRAD stations (Table 15) and selected ARM stations (Table 16) ensures good opportunity for matchups of in-situ LST with satellite LST products.

5.2.2. NOAA SURFRAD Stations

The SURFRAD (Surface Radiation) network was established in 1993 through the support of NOAA's Office of Global Programs and has been operational since 1995 [RD-85, RD-87]. Its primary objective is to support climate research with accurate, continuous, long-term measurements pertaining to the surface radiation budget over the United States [RD-90]. Six of the seven SURFRAD sites were identified as useful for validating spatially moderate to coarse LST products [RD-86, RD-87]; the seventh site - Sioux Falls, SD – is to too heterogeneous in terms of land cover, making the in-situ measurements un-representative on the scale of the satellite pixel.

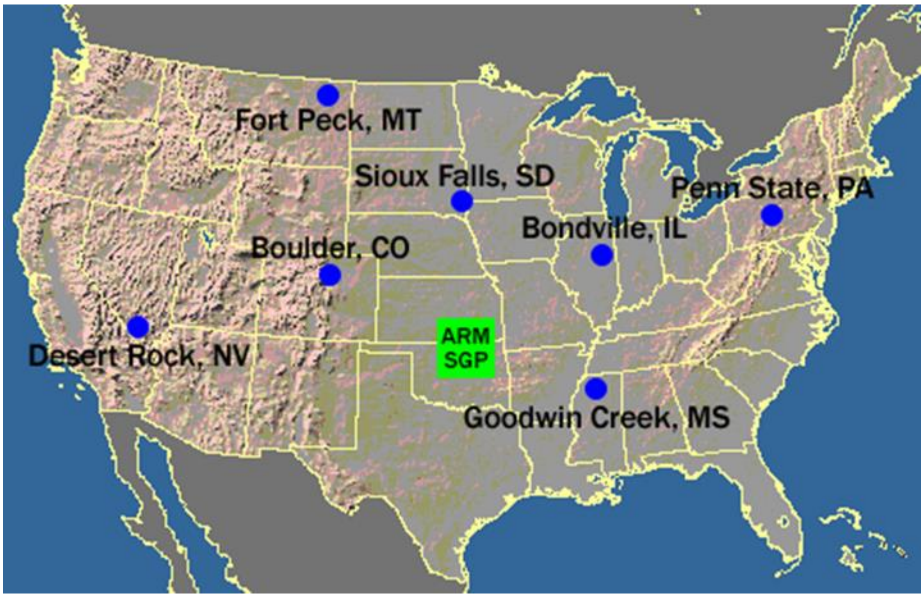


Figure 8: Locations of NOAA SURFRAD stations and ARM Southern Great Plains (SGP). Source: NOAA ESRL.

Table 15: SURFRAD stations (http://www.esrl.noaa.gov/gmd/grad/surfrad/index.html), category/class A4 according to [RD-5]. In-situ LST have been derived for the period 2004-2013 and are already available at the time of writing this report.

Code	Name	Latitude	Longitude	Elevation	Data period	Comment
BND	Bondville, Illinois	40.05155	-88.37325	230 m	1994 – now	Data files labelled 'BON'
TBL	Table Mountain, Boulder, Colorado	40.12557	-105.23775	1689 m	1995 – now	
DRA	Desert Rock, Nevada	36.62320	-116.01962	1007 m	1998 – now	
FPK	Fort Peck, Montana	48.30798	-105.10177	634 m	1994 - now	
GCM	Goodwin Creek, Mississippi	34.2547	-89.8729	98 m	1994 - now	
PSU	Penn. State Univ., Pennsylvania	40.72033	-77.93100	376 m	1998 - now	
SXF	Sioux Falls, South Dakota	43.73431	-96.62334	473 m	2003 - now	**not useful for LST val.**

5.2.3. ARM Stations

The U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) site SGP CF1 (Central Facility), Lamont, Oklahoma (http://www.arm.gov/sites/sgp/C), has been identified as the most appropriate ARM site for LST validation (Table 16). The station is equipped with Infrared Thermometers (IRT) Wintronics (Heitronics KT15) and it is located in a large area with cattle pasture and wheat fields. Due to the specific instrumentation at the sites, higher surface heterogeneity and/or small areas of the sites, many of the remaining ARM sites in Table 16 are less suitable for LST validation. Furthermore, the TWP sites are on the coast which complicates the validation of spatially coarse satellite LST. GlobTemperature will focus on the 'Southern Great Plains Facility' SGP-CF1 site and then consider the NSA-sites, which in winter are covered by snow (Figure 9).

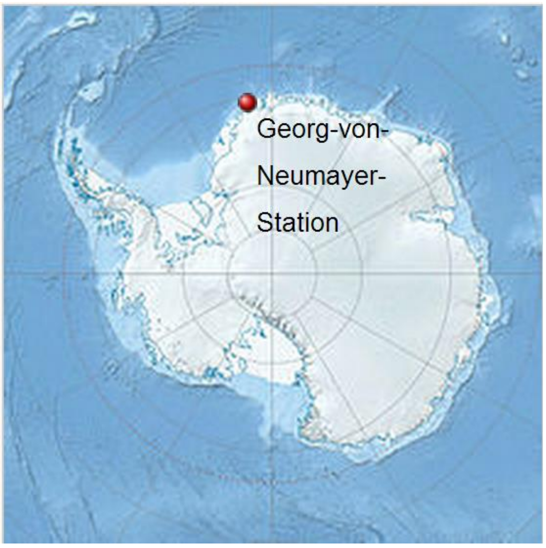
Figure 9: Locations of ARM climate research facilities. Source: DOE ARM CRF.

Table 16: ARM stations, category/class A4 according to [RD-5]. The data period given is approximate.

Code	Name	Latitude	Longitude	Elevation	Data period	Comment
SGP-CF1	Southern Great Plains Facility, Oklahoma	36.605° N	97.485° W	318 m	2003 - now	
NSA-Barrow	Barrow, North Slope of Alaska	71.32° N	156.60° W	8m	2003 - now	
NSA-Atqasuk	Atqasuk, North Slope of Alaska	70.47° N	157.40° W	20m	2003 - now	
TWP-Darwin	Darwin, Tropical Western Pacific	12.42° S	130.89° E	30m	2003 - now	Heterogeneous
TWP-Nauru	Nauru, Tropical Western Pacific	0.52° S	166.91 E	7m	2003 - now	Heterogeneous – potential mixture of land and sea pixels

5.2.4. Georg-von-Neumayer-Station

The Alfred-Wegener-Institute (Bremerhaven, Germany) has been operating the Georg-von-Neumayer-Station on Antarctica since 1981 (Neumayer I: 1981-1992, Neumayer II: 1992-2009, Neumayer III: 2009-now) (Figure 10 and Table 17). Neumayer’s meteorological observatory is designed as a radiation and climate monitoring station. Measurements of radiation are carried out on a large scale as part of a global observation network to detect long-term changes in the Earth's radiation budget and their impacts on climate. Since 1998 derived surface temperatures at 1 min interval are available from the Alfred Wegener Institute (AWI) in Bremen, Germany. These are obtained from broadband hemispherical longwave fluxes (PIR and CGR4 pyrgeometers from Eppley and Kipp+Zonen), which are part of Neumayer’s Baseline Surface Radiation Network (BSRN) station.



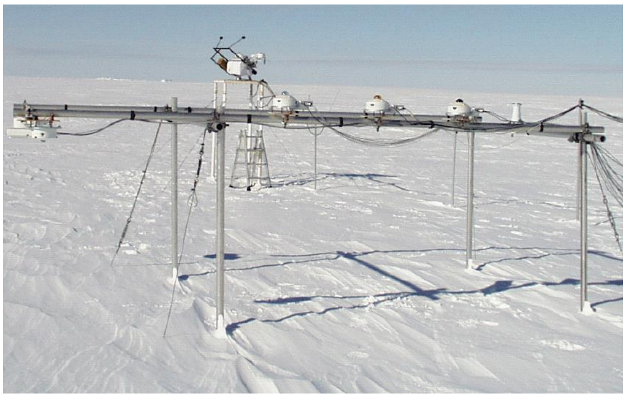


Figure 10: Antarctica with the location of Georg-von-Neumayer Station (left) and Surface Radiation Measurements at Neumayer (right). Source: Alfred-Wegener-Institute (AWI)

Table 17: Georg-von-Neumayer-Station, category/class A3 according to [RD-5]

Code	Name	Latitude	Longitude	Elevation	Data period	Comment
GVN	Georg-von-Neumayer station, Antarctica	70.67° S	8.27° W	40 m	1998 - now	

5.2.5. Lake Tahoe Site

The Lake Tahoe LST validation site (http://laketahoe.jpl.nasa.gov) is located at the border between California and Nevada (USA) and is operated by the Jet Propulsion Laboratory [RD-91, RD-92] (Figure 11 and Table 18). The lake is 33 km long and 18 km wide and has an average depth of 330 m. The site consists of four fixed buoys (TB1 - TB4) equipped with highly accurate, self-calibrating radiometers (7.8 µm - 13.6 µm) for measuring the lake's skin temperature. The radiometer uses a cone blackbody for calibration and has an accuracy of ±0.1 K. The site has provided continuous data since 1999 at an interval of 2 minutes.

Measurements performed at the buoys are: upward and downward long wave radiation, upward and downward shortwave radiation, wind speed & direction, air pressure, air temperature, relative humidity, net radiation, aerosol optical depth, total column water vapour, skin temperature (from radiometer) and water temperature measured 1cm below the surface. There is also a total sky imager. Contact: Dr Simon J. Hook (Simon.J.Hook@jpl.nasa.gov).

Figure 11: One of the four buoys maintained by JPL on Lake Tahoe.

Table 18: Lake Tahoe Site (four buoys), category/class A2 according to [RD-5].

Code	Name	Latitude	Longitude	Elevation	Data period	Comment
LTB-1	Lake Tahoe TB1, USA	39.1530° S	120.0003° W	1895 m	1999 - now	
LTB-2	Lake Tahoe TB2, USA	39.1094° S	120.0108° W	1895 m	1999 - now	
LTB-3	Lake Tahoe TB3, USA	39.1102° S	120.0754° W	1895 m	1999 - now	
LTB-4	Lake Tahoe TB4, USA	39.1550° S	120.0722° W	1895 m	1999 - now	

5.2.6. Salton Sea Site

The Salton Sea is an inland saline lake (approx. 60 km long and 20 km wide) located in south-eastern California (Figure 12 and Table 19). The sea has a maximum depth of 16 m and an average depth of 9 m. The salinity of Salton Sea is approximately 45 g/l, thirty percent greater than that of the ocean [RD-93]. The Jet Propulsion Laboratory operates a platform in the sea which provides the same set of parameters as the Lake Tahoe Site (http://saltonsea.jpl.nasa.gov). Data has been available since 2006 at an interval of 2 minutes. Contact: Dr Simon J. Hook (Simon.J.Hook@jpl.nasa.gov).

Figure 12: Measuring platform operated by JPL in the Salton Sea. The yellow box contains the precision radiometer.

Table 19: Salton Sea Site, category/class A2 according to [RD-5].

Code	Name	Latitude	Longitude	Elevation	Data period	Comment
SSP	Salton Sea Platform, USA	33.22532° S	115.82425° W	-69 m	2006 - now	

GT-TS-22*: Ensure quality of GlobTemperature datasets through comprehensive validation, intercomparison, and user evaluation*

5.3. Datasets for Intercomparison

A summary of which datasets are to have intercomparison matchups extracted and a brief description of the matchup specifications are given in Table 20. Only feasible matchup combinations are listed; where the orbit characteristics of two sensors are not compatible for matching LST then no entry is made. Matchups are to be used both globally in the derivation of correction factors for the GEO/LEO merging, and within the framework of the Validation and Intercomparison activities centred on the validation sites.

For matchups between datasets with different spatial resolutions or different orbital tracks the standard spatial resolution for re-gridding is proposed as being 0.05º x 0.05º. This additionally is the same as proposed for the merged LST products and the CDR. As for temporal matching, for the most part the nearest temporal matchup – within a predefined project-wide threshold (7.5 minutes, which is half the temporal difference between temporally adjacent SEVIRI observations) – will be used. For matchups between LEO and GEO satellites where the temporal frequency of the GEO observations are high the possibility of interpolating between bracketing GEO observations to the LEO overpass time may provide more representative matchups; only data from SEVIRI offers such potential.

For analysis of matchups specific auxiliary is recommended, such as viewing geometry, orography, emissivity, and land cover classification. Where available these should be supplied with the input satellite vs. satellite matchup datafiles (Section 6.5.3). These matchups provide the raw material for temporal / spatial compositing for delivery of user required intercomparison information via Data Portal visualisation tools (**addresses requirement REQ-39-TR**).

GT-TS-23*: Data Portal to provide visualisation tools and statistics for LST data, LST anomalies, validation information and intercomparison data*

Table 20: Summary of intercomparison dataset matchups to be produced in GlobTemperature

Dataset 1	Dataset 2	Spatial matching	Temporal matching
AATSR	ATSR-2	Satellites on same orbit track	AATSR is 30 minutes ahead of ATSR-2
AATSR	SEVIRI	Datasets re-gridded to 0.05° x 0.05° for matchup	Nearest temporal match within project defined threshold <u>OR</u> interpolating the GEO measurements that temporally bracket the LEO overpass time
AATSR	GOES	Datasets re-gridded to 0.05° x 0.05° for matchup	Nearest temporal match within project defined threshold
AATSR	MTSAT	Datasets re-gridded to 0.05° x 0.05° for matchup	Nearest temporal match within project defined threshold
AATSR	Terra-MODIS	Datasets re-gridded to 0.05° x 0.05° for matchup	Nearest temporal match within project defined threshold
ATSR-2	Terra-MODIS	Datasets re-gridded to 0.05° x 0.05° for matchup	Nearest temporal match within project defined threshold
AATSR	Metop-AVHRR	Datasets re-gridded to 0.05° x 0.05° for matchup	Nearest temporal match within project defined threshold
Aqua-MODIS	AMSR-E	MODIS dataset re-gridded to AMSR-E spatial grid	Instruments on same platform
Terra-MODIS	SEVIRI	Datasets re-gridded to 0.05° x 0.05° for matchup	Nearest temporal match within project defined threshold <u>OR</u> interpolating the GEO

Dataset 1	Dataset 2	Spatial matching	Temporal matching
			measurements that temporally bracket the LEO overpass time
Terra-MODIS	GOES	Datasets re-gridded to 0.05° x 0.05° for matchup	Nearest temporal match within project defined threshold
Terra-MODIS	MTSAT	Datasets re-gridded to 0.05° x 0.05° for matchup	Nearest temporal match within project defined threshold
Aqua-MODIS	SEVIRI	Datasets re-gridded to 0.05° x 0.05° for matchup	Nearest temporal match within project defined threshold OR interpolating the GEO measurements that temporally bracket the LEO overpass time
Aqua-MODIS	GOES	Datasets re-gridded to 0.05° x 0.05° for matchup	Nearest temporal match within project defined threshold
Aqua-MODIS	MTSAT	Datasets re-gridded to 0.05° x 0.05° for matchup	Nearest temporal match within project defined threshold
Metop-AVHRR	SEVIRI	Datasets re-gridded to 0.05° x 0.05° for matchup	Nearest temporal match within project defined threshold OR interpolating the GEO measurements that temporally bracket the LEO overpass time
Metop-AVHRR	GOES	Datasets re-gridded to 0.05° x 0.05° for matchup	Nearest temporal match within project defined threshold
Metop-AVHRR	MTSAT	Datasets re-gridded to 0.05° x 0.05° for matchup	Nearest temporal match within project defined threshold

6. GlobTemperature Data Products

This section sets out the scope of the GlobTemperature Products and their formats based on the inputs from the Requirements Baseline Document [AD-3].

6.1. Web Portal Design and Development

6.1.1. GlobTemperature Website

The GlobTemperature website, available at http://www.globtemperature.info aims at providing information about the project. The website is publicly available and will deliver:

- A description of the project and partners;
- A library with all public documentation;
- The latest news, including the executive summaries of MPRs;
- The list of events;
- A contact form;
- A link to the data portal.

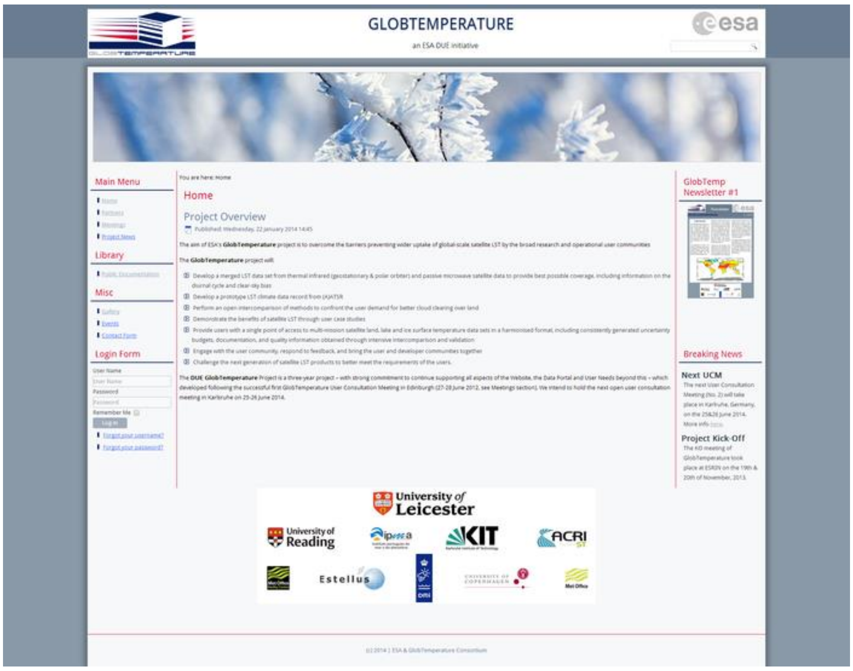


Figure 13: Screenshot of the GlobTemperature website home page

***GT-TS-24**: Provide information and documentation, including news and events, to the users via the GlobTemperature Website*

In addition, the website also includes a restricted area dedicated to ESA and the partners of the project whose main objective is to share project documents.

6.1.2. Web Portal

The web portal aims at providing access to the LST data and the associated documents and tools. It will be available on the sub-domain named "data" at http://data.globtemperature.info. This portal must be an open system, easy to use and must be consistent with the users' needs. In the final version, the portal will comprise three main sections dedicated to:

- **Data access**: this part will give access to the data sets and information such as links and documents related to the data.
- **Visualization** section that will contain online functionality to easily visualize the products, especially for quality control and validation purpose.
- **Tools:** downloadable tools will be provided in this section. They will be dedicated to the conversion of format and projection.

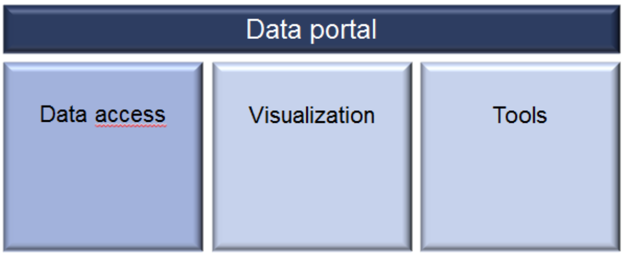


Figure 14: Main components of the web portal

6.1.3. Data access and dissemination

This section will be composed of:

- a request interface in order to submit orders and to download products
- a registration procedure
- a catalogue of the available data sets including the metadata
- a section dedicated to the information on the products and related topics

Catalogue and metadata

A catalogue of all the available data sets will be available online, presenting the main characteristics of the products. For each data set, the user will be able to consult a detailed version of the metadata. In particular, the access policy and the acknowledgements associated to the data set will be available on the interface. This kind of information must be given by the provider of the data set when it is included in the GlobTemperature Archive of the data portal (information often included in the header of the products).

Information section

This section will host two essential types of document:

- The Satellite LST handbook
- The Product User Guides provided as PDF files

It will be complemented with other useful information concerning the data sets, such as links to other websites, validation information or external online documents (**addresses requirements REQ-19-TR, REQ-20-TR and REQ-38-TR**).

GT-TS-25*: Data portal to provide information page on metadata, and links to validation reports and Products User Guide (PUG) for each disseminated dataset*

Registration procedure

A registration procedure must be followed through a web form in order to gain access to project information and datasets. This procedure is to be simple in that the only the mandatory fields are:

- Last Name
- Organization
- Email address
- A password chosen by the user himself

A procedure will also be developed to allow the user to enter a new password in case of password lost (Figure 15).

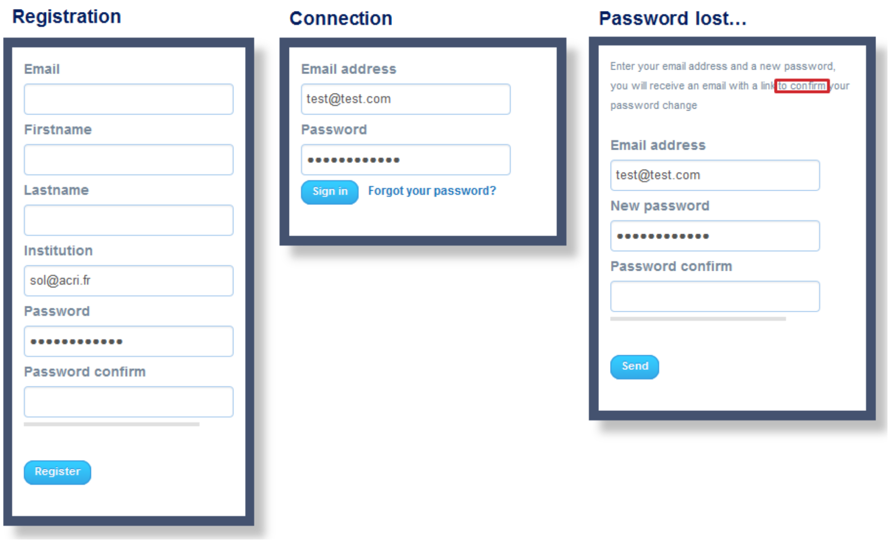


Figure 15: Forms for the management of identification on the data portal

GT-TS-26*: Ensure straightforward user access to the GlobTemperature Website and Data Portal with minimal required information for registration*

<u>Infrastructure</u>

The data portal infrastructure will be based on the following servers (preference is given for open-source software):

- a HTTP server (APACHE)
- a database server (PostgreSQL)
- a storage server (RAID System)
- a FTP server (ProFTPD)

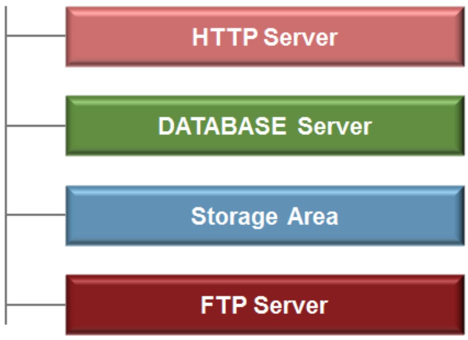


Figure 16: Components of the web portal infrastructure

Structure of the database

The global GlobTemperature database will be separated in to parts (two different schemas in PostgreSQL).

The first will be dedicated to the data themselves. It will host the metadata at the dataset level and at the product level. In particular, the logical structure of the GlobTemperature archive (location of the products on disk) is stored in this database.

The second will be dedicated to the management of users (information on registration) and requests (parameters of the request). For each order, the link between the registered user and the associated order will be stored in the database.

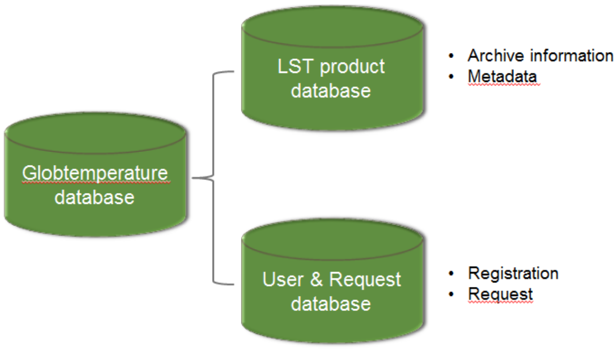


Figure 17: GlobTemperature Web Portal database structure

Architecture of the dissemination system

The schematic of the architecture is shown in Figure 18. In this schematic, a user accesses the system through a DATA Interface. This interface, representing the front-end, includes a form with all the parameters necessary to send a request to the system. This request is then processed on the back-end by the DATA management system. This component has a direct access to the data sets (physical on the local storage area or virtual in the case of external storage). It is also in charge of the I/O actions on the User & Request database and on the product database. In response to the order received, the data is transferred from the archive to the Download area. The DATA management system also controls the access to the metadata, stored in the product database, from the DATA Interface.

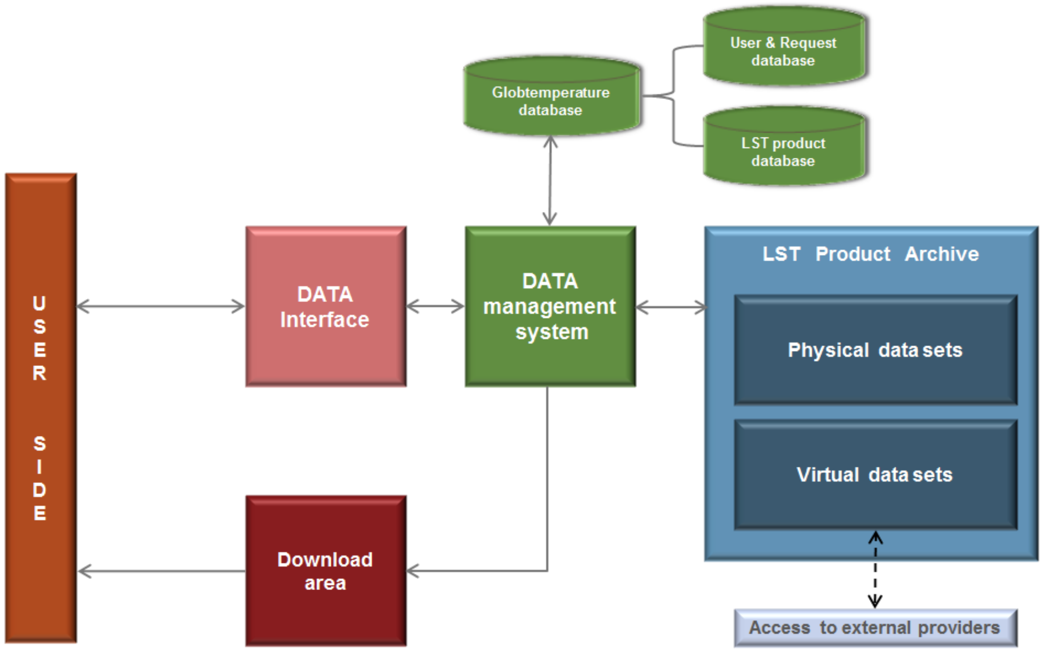


Figure 18: Logical structure of the dissemination system

Request processing

Figure 19 shows the general proceedings of a request submitted on the data portal. It can be described as follow:

- First of all, the user chooses a data set on the web interface and selects the parameters on the form associated with the data set
- The "Search" action generates a list of products corresponding to the criteria. The total size and the number of products shall be indicated in real time on the interface
- The user selects some products from the list (each product is associated to a checkbox)
- The order is then sent to the system and the information concerning the order is stored in the database, including the user identification and the final list of requested products.
- After confirmation, the products are transferred to the FTP area.
- The information concerning downloading is then shown on the web interface (Figure 20) and also emailed to the user.

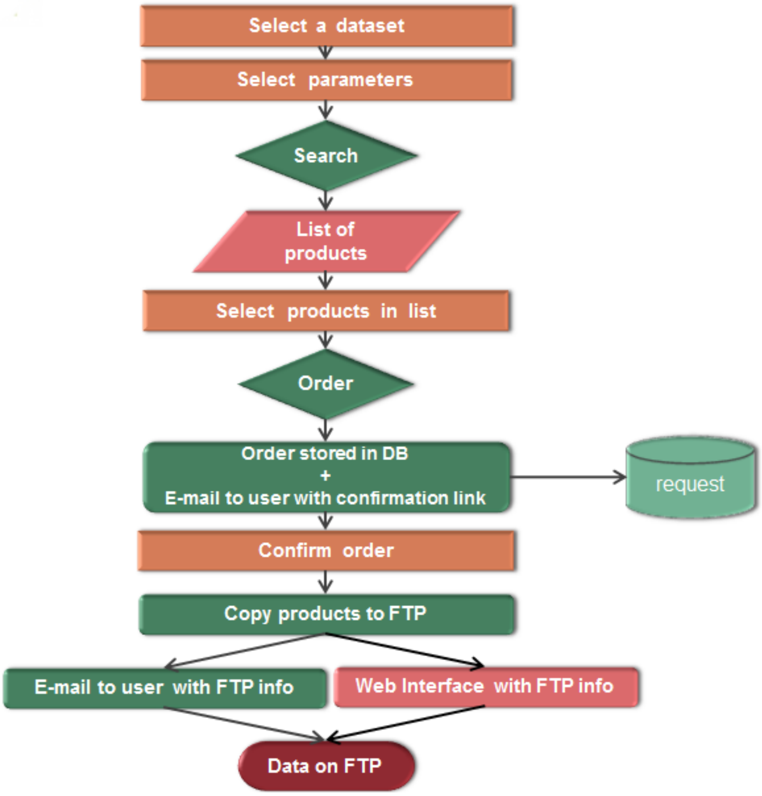


Figure 19: Diagram showing the process of a request

Figure 20: Final interface for FTP information

Parameters of the DATA Interface

This interface will contain a form with the parameters needed to request products. In the initial version of the data portal, these parameters will be:

- a period
- an orbit range

The list of parameters will be modified and completed during the project to be in accordance with the users 'needs and the characteristics of the datasets.

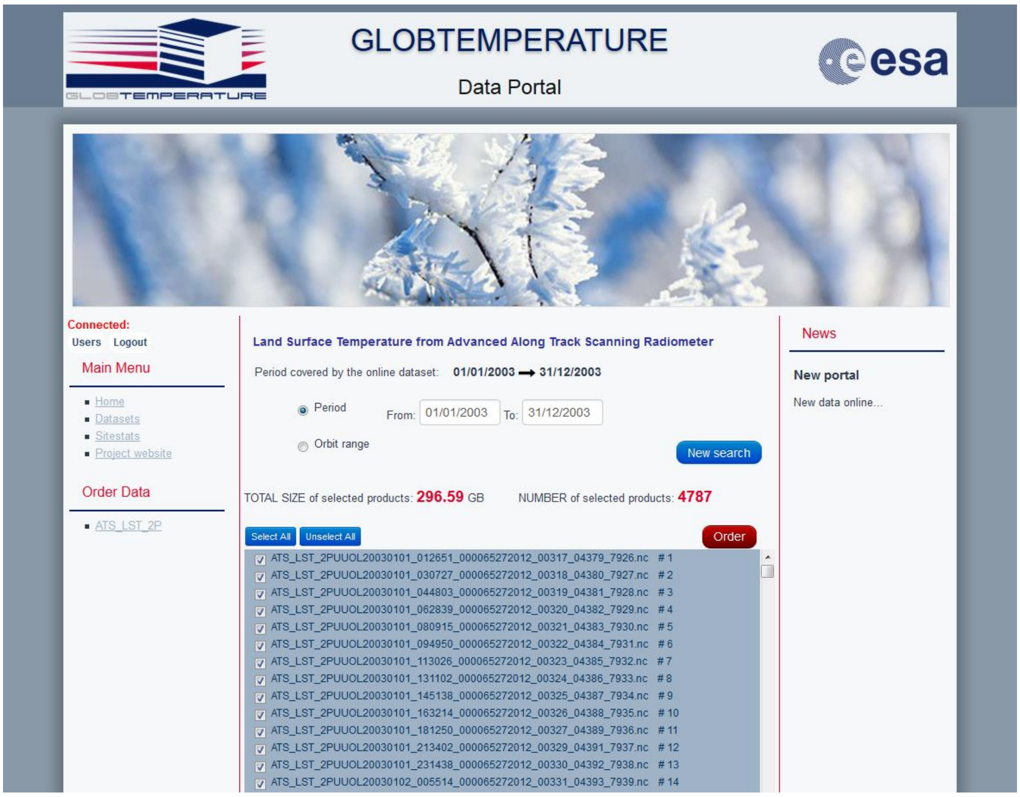


Figure 21: Screenshot of the data access interface (beta version of the data portal)

Products download

Different ways can be used to download the data from the FTP server (**addresses requirement REQ-11-TR**):

- **Web browser** - by clicking on the ftp link, the user is directly connected to the FTP area with his favourite browser as shown in Figure 22. This though would not be suitable for downloading large quantities of products depending of the browser used.

- **FTP client** - the connection to the FTP area can be initialized by an FTP client using ones registered login details (Figure 23).
- **Command line utility** - such as GNU Wget under Linux. An example command would be:

```
wget --retr-symlinks -r
ftp://ftp_globtemperature:globtemp%2514@ftp.globtemperature.info/user/
968579514
```

For the latter two options, bulk orders could be downloaded as one request.

Other solutions will be introduced depending on the user's need, particularly in the case of non-interactive mode, which is a good way to include automated actions in scripts. These could include transfer of data products onto portable media provided by the user.

*Addresses user feedback **GT-UF-17**: Enable users to send a disk and have an entire archive uploaded and posted back*

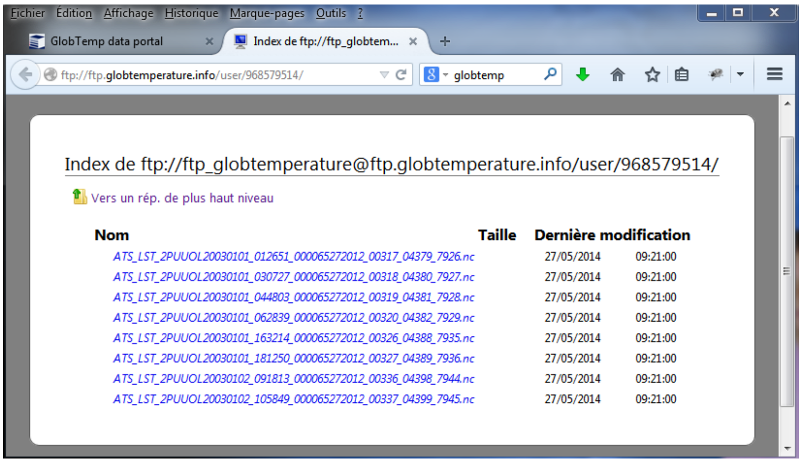


Figure 22: Example downloads using a web browser

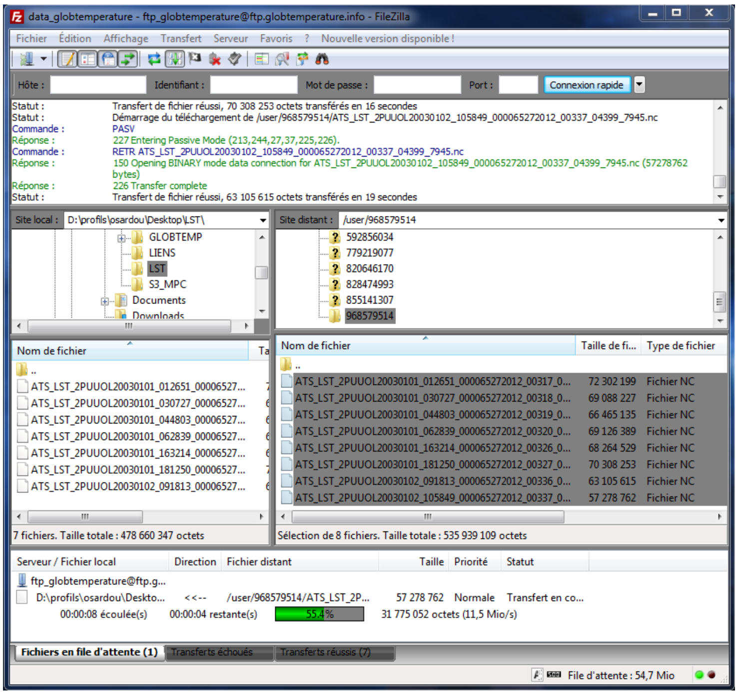


Figure 23: Example downloads using a FTP client

GT-TS-27*: Provide access to data archived and disseminated by GlobTemperature via FTP client, command line utilities, and interactive web browser*

Automatic deletion of ordered products on the server side

A script will be set up on the dissemination system to automatically delete any ordered products older than 15 days. It will be included in a confab on a Linux server.

Introduction of functionalities

Extraction functionality can be added to the data portal. It is a useful tool in the context of a dissemination system because users may work on a region of interest (ROI). In such a case, the specification of the coordinates can be done at the level of the interface and the extraction can be processed on the server side, before download. This kind of tool is included in the Hermes service, dedicated to the dissemination of level-3 ocean color data (GlobColour products). A screenshot of the service is shown in (Figure 24) (new version will be online soon). The current version can be viewed at the http://hermes.acri.fr. On this interface, the coordinates of the ROI can be directly inserted in the form (North, South, East, West fields) or can be selected using an interactive mode (by drawing a rectangular area in a web mapping environment).

*Addresses user feedback **GT-UF-14**: Facilitate user selectable data extraction for multi-mission Level-2 and Level-3, for area (tiles, global files as single zip-files, or ROI selection) and data fields; with optimised folder structure*

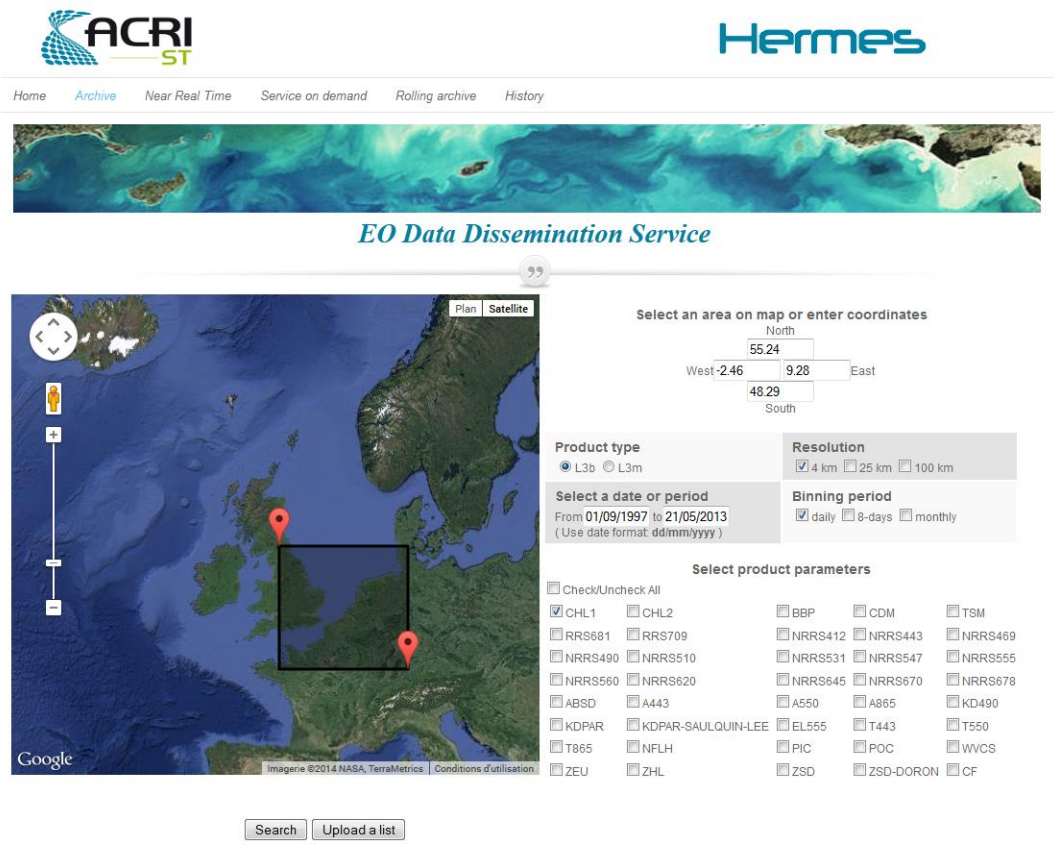


Figure 24: Example of the interface with geographical extraction on the Hermes service

One can note that a module of quicklook visualization is also provided on the Hermes interface (Figure 25). For example, this functionality can allow the user to estimate at a glance the coverage or the percentage of validated pixels in a product.

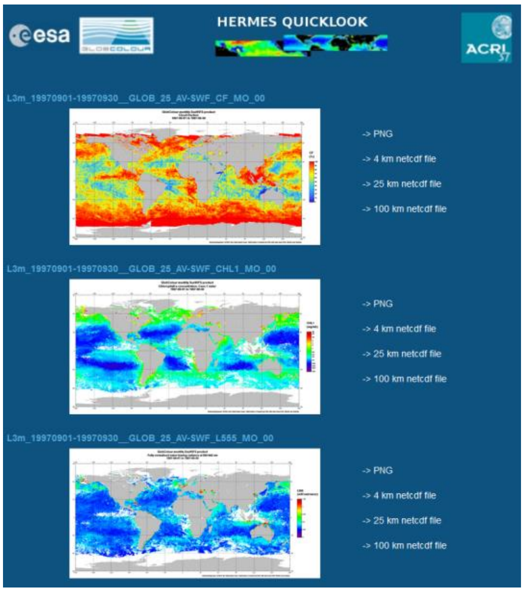


Figure 25: Quicklook visualization on the Hermes service

6.1.4. Visualization

Analysis tools will be provided on the data portal. Graphs and maps showing various statistics and comparisons on the LST data sets will be available online. These plots will be self-explanatory; they will include a legend and an acknowledgement to the data sources. Detailed specifications will be appended in further versions in response to the users need and to recommendations of the International LST & E Working Group.

GT-TS-23*: Data Portal to provide visualisation tools and statistics for LST data, LST anomalies, validation information and intercomparison data*

6.1.5. Tools

This section will provide access to projection and conversion tools. A particularly useful tool is for all users to be able to read GlobTemperature data with minimal effort. Thus a tool for reading the harmonized formats described in Section 6.5 would be beneficial. This requires any tool to be platform independent, with functionality for extracting subsets of data from the downloaded datafiles. Additional detailed specifications will be appended in further versions in response to the users need and to recommendations of the International LST & E Working Group.

The most commonly currently used tools are for data reading/sub-setting, data visualisation, data processing and data analysis, developed either internally or made available by external providers. Many such tools already exist and are exploited by many users of LST data. As such, an optimum approach would be to allow users to share such tools, with GlobTemperature providing the facility to do this. There are expected to be reservations in ensuring that the shared tools are error free; while some LST data users are likely to be unable to share tools due to copyright issues. Even so, the benefits to the community would appear to outweigh any drawbacks. Thus, to meet this need within the user community a tool repository area on the GlobTemperature Data Portal will be set up whereby users will be able to upload tools they are willing to share (**addresses requirement REQ-42-TR**).

While some basic tests can be carried out on the uploaded tools to detect viruses for example, responsibility for the integrity, security and licensing implications must reside with the user who uploaded the tool. The user would also be responsible for providing the necessary information to install and exploit the tool. Furthermore, since many of these tools are likely to be written in a multitude of computer languages and delivered as a "black box" GlobTemperature is not able to support ongoing maintenance of such a suite of tools. Any bugs would be reported to the user who uploaded the tool – whether they then are in a position to deliver a fix is outside the influence of the Project.

***GT-TS-48**: Provide a data repository for users to share tools within the community*

*Addresses user feedback **GT-UF-10**: Provide a repository on the Data Portal for users to share extraction / visualisation tools*

A further tool, in high demand within the LST user community is the ability to screen data for cloud prior to downloading it. The presence of the cloud bits within the QC flags enable easy filtering of cloud from the delivered data. Furthermore, this tool will be designed to operate as a function of selected cloud cover fraction for the area of interest to be downloaded. The cloud-screening algorithm applied is to be documented (**addresses requirement REQ-43-TR**).

Cloud filtering will also be applied within the proposed time series extraction tool. This time series extraction tool will be able to cover an entire instrument mission, although it is initially proposed to operate on single grid-cell given the huge overhead of extracting and processing datafiles for the entire archive. Output of the time series extraction will be both as a plot and a datafile (in .csv format) (**addresses requirement REQ-39-TR**).

***GT-TS-28**: Develop platform independent tools for reading and sub-setting datasets provided in the harmonised formats, and cloud filtered time series extraction*

***GT-TS-49**: Provide a Data Portal tool to screen data as a function of cloud cover prior to download*

*Addresses user feedback **GT-UF-9**: Provide extraction tools to subset datafiles with all information retained through the extraction process, and simple visualisation tools / Quick Looks to examine data at different resolutions, with a filter for cloud cover*

6.2. Current Best Practices: LST Algorithms

ESA standard / UOL_LST_2P algorithms for (A)AATSR

Both the standard ESA (A)ATSR LST algorithm (ESA_V3_algm) [RD-22] and the enhanced ULeic LST algorithm (UOL_LST_algm) for AATSR (UOL_LST_2P) and SLSTR (SL_2_LST) use a nadir-only split-window approach with classes of coefficients for each combination of biome-diurnal (day/night) condition. The full form of the algorithm is presented as follows:

$$\begin{aligned} LST = {} & d(\sec(\theta) - 1)pw + \left(f a_{v,i} + (1 - f) a_{s,i}\right) + (f b_{v,i} \\ & + (1 - f) b_{s,i})(T_{11} - T_{12})^{1\,/\,(\cos(\theta\,/\,m))} \\ & + \left((f b_{v,i} + (1 - f) b_{s,i}) + (f c_{v,i} + (1 - f) c_{s,i})\right) T_{12} \end{aligned}$$

where the six retrieval coefficients $a_{s,i}$, $a_{v,i}$, $b_{s,i}$, $b_{v,i}$, $c_{s,i}$ and $c_{v,i}$ are dependent on the biome (*i*), fractional vegetation cover (*f*) - the retrieval coefficients $a_{s,i}$, $b_{s,i}$ and $c_{s,i}$ relate to bare soil ($f = 0$) conditions, and $a_{v,i}$, $b_{v,i}$ and $c_{v,i}$ relate to fully vegetated ($f = 1$) conditions. The fractional vegetation cover (*f*) and precipitable water (*pw*) are seasonally dependent whereas the biome (*i*) is invariant. The retrieval parameters *d* and *m* are empirically determined from validation and control the behaviour of the algorithm for each zenith viewing angle (ϑ) across the nadir swath. The parameter *d* resolves increases in atmospheric attenuation as the zenith viewing angle increases due to increased water vapour. The parameter *m* is supported by previous studies [RD-23, RD-24] which suggest a non-linear dependence term on the BT difference T_{11} - T_{12} would elicit improvement in the accuracy of the LST retrievals. The rationale here is that the BT difference increases with increasing atmospheric water vapour, since attenuation due to water vapour is greater at 12µm than at 11µm. The nature of the algorithm means that land surface emissivity is implicitly dealt with.

For the ESA_V3_algm there are 13 land biome classes and one lake class [RD-94] at a spatial resolution of 0.5°. The SiB/ISLSCP fractional vegetation cover product [RD-94] and the precipitable water auxiliary data from the NASA Water Vapour Project (NVAP) climatology [RD-95] also have a spatial resolution of 0.5°. These latter two are composed of separate global datasets for each month of the year.

Validation of the standard AATSR LST product (ESA_V2 following the 2nd ATSR re-processing) [RD-23, RD-24] identified deficiencies in the choice of auxiliary data utilised by the retrieval algorithm, which exploits 1 km BTs from the ATSRs to derive LST whereas the auxiliary data is at the much coarser spatial resolution of 0.5^{o}; this restricts the capability to make the necessary corrections for land surface emissivity and atmospheric effects. These scale differences cause artefacts in the LST products which often appear as sharp, straight boundaries aligned with lines of latitude and longitude [RD-25]. In some cases large biases and absent values in the retrieved data were attributed to inaccuracies in the auxiliary data; the conclusion being that the resolution of these auxiliary data are not fine enough for their intended purpose.

The UOL_V3_algm incorporates higher resolution auxiliary data files (ADFs) [RD-16, RD-25]. The new biome auxiliary data is a variant of the Globcover classification [RD-26], with the original 1/360° spatial resolution product having been re-gridded to 1/120°. In addition, the original Globcover bare soil class has been divided into six separate classes, taking the total number of land and inland water classes to 27. To incorporate these changes the Globcover nomenclature has been replaced, with the new classification system known as the ATSR LST Biome version-2 (ALB-2).

In addition to the 27 land and inland water classes an additional biome class (ALB-2 class 0) is included for completeness and represents the ocean and large lakes – this corresponds to where the AATSR land-sea mask identifies a pixel as sea – whereby SST is retrieved rather than LST. Inland and coastal water (ALB-2 class 26) represents the remaining water - classified as land by the land-sea mask. Although the biome classification is invariant - being based on the 2006 Globcover product - on any given orbit every pixel including class 0 is assessed for snow and ice cover. Where snow or ice is identified the pixel is reclassified as permanent ice (ALB-2 class 27) and LST is retrieved by applying the associated coefficients.

Fractional vegetation cover is taken now from the Geoland-2 FCOVER dataset, which is available globally at the desired near 1-km resolution of 1/112° every 10-days from 1999 and acquired from a moving temporal window of approximately 30-day composites of observations [RD-27]. The values of FCOVER are computed from leaf area index and other canopy structural variables available in the CYCLOPES (Carbon cYcle and Change in Land Observational Products from an Ensemble of Satellites) product using a neural network trained from the 1-D radiative transfer models SAIL and PROSPECT. The 10-day AATSR fractional vegetation cover auxiliary dataset is created from the FCOVER dataset with missing values gap-filled from climatology.

Precipitable water is derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis [RD-96]. Each auxiliary data file is derived from 6-hourly monthly climatology corresponding to the 4 synoptic times - 00UTC, 06UTC, 12UTC and 18UTC - covering the 10-year period 2002 – 2011 inclusive.. As such, the retrieval has established an updated set of retrieval coefficients to complement the use of higher resolution auxiliary data in the retrieval of LST from the AATSR instrument. Necessarily, this work has also established the requirement to optimise the parameterisation of the retrieval across the nadir swath.

For the generation of the retrieval coefficients for each biome–diurnal (day/night) combination vertical atmospheric profiles of temperature, ozone, and water vapour, surface and near-surface conditions and the surface emissivities are input, in addition to specifying the spectral response functions of the instrument, into a radiative transfer model in order to simulate TOA BTs. Retrieval coefficients are determined by minimizing the l_2-norm of the model fitting error (ΔLST).

These algorithms do not take advantage of the dual angle capability of AATSR. The rationale being that the disadvantages, such as surface heterogeneity and non-simultaneity of the two views – significant over most land surfaces – outweigh any potential benefits [RD-22]. Indeed, over homogeneous surfaces [RD-21] have illustrated that a dual angle algorithm may retrieve LST with more accuracy, but performance degrades as the surface becomes increasingly heterogeneous.

Generalised Split Window (GSW) algorithm: MODIS and SEVIRI

The standard operational MODIS LST products MOD11_L2 (Terra) and MYD11_L2 (Aqua) uses the generalized split-window algorithm [RD-10] to retrieve LST of clear-sky pixels from BTs in bands 31 and 32:

$$LST = \mathrm{C} + \left(A_1 + A_2\frac{1-\varepsilon}{\varepsilon} + A_3\frac{\Delta\varepsilon}{\varepsilon^2}\right)\frac{T_{11}+T_{12}}{2} + \left(B_1 + B_2\frac{1-\varepsilon}{\varepsilon} + B_3\frac{\Delta\varepsilon}{\varepsilon^2}\right)\frac{T_{11}-T_{12}}{2}$$

whereby this algorithm operates with classification-based emissivities. The retrieval coefficients are determined by interpolation on a set of multi-dimensional look-up tables; these are obtained by linear regression of the simulation data generated by radiative transfer over a broad wide range of surface and atmospheric conditions. The look-up tables incorporate several improvements for the Split-Window LST algorithm such as view-angle dependence, water vapour dependence, and atmospheric lower boundary temperature dependence.

In addition, a physics-based day/night algorithm [RD-97] is employed to retrieve both surface spectral emissivity and temperature at 5 km resolution. It achieves this by utilising seven MODIS TIR bands (20, 22, 23, 29, 31, 32 and 33) to achieve LST – LSE separation; based on the concept that LST changes more rapidly than LSE. The SW approach has high accuracy over graybody surfaces, but a lower accuracy over semi-arid regions.

The LSA SAF operational LST algorithm applied to SEVIRI data is a SW algorithm also based on the formulation proposed by [RD-10] for AVHRR and MODIS – the exact formulation being

$$LST = \left(A_1 + A_2\frac{1-\varepsilon}{\varepsilon} + A_3\frac{\Delta\varepsilon}{\varepsilon^2}\right)\frac{T_{10.8}+T_{12.0}}{2} + \left(B_1 + B_2\frac{1-\varepsilon}{\varepsilon} + B_3\frac{\Delta\varepsilon}{\varepsilon^2}\right)\frac{T_{10.8}-T_{12.0}}{2} + C$$

where $T_{10.8}$ and $T_{12.0}$ are the TOA-BTs for SEVIRI channels 10.8µm and 12µm respectively, ε is the mean land surface emissivity of the two channels, and $\Delta\varepsilon$ the emissivity difference between the channels ($\varepsilon_{10.8}$ – $\varepsilon_{12.0}$). The retrieval coefficients: A_j, B_j $(j = 1,2,3)$ and C are dependent on water vapour and zenith view angle. The algorithm is dependent on a linearization of the TOA BTs with the surface temperature and the controlling factors are the surface emissivity, atmosphere and satellite view-angle.

The coefficients are calculated using a regressive analysis technique, whereby simulated $T_{10.8}$ and $T_{12.0}$ are obtained from radiative transfer simulations performed over a wide variety of atmospheric profiles. When compared with an independent dataset of radiative transfer simulations the algorithm and it's coefficients were found to be bias free, although random errors tended to increase with increasing water vapour content and at high view-angles [RD-50]. For the operational LST product the water vapour database used is that provided by ECMWF ERA-Interim.

The channel surface emissivity is calculated from an average of bare-ground and fully vegetated emissivities weighted by the fractional vegetation cover (FV) and by the fraction of water within the pixel. In a similar fashion to the AATSR algorithm, the emissivity extremes are selected from a look-up-table in accordance to the land cover classification. The FV data used is another product produced by the LSA SAF from SEVIRI/Meteosat and corresponds to a 5-day composite updated daily [RD-98]. The input emissivities ε_{eff_IRn}, are calculated thus:

$$\varepsilon_{LAND\_IRn} = \varepsilon_{veg\_IRn} FV + \varepsilon_{bg\_IRn}(1 - FV)$$

$$\varepsilon_{eff\_IRn} = \varepsilon_{LAND\_IRn} F_{Land} + \varepsilon_{WATER\_IRn}(1 - F_{LAND})$$

where, ε_{veg_IRn} and $\varepsilon_{bg_IRn}$are the previously assigned emissivity values for fully vegetated (FV=1) and bare-ground (FV=0), ε_{WATER_IRn} is the emissivity value for water and F_{Land} is the fraction of land within the pixel.

In contrast, a new MODIS LST product (MOD21) being generated by international collaborators at NASA-JPL applies a physics based approach - the Temperature Emissivity Separation (TES) algorithm, which was originally designed for ASTER LST retrievals, but has been adapted to MODIS data to retrieve LST and LSE in MODIS bands 29, 31 and 32 [RD-61]. One rationale for this development is to improve on the retrieval in semi-arid regions. TES attempts to solve the ill-posed LST problem through the use of empirical methods to predict the minimum emissivity observed from a given spectral contrast. This relationship is referred to as the TES calibration curve, and can be adjusted for any sensor's spectral response function in the TIR.

Offline AATSR / SLSTR algorithms

Although the AATSR instrument does not observe the surface with sufficient TIR channels to separate the LST and LSE explicitly, it is still possible to consider retrieval algorithms with an explicit emissivity term. The rationalisation here is the linear equation for deriving channel emissivity ε_λ from fractional vegetation cover (*f*):

$$\varepsilon_\lambda = \varepsilon_{v,\lambda} f + \varepsilon_{b,\lambda}(1 - f)$$

Much work has been carried out in the LST community on developing alternative algorithms for LST from (A)ATSR. These include most notably the candidate algorithms developed for the SEN4LST Project [RD-66] amongst others [RD-99]. The SEN4LST SW candidate algorithm takes the form:

$$LST = T_{11} + c_1(T_{11} - T_{12}) + c_2(T_{11} - T_{12})^2 + c_0 + (c_3 + c_4 W)(1 - \varepsilon) + (c_5 + c_6 W)\Delta\varepsilon$$

where W is the atmospheric water vapour content, ε is the mean land surface emissivity of the two channels, and $\Delta\varepsilon$ the emissivity difference between the channels ($\varepsilon_{11} - \varepsilon_{12}$). [RD-21] have also derived an alternative SW algorithm from AATSR which includes a quadratic term for BT difference. Their algorithm takes the form:

$$T = T_{11} + a_0 + a_1(T_{11} - T_{12}) + a_2(T_{11} - T_{12})^2 + \alpha(1 - \varepsilon) - \beta\Delta\varepsilon$$

where a_0, $a_1$and a_2 are atmospheric correction coefficients which hold for all retrievals, and α and β coefficients which are dependent on the water vapour and viewing angle.

The SEN4LST DA candidate algorithm has the same mathematical structure as that used for the SEN4LST

SW algorithm. Here though, observations from the same channel (centred at 11µm) are applied at two different angles – nadir and forward (~53°) – rather than from two different channels at nadir, and is expressed such:

$$LST = T_{\mathrm{n}} + c_1(T_{\mathrm{n}} - T_{\mathrm{f}}) + c_2(T_{\mathrm{n}} - T_{\mathrm{f}})^2 + c_0 + (c_3 + c_4W)(1 - \varepsilon_n) + (c_5 + c_6W)\Delta\varepsilon$$

where "n" and "f" refer to the nadir and forward views respectively, and c_0 to c_6 are the biangular coefficients obtained from simulations.

Optimal estimation approaches to LST retrieval

Optimal Estimation (OE), sometimes referred to as Inverse Theory, is a technique developed to help solve problems which are either over- or under- constrained and there is some degree of uncertainty in the measurements or formulation. It has proved to be of great use in Earth Observation, specifically in resolving multispectral measurements to give multi-level atmospheric profiles.

In comparison to SW techniques, OE methods ensure that more consideration of the true physics is considered. Generally this ensures that the retrieved state is more likely to reproduce the observation vector when used as input in a forward model, hence provides more confidence in the result. However, the cost is whether or not the extra computation required is operationally feasible in the context of a global dataset.

1D-Var is an optimal estimation software solution designed and developed by the NWP-SAF. The NWP-SAF provide three 1D-Var packages: a Met Office version; an ECMWF version; and an SSMIS version. The Met Office 1D-Var package is a flexible stand-alone optimal estimation routine suitable for user adaptation [RD-100]. It was initially designed with the primary purpose of retrieving water vapour profiles using data from the IASI and AIRS instruments in conjunction with the RTTOV forward model. It has been constructed such that it can be easily adapted to use a number of different radiative transfer models and satellite instruments [RD-101].

6.3. Algorithm Trade-off Summary

In this project, the single-sensor data sets disseminated via the Data Portal will continue to be produced largely with the existing algorithms because of the nature of operational systems. The innovation in understanding of algorithms will come in two ways. Firstly, in the merging work, the effects of algorithm bias is to be examined more closely by analysing more than one instrument data set with the same algorithm. This will provide information on which are the dominant sources of bias, which components are due to the algorithms, and which are due to "auxiliary" information, thus allowing a better understanding of the algorithms to develop. Secondly, an algorithm trade-off is being carried out prior to the derivation of an (A)ATSR Climate Data Record. The results of this trade-off analysis will feed in to the algorithm trade-off and optimisation as part of the extension to SLSTR.

A number of algorithms are being assessed as potential candidates for the development of the (A)ATSR Climate Data Record; with these also pertinent for the Multi-Sensor Merged LST Product. Nonetheless simple technical and logistical constraints immediately narrow the focus even further. The Prototype Sentinel-3 LST Product will use these as inputs but additionally may consider other alternatives not previously suitable. For ease of reference we define the following algorithms as the potential candidates for GlobTemperature developments:

1) ULeic enhanced ATSR / SLSTR algorithm (UOL_V3_algm)
2) Generalised Split-Window (and single channel implementation) algorithm for SEVIRI (SEV_algm)
3) Generalised Split-Window (and single channel implementation) algorithm for MODIS (GSW_algm)
4) SEN4LST Split-Window algorithm (S4L_SW _algm)
5) SEN4LST Dual-Angle algorithm (S4L_DA_algm)
6) Optimal Estimation and 1D-Var approaches

The standard ESA ATSR LST algorithm (ESA_V3_algm) is not considered a potential candidate algorithm since studies [RD-16, RD-68] have illustrated the significant improvement in accuracy and precision of the UOL_V3_algm compared to the ESA_V3_algm. Nevertheless, the ESA_V3 LST Product will still be utilised for comparison purposes.

The comprehensive Climate Data Record Trade-off Analysis is being delivered as a separate report (LST CDR Algorithm Trade-Off Analysis (DEL-8)) [AD-5] and thus only summarised here.

- Only the first four candidate algorithms (and minor variants on these have been considered)
    i. Since the algorithm selected for a CDR should be sensor-independent this removes dual angle algorithms from consideration
    ii. An optimal estimation technique has not been considered here because of its sensitivity to atmospheric profiles of temperature and water vapour with their time dependence possibly introducing unwanted biases in the LST record
- Algorithm intercomparison
    i. A single radiative transfer model is being utilised for simulating the radiances
        a. Radiative transfer model – RTTOV 10.2
        b. Consistent profile datasets for coefficient derivation:
            - ECMWF ERA-Interim profiles
            - CIMSS emissivities

- Uniform random distribution for spatial and temporal profile selection

ii. Construction of GlobTemperature Benchmark Database (GT_BDB):

a. Reference Atmospheres

- A set of climatological atmospheric profiles for RTTOV gases and temperature
- Based on v4 MIPAS reference atmospheres
- High vertical resolution profiles (1 km) interpolated onto RTTOV 51 level pressure array
- Profiles categorised by seasons (4) and latitudinal bands (6)

b. ASTER emissivities

- ASTER spectral library used to create the emissivity records
- Emissivities convolved using instrument spectral response

c. Simulated brightness temperatures

For global production of a CDR several techniques may be employed to decouple surface emissivity and surface temperature. The most widely used are: the Day/Night method, which require acquisitions twice per day and assumes that day/night emissivity differences are negligible; the Temperature Independent Spectral Indices (TISI) method, which provides relative emissivity values; the Temperature and Emissivity Separation (TES) algorithm, which requires multispectral thermal infrared data (TIR); and methods based on retrieval from vegetation indices, such as the NDVI THresholds Method ($NDVI^{THM}$) [RD-102].

The additional thermal infrared (TIR) channels of MODIS permit a choice of algorithms to be exploited. For instruments without multispectral thermal infrared capabilities, such as (A)ATSR and AVHRR, we are primarily reduced to approaches based on vegetation indices or enhancements on this by incorporation of land cover classification. Emissivity retrieval from vegetation indices is based on a simple approach between emissivity and Fractional Vegetation Cover (FV) constrained by reference values of vegetation and soil emissivities from laboratory measurement, such as the ASTER spectral library [RD-103]. Land cover information can be also used to categorise these emissivity values by land cover types. The final approach is to utilise a third-party emissivity product, such as the ASTER-GED or the CIMSS dataset.

For the Prototype Sentinel-3 LST Product similar arguments are applicable as for the LST CDR Algorithm Trade-Off Analysis (DEL-8) [AD-5]. However, the SEN4LST Dual-Angle algorithm (S4L_DA_algm) is also a viable option since this is a single-sensor algorithm for an instrument with both nadir and oblique views. However, implementations of Dual-Angle algorithms have shown considerable errors so far [RD-21, RD-104] and the community consensus is that single view algorithms are superior. This is because dual-angle algorithms suffer problems because of the angular distribution of temperature, the angular distribution of emissivity and the sensitivity to relative co-alignment errors of the two views; the latter is more significant over land than over ocean. A full analysis of the candidate algorithms will be carried out within the Sentinel LST Product Development Plan (DEL-23) activity.

GT-TS-14*: Develop Climate Data Record of over 10-years for (A)ATSR in harmonised format with low bias, high precision, and high stability. Targets: 1.0 K, 1.0 K and 0.3 K respectively*

GT-TS-29*: Evaluate retrieval methods for optimisation of the LST products from Sentinel-3*

Finally, the optimal estimation / 1D-var approaches, which are a very different alternative to the coefficient based algorithms in that they provide fits to the observed radiances within the constraints of the system, may be considered during the merged LST NRT activities where climate accuracy and stability may be less important. Further information on these approaches is expected to come from the study on assimilation of LST into NWP models (Section 7.5).

6.4. Co-operative agency developments

The structure, format, and purpose of the ILSTE-WG has been developed as a joint effort between U. Leicester (representing the requirements of the GlobTemperature Project) but also IPMA (representing both GlobTemperature and EUMETSAT through the LSA SAF) and NASA-JPL. The aim being to create a truly international group dedicated to the development of products and exploitation by users of LST and LSE data with multi-agency support. This is particularly important in the post-GlobTemperature era where continuing development of this Group may be sustained by various inter-agency funding streams.

The ILSTE-WG Steering Committee has been set up with key personnel representing different agencies involved in the satellite-retrieval of LST and LSE: ESA, NASA, NOAA and EUMETSAT. Furthermore, in addition to the invitation pack sent out to prospective members of the ILSTE-WG a tailored presentation has also been compiled for NASA Headquarters in order to gain high level support for the Group.

A key aspect of the ILSTE-WG is to build partnerships across the community, with inter-agency support important for underpinning such cooperation:

- To build partnerships with international bodies (e.g. WMO, CEOS, IPCC), scientific programmes (e.g. GCOS, GEWEX, GEOSS), and user agencies (e.g. meteorological offices, environment agencies) to harmonise international efforts and advance LST and LSE science and applications
- Specific activities will be needed to work with GCOS to promote the case for LST & E to be classified as an Essential Climate Variable (ECV), with CEOS to promote virtual constellations for LST and standardised data protocols, and with GEO to build new user communities:
    - First progress on this being made with GlobTemperature influenced presentation delivered by colleague at GCOS Terrestrial Observation Panel for Climate (TOPC) meeting in March 2014

- The ILSTE-WG will to link to other international groups in technical practice, such as CEOS and its Land Product Validation (LPV) working group:

    i. Indeed, Simon Hook (ILSTE-WG Steering Committee member) and Jose Sobrino (ILSTE-WG general member) are leading the LST/Emissivity focus area within the LPV.

    ii. A consistent approach to data validation, in line with CEOS-LPV Best Practices has been proposed from the LST Validation Protocol of [RD-5] and which is utilised here (Section 5.1).

- The ILSTE-WG will need to link to existing networks such as the EarthTemp network:

    i. Alignment of meetings between the 3rd EarthTemp Network Meeting and the 2nd User Consultation Meeting (concluding with the ILSTE-WG meeting) has been arranged

    ii. Alignment of future meetings is also planned

- The ILSTE-WG will manage Technical Advisory Groups to support the development and use of satellite LST information, to promote scientific insight and innovation, to identify best-practices, and to facilitate the transfer of new science into user's applications. These groups will seek to develop partnerships with these identified international bodies.

A further key aspect of the ILSTE-WG is to provide an independent source of advice and appraisal, as requested, for related projects run by supporting agencies. In addition to the ESA DUE GlobTemperature Project another initial recognised project is the NASA MEaSUREs (Making Earth System Data Records for Use in Research Environments) for which key ILSTE-WG Steering Committee members are involved in. An objective of this project, in terms of LST and LSE, is to merge MODIS and GEO data. Considerable prospects of cross-collaboration between projects are envisaged through the focal point of the ILSTE-WG.

Data sharing and dissemination to users is also an important goal of the ILSTE-WG, and through early negotiation with NASA-JPL agreement has been sought and given for the GlobTemperature Data Portal to externally link with their datasets – MOD21 (Section 4.2.6) and ASTER GED (Section 4.2.12).

Strong links have been developed with the Sentinel-3 Validation Teams in the Land domain. This brings the benefit of community agreement to share both LST data and associated validation data. For example, data collected by our international partners at NASA JPL are to be made available to both the Sentinel-3 LST Validation Team and GlobTemperature from the well calibrated and established validation sites at Lake Tahoe and Salton Sea.

6.5. GlobTemperature Product Specifications

This section describes the proposed harmonised format for all Level-2, -3 and -4 GlobTemperature data products. Satellite datasets for gridded extractions for processing within the GlobTemperature Matchup

Database (GT_MDB) are also proposed to conform to a harmonised format (Table 26 and Table 29). Appendix C – Harmonised Format Examples provides example netCDF-4 outputs for selected example orbits. Where available in the source data for a given data stream optional fields will be supplied as mandatory in the corresponding output product, albeit in accompanying auxiliary datafiles (**addresses requirement REQ-33-TR**).

To meet the user needs of a harmonised format (REQ-16-33: Establish a single file specification covering all metadata requirements) a distinction needs to be made between the tier of data this refers to. In other words, single-sensor level-2 swath datafiles are to conform to a one harmonised format – with respect to the variables, metadata, and filename conventions - and higher-level (single-sensor, and merged products) are to conform to a harmonised format more appropriate to gridded data. While both formats are to be netCDF-4 with common CF-compliant metadata (**addresses requirement REQ-34-TR**) and the majority of variables to be common, several differences due to the individual requirements of swath / gridded datasets are necessary. Data providers are tasked with ensuring their products meet CF compliance, and a CF compliance checker is available online at http://titania.badc.rl.ac.uk/cgi-bin/cf-checker.pl for confirmation.

GT-TS-3*: The basis for the GlobTemperature harmonised formats will be CF-compliant netCDF-4 with individual file sizes < 200 Mb*

GT-TS-30*: All harmonised formats to adhere to common metadata compliant with CF conventions*

All output datasets will be delivered in consistent data format, with the objective to provide consistent standardised metadata across all LST products at both file and granule level and a common data format which is well established and internationally accepted by the user community. The choice on datafile format has been driven by the User Requirements, with detailed specifications influenced by the success of the standard formats of GHRSST. For example, the standard Level-3 resolution for single-sensor datasets, the merged LST products, and the (A)ATSR LST CDR has been chosen to be 0.05° equal-angle daily data (with day and night distinguished); experience from GHRSST and SST_CCI informs that this is optimal and allows aggregation to many of the coarser spatio-temporal scales. Section 6.5.5 also specifies additional possible spatial / temporal resolutions which could be available from the Data Portal given sufficient user demand following feedback from User Consultations.

GT-TS-10*: Standard spatial resolution of Level-3 and -4 datasets to be 0.05° unless designated otherwise*

The final harmonised formats are necessarily subject to approval with ILSTE-WG. To facilitate optimum user uptake of the GlobTemperature products in harmonised format a set of tools will be developed in Python, which is open-source and platform independent software for reading and sub-setting the datafiles created in the harmonised formats.

GT-TS-28*: Develop platform independent tools for reading and sub-setting datasets provided in the harmonised formats, and cloud filtered time series extraction*

6.5.1. Single-sensor Level-2 products

Level-2 products can be defined as geophysical variables derived from Level-1b source data at approximately the same spatial resolution and location as the Level-1b data. Generally the projection is in a satellite projection with geographic information, although for more obscure satellite projections data may be re-projected onto an equal-angle grid of equivalent geospatial resolution. These data form the fundamental basis for higher-level products (**addresses requirement REQ-1-TR**).

GT-TS-5*: Provide Level-2 single-sensor datasets in harmonised format*

GT-TS-32*: Provide ancillary information as optional to users and be stored in auxiliary datafiles*

Table 21 and Table 22 describe the proposed Level-2 swath data format for the GlobTemperature single-sensor datasets. It is acknowledged that although the size of each datafile will be less than 200 Mb (**addresses requirement REQ-10-TR**) many users may only be able to successfully exploit datafiles considerably smaller. As such, the GlobTemperature single-sensor Level-2 harmonised format is proposed to only include essential variables as mandatory. This will ensure the minimum datafile size for a given sensor is not restrictive to wide user uptake.

GT-TS-31*: As default datafiles to be disseminated with mandatory variables only. User functionality to be provided to allow selection of optional variables from auxiliary datafiles*

Optional fields are proposed to be included in accompanying datafiles. Data Providers are to be tasked with providing all mandatory fields in their GlobTemperature primary LST datafiles (labelled LST). For optional fields, where information is available for the given sensor then these are to be provided as mandatory fields in the accompanying auxiliary datafiles (labelled AUX).

GT-TS-32*: Provide ancillary information as optional to users and be stored in auxiliary datafiles*

Table 21: Proposed harmonised format for Primary (LST) GlobTemperature Level-2 LST products in netCDF-4

Dimensions	Name			
	time			
	nj			
	ni			
Variables	**Name**	**Dimensions**	**Units**	**Comment**
	jul_date	time	days	reference time at start of datafile in seconds Julian Date
	lat	nj, ni	degrees_north	Pixel centre latitude in decimal degrees north
	lon	nj, ni	degrees_east	Pixel centre longitude in decimal degrees east
	dtime	nj, ni	seconds	time difference from reference time in seconds
	LST	nj, ni	K	LST
	LST_uncertainty	nj, ni	K	total LST uncertainty
	QC	nj, ni	unitless	Quality control flags (see Table 31)
	Satze	nj, ni	degree	satellite zenith viewing angle
	Sataz	nj, ni	degree	satellite azimuth angle

GT-TS-33*: Provide uncertainty information per pixel for Level-2 data and per grid cell for Level-3 data as mandatory*

GT-TS-34*: Provide cloud flags in Level-2 harmonised format and information on number of cloud affected pixels in Level-3 harmonised format*

Table 22: **Proposed harmonised format for Auxiliary (AUX) GlobTemperature Level-2 LST products in netCDF-4**

Dimensions	Name			
	channel			
	nj			
	ni			
	ch_length			
	systematic			
Variables	**Name**	**Dimensions**	**Units**	**Comment**
	Channel	ch_length, channel	unitless	channel description
	emis	channel, nj, ni	unitless	channel emissivity
	BT	channel, nj, ni	K	channel brightness temperature
	Lcc	nj, ni	unitless	land cover classification (biome)
	Fv	nj, ni	unitless	fractional vegetation cover
	Tcwv	nj, ni	kg m^{-2}	total column water vapour
	NDVI	nj, ni	unitless	normalised difference vegetation index
	Solze	nj, ni	degree	solar zenith angle
	Solaz	nj, ni	degree	solar azimuth angle
	Lwm	nj, ni	unitless	land-water mask

	LST_unc_ran	nj, ni	K	uncertainty due to random effects
	LST_unc_loc	nj, ni	K	uncertainty due to locally correlated effects
	LST_unc_sys	systematic	K	uncertainty due to large scale systematic effects
	t2m	nj, ni	K	corresponding 2m air temperature from reanalysis
	sh2m	nj, ni	unitless	corresponding 2m specific humidity from reanalysis
	ws2m	nj, ni	m s^{-1}	corresponding 2m wind speed from reanalysis
	Albedo	nj, ni	unitless	albedo
	Elevation	nj, ni	m	elevation of land surface

***GT-TS-35**: Where information is available provide full uncertainty breakdown for Level-2, -3 and -4 data in a consistent manner*

***GT-TS-36**: Where available provide ancillary data in harmonised format datafiles: meteorological data, emissivity, land cover classification, fractional vegetation cover, NDVI and albedo*

As standard, the Level-2 datafiles disseminated to the users will contain all the mandatory fields from the primary (LST) datafiles. For dissemination of auxiliary fields a proposed approach to be agreed with the ILSTE-WG following feedback obtained from the 2nd and 3rd User Consultation Meetings is to offer both dissemination of the full auxiliary (AUX) datafiles, and the addition of user selected fields to the primary (LST) datafiles including select meteorological data (**addresses requirements REQ-8-TR, REQ-9-TR, REQ-29-TR and REQ-32-TR**).

Where emissivity data are explicit these can be provided in the AUX datafiles. Nonetheless, the approach to deriving emissivity for any given algorithm will be described in the accompanying Product User Guide (PUG).

*Addresses user feedback **GT-UF-12**: Document emissivity approach for each algorithm in the Product User Guide (PUG)*

In addition to the provision of netCDF datafiles, the option of disseminated the LST field alone will also be provided by way of GIS-compatible GeoTIFF format.

To achieve such user definition of output files the optimum solution is to utilise the open source netCDF Operator (NCO) tools (http://nco.sourceforge.net/). These allow single command-line manipulation of netCDF-4 datafiles including the extraction and concatenation of variables. They allow preservation of metadata, chunking and compression options. For example, to append emissivity and total column water vapour data from the AUX datafile to the output datafile containing all the mandatory variables a simple command of the following form can be used:

```
ncks -v emis,tcwv aux.nc -A out.nc
```

GT-TS-31*: As default datafiles to be disseminated with mandatory variables only. User functionality to be provided to allow selection of optional variables from auxiliary datafiles*

Addresses user feedback ***GT-UF-5****: Deliver consistent and accurate LST products, with unified formats (NetCDF and GIS-friendly GeoTiff) and metadata, product lists and dissemination schedules; with the provision of as much ancillary information as possible through the option of being able to customise the dataset files*

NetCDF-4 incorporates in-built compression, where it is recommended that all data providers supply their products with the highest level of compression available (level 9), and customise the chunking of data for optimal storage. High compression will increase the time to write the files, whereas no impact can be detected on the subsequent reading of these files. Thus users will not be affected by reading highly compressed datafiles, while benefitting from much reduced datafile sizes. Further necessary account is taken of file size in the scaling of variables. Where possible floats should be scaled (using the `add_offset` and `scale_factor` attributes) and stored as short integers (which is a very efficient way of compressing the data of individual variables).

GT-TS-32*: Provide ancillary information as optional to users and be stored in auxiliary datafiles*

Table 21For the geolocation coordinates (latitude and longitude) the numerical precision required does not allow for reduced storage by storing as integers. In GHRSST the geolocation in the L2P datafiles are stored as floats to 3 decimal places. For LST the proposal is that these are stored to 4 decimal places. This provides geolocation to an accuracy of approximately 11 m at the equator, and considering the uncertainty in most pixel geolocation is greater than this the inference is that the proposed numerical precision for the harmonised format is satisfactory for all user applications of medium resolution swath data.

***GT-TS-37**: All datafiles in harmonised format to be compressed at highest level (9), with `float` variables scaled to `short` where designated and geolocation data stored to 4 decimal places*

6.5.2. Higher level products

Level-3 products can be defined as products on a defined spatial / temporal grid mapped from the Level-2 single-sensor GlobTemperature products with reduced requirements for auxiliary data but additional requirements for fields related to the sampling. Level-4 products can be defined as datasets created from lower level data from multiple data streams that may or may not be gap-filled (**addresses requirement REQ-2-TR**). These products will be disseminated in datafiles of 10° x 10° tiles to reduce the output size of individual datafiles (**addresses requirements REQ-10-TR and REQ-44-TR**).

***GT-TS-6**: Provide Level-3 and Level-4 datasets in harmonised format to be disseminated as 10° x 10° tiles*

As for the single-sensor Level-2 swath data format many users may only be able to successfully exploit datafiles up to a certain size, considerably smaller than the 200 Mb from REQ-10-TR. For higher spatial resolution global Level-3 (single-sensor averaged products) and Level-4 (multi-sensor merged products) size becomes a pertinent consideration. As such, optional fields are proposed to be included in accompanying datafiles similar to the structure for the Level-2 products. This framework ensures all GlobTemperature higher level products are delivered in datafiles appropriate to the user community (**addresses requirement REQ-10-TR**).

All information, such as observation time, will be preserved from Level-2 products to higher-level products. In addition, the number of pixels averaged and the number excluded due to cloud will also be provided.

*Addresses user feedback **GT-UF-6**: Preserve information from Level-2 products in higher level products including number of data points/pixels used in averages as well as the times of the observations*

Data Providers are to be tasked with providing all mandatory fields in their GlobTemperature primary LST datafiles (labelled LST). For optional fields, where information is available for the given sensor then these are to be provided as mandatory fields in the accompanying auxiliary datafiles (labelled AUX).

Table 23 and Table 25 describe the proposed higher level gridded format for GlobTemperature products.

Table 23a: Proposed harmonised format for Primary (LST) GlobTemperature Level-3 and -4 uncollated products in netCDF-4.

Dimensions	Name

	time			
	lat			
	lon			
Variables	**Name**	**Dimensions**	**Units**	**Comment**
	jul_date	time	days	reference time at start of datafile in seconds Julian Date
	Lat	lat	degrees_north	Grid cell centre latitude in decimal degrees north
	Lon	lon	degrees_east	Grid cell centre longitude in decimal degrees east
	dtime	nj, ni	seconds	Grid cell mean time difference from reference time in seconds
	LST	lat, lon	K	Mean LST of the grid cell from cloud cleared input pixels
	LST_uncertainty	lat, lon	K	Grid cell LST uncertainty
	n	lat, lon	unitless	the total number of equivalent whole pixels assigned to the grid cell in the production of the averaged data
	ncld	lat, lon	unitless	the total number of equivalent whole pixels assigned to the grid cell in the production of the averaged data that are identified as cloud contaminated by the product's cloud clearing algorithm
	Satze	lat, lon	degree	Mean satellite zenith viewing angle for the grid cell
	Sataz	lat, lon	degree	Mean satellite azimuth angle for the grid cell

Table 24b: Proposed harmonised format for Primary (LST) GlobTemperature Level-3 and -4 collated products in netCDF-4.

Dimensions	Name
	time
	lat

	lon			
Variables	**Name**	**Dimensions**	**Units**	**Comment**
	Time	time	unitless	Diurnal index; day should have the value 0, night should have the value 1
	Lat	lat	degrees_north	Grid cell centre latitude in decimal degrees north
	Lon	lon	degrees_east	Grid cell centre longitude in decimal degrees east
	LST	time, lat, lon	K	Mean LST of the grid cell from cloud cleared input pixels
	LST_uncertainty	time, lat, lon	K	Grid cell LST uncertainty
	n	time, lat, lon	unitless	the total number of equivalent whole pixels assigned to the grid cell in the production of the averaged data
	ncld	time, lat, lon	unitless	the total number of equivalent whole pixels assigned to the grid cell in the production of the averaged data that are identified as cloud contaminated by the product's cloud clearing algorithm
	Satze	time, lat, lon	degree	Mean satellite zenith viewing angle for the grid cell
	Sataz	time, lat, lon	degree	Mean satellite azimuth angle for the grid cell

GT-TS-33*: Provide uncertainty information per pixel for Level-2 data and per grid cell for Level-3 data as mandatory*

GT-TS-34*: Provide cloud flags in Level-2 harmonised format and information on number of cloud affected pixels in Level-3 harmonised format*

Table 25: Proposed harmonised format for Auxiliary (AUX) GlobTemperature Level-3 and -4 products in netCDF-4

Dimensions	**Name**
	time
	channel

	lat
	lon
	ch_length
	systematic

Variables	Name	Dimensions	Units	Comment
	channel	ch_length, channel	unitless	Channel description
	vtime	time, lat, lon	hours	Mean observation time (time of day - UTC)
	lwm	lat, lon	unitless	land-water mask (proportion of land)
	Elevation	lat, lon	m	Mean elevation of land surface
	lcc	time, lat, lon	unitless	Land cover classification (biome)
	emis	channel, time, lat, lon	unitless	Mean grid cell channel emissivity
	Fv	time, lat, lon	unitless	Mean grid cell fractional vegetation cover
	Tcwv	time, lat, lon	$kg\ m^{-2}$	Mean grid cell total column water vapour
	NDVI	time, lat, lon	unitless	Mean grid cell normalised difference vegetation index
	Solze	time, lat, lon	degree	Mean grid cell solar zenith angle
	Solaz	time, lat, lon	degree	Mean grid cell solar azimuth angle
	LST_variance	time, lat, lon	K	variance of the LST observations used in the average for the grid cell
	LST_unc_ran	time, lat, lon	K	uncertainty due to random effects
	LST_unc_loc_atm	time, lat, lon	K	uncertainty due to locally correlated atmospheric effects
	LST_unc_loc_sfc	time, lat, lon	K	uncertainty due to locally correlated surface effects
	LST_unc_sys	systematic	K	uncertainty due to large scale systematic effects
	t2m	time, lat, lon	K	corresponding 2m air temperature from reanalysis

	sh2m	time, lat, lon	unitless	corresponding 2m specific humidity from reanalysis
	ws2m	time, lat, lon	$m\ s^{-1}$	corresponding 2m wind speed from reanalysis
	Albedo	time, lat, lon	unitless	Albedo

***GT-TS-35**: Where information is available provide full uncertainty breakdown for Level-2, -3 and -4 data in a consistent manner*

***GT-TS-36**: Where available provide ancillary data in harmonised format datafiles: meteorological data, emissivity, land cover classification, fractional vegetation cover, NDVI and albedo*

The dissemination of optional variable and the compression of variables is proposed as per described in section 6.5.1.

6.5.3. GlobTemperature Matchup Database (GT_MDB)

The GlobTemperature Matchup Database (GT_MDB) encompasses datafiles for both in situ validation and multi-sensor intercomparisons. Similar to the Level-2 and Level-3 format descriptions (Section 6.5.1 and Section 6.5.2 respectively) the datafiles have unique features in addition to the core requirements. Thus, core variables will be included in each output type in harmonised format with common metadata across all types. Since matchup datafiles by design are gridded and localised the constraints of file size are not restrictive here. Moreover, the GT_MDB contains datafiles that are also internal to the database but nevertheless require definition so each data provider is able to adhere to a single format to expedite optimal matchup processing.

From the User Requirements REQ-39-TR requires tools for generation of match-up datasets and data inter-comparison tools. To facilitate these requirements internal datafiles in harmonised format independent of the data source are required. Table 26 describes the proposed harmonised format for satellite data providers to deliver their LST extractions for each in situ validation site.

Data Providers are to be tasked with providing all mandatory fields in their input satellite LST extractions over each validation site, and if exists accompanying optional fields. This facilitates optimum knowledge of the different characteristics of individual LST datasets for understanding accuracy and precision with respect to in situ reference measurements. For any given site, the satellite input LST is to be provided on a fixed grid as designated by the validation scientist.

Table 26: Proposed harmonised format for GlobTemperature Matchup Database (GT_MDB) input satellite LST products in netCDF-4.

Dimensions	Name
	channel

Variables	Name	Dimensions	Units	Comment
	lat			
	lon			
	ch_length			
Mandatory	Lat	Lat	degrees_north	Centre latitude in decimal degrees north
	Lon	Lon	degrees_east	Centre longitude in decimal degrees east
	jul_date	lat, lon	days	Julian date
	QC	lat, lon	unitless	Quality control flags (see Table 31)
	LST	lat, lon	K	LST
	LST_uncertainty	lat, lon	K	LST uncertainty
	Satze	lat, lon	degree	Satellite zenith viewing angle
	Sataz	lat, lon	degree	Satellite azimuth angle
Optional	channel	ch_length, channel	unitless	channel description
	Emis	channel, lat, lon	unitless	channel emissivity
	BT	channel, lat, lon	K	channel brightness temperature
	Lcc	lat, lon	unitless	land cover classification (biome)
	Fv	lat, lon	unitless	fractional vegetation cover
	Tcwv	lat, lon	kg m^{-2}	total column water vapour
	Solze	lat, lon	degree	solar zenith angle
	Solaz	lat, lon	degree	solar azimuth angle

GT-TS-16*: Provide input satellite datasets for GlobTemperature Matchup Database (GT_MDB) in harmonised format*

Table 27 describes the proposed harmonised format for in situ measurements for each validation site. All mandatory fields are to be filled for each validation site, and if exists accompanying optional fields. This facilitates optimum knowledge of the site characteristics including instrument details for understanding accuracy and precision.

Table 27: Proposed harmonised format for GlobTemperature Matchup Database (GT_MDB) in situ measurements in netCDF-4

Dimensions	Name			
	sensor			
	time			
	sr_length			
Variables	**Name**	**Dimensions**	**Units**	**Comment**
Mandatory	Lat	Time	degrees_north	Centre latitude in decimal degrees north
	Lon	Time	degrees_east	Centre longitude in decimal degrees east
	jul_date	Time	days	Julian date
	elevation	Time	m	Elevation of land surface
	LST	time	K	LST
	LST_uncertainty	time	K	LST uncertainty
Optional	endmember	sr_length, sensor	unitless	name of end-member observed by sensor
	BT	sensor, time	K	brightness temperature of end-member observed by sensor. Uncertainty constant per sensor and to be provided as variable attribute
	weight	sensor, time	unitless	relative weight of measured BT; sum over sensors has to equal 1.0
	emis	sensor, time	unitless	emissivity of end-member observed by sensor
	senze	sensor, time	degree	sensor zenith viewing angle
	senaz	sensor, time	degree	sensor azimuth angle
	BT_sky	time	K	BT representing hemispherical sky radiance in sensor's spectral range
	QC	time	unitless	Quality control flags (see Table 31)
	BT_unc	sensor, time	K	uncertainty of radiometer
	BT_sky_unc	time	K	uncertainty of sky facing radiometer
	solze	time	degree	solar zenith angle

	solaz	time	degree	solar azimuth angle
	t2m	time	K	corresponding 2m air temperature
	sh2m	time	unitless	corresponding 2m specific humidity
	ws2m	time	$m\ s^{-1}$	corresponding 2m wind speed
	tcwv	time	$kg\ m^{-2}$	total column water vapour
	t_subsfc	time	K	subsurface temperature from thermometer; depth given as attribute
	albedo	time	unitless	Albedo
	lcc	time	unitless	land cover classification (biome)
	fv	time	unitless	fractional vegetation cover
	NDVI	time	unitless	normalised difference vegetation index

Taking the inputs described in Table 26 and Table 27 matchups between the satellite LST and coincident in situ measurements can be derived. Table 28 describes the proposed harmonised format for in situ vs. satellite LST for each validation site – satellite sensor pair over designated time windows. Note that matchups between in situ and satellite data may not be at the same location; for example, at the Gobabeb station satellite LST are taken from a location on the homogeneous gravel plains about 10 km east of the station.

Table 28: Proposed harmonised format for GlobTemperature Matchup Database (GT_MDB) in situ vs. satellite matchups in netCDF-4

Dimensions	Name			
	time			
Variables	**Name**	**Dimensions**	**Units**	**Comment**

Mandatory	insitu_lat	Time	degrees_north	In situ latitude in decimal degrees north
	insitu_lon	Time	degrees_east	In situ longitude in decimal degrees east
	station_LST	Time	K	In situ LST
	station_LST_unc	Time	K	In situ LST uncertainty
	sat_lat	Time	degrees_north	Satellite centre latitude in decimal degrees north
	sat_lon	Time	degrees_east	Satellite centre longitude in decimal degrees east
	jul_date	Time	days	Julian date
	LST	Time	K	LST
	LST_uncertainty	Time	K	LST uncertainty
	satze	Time	degree	sensor zenith viewing angle
	sataz	Time	degree	sensor azimuth angle
Optional	n	Time	unitless	Number of aggregated pixels in matchup
	ncld	Time	Unitless	Number of cloudy pixels in matchup
	dn_index	Time	unitless	Day / Night index (day = 0, night = 1)
	solze	Time	degree	solar zenith viewing angle
	solaz	Time	degree	solar azimuth angle
	sat_lcc	Time	Unitless	land cover classification (biome) in satellite data

GT-TS-17*: Provide in situ matchup datasets for GlobTemperature Matchup Database (GT_MDB) in harmonised format*

For satellite vs. satellite intercomparison matchups the proposed harmonised format is described in Table 29. These single matchup datafiles provide the ingredients for Data Portal tools to deliver information to the users on multi-sensor matchups. For example, monthly composites can be derived based on the individual matchup data and stored on the Data Portal for visualisation tools to map intercomparisons over user-defined spatial and temporal extents.

Table 29: Proposed harmonised format for GlobTemperature Matchup Database (GT_MDB) multi-sensor satellite intercomparison matchups in netCDF-4

Dimensions	Name

	sensor
	lat
	lon
	s1_channel
	s2_channel
	ch_length

Variables	Name	Dimensions	Units	Comment
Mandatory	sensor	sr_length, sensor	unitless	Sensor name
	lat	lat	degrees_north	Centre latitude in decimal degrees north
	lon	lon	degrees_east	Centre longitude in decimal degrees east
	n	sensor, lat, lon	unitless	Pixel count
	ncld	sensor, lat, lon	unitless	Cloudy pixel count
	jul_date	sensor, lat, lon	days	Julian date
	LST	sensor, lat, lon	K	LST
	LST_uncertainty	sensor, lat, lon	K	LST uncertainty
	satze	sensor, lat, lon	degree	Satellite zenith viewing angle
	sataz	sensor, lat, lon	degree	Satellite azimuth angle
Optional	s1_channel	Ch_length, s1_channel	unitless	Sensor 1 channel name
	s2_channel	Ch_length, s2_channel	unitless	Sensor 2 channel name
	s1_emis	s1_channel, lat, lon	unitless	Sensor 1 channel emissivity
	s2_emis	s2_channel,	unitless	Sensor 2 channel emissivity

		lat, lon		
	matchup_flag	lat, lon	unitless	Flag indicating if LST is computed using one time (1) or two times linearly interpolated (2)
	solze	lat, lon	degree	Solar zenith viewing angle
	solaz	lat, lon	degree	Solar azimuth angle
	fv	sensor, lat, lon	unitless	Fractional vegetation cover
	tcwv	sensor, lat, lon	kg m^{-2}	total column water vapour
	lcc	lat, lon	unitless	land cover classification (biome) in satellite data
	elevation	lat, lon	m	Elevation of land surface

GT-TS-19*: Provide satellite vs. satellite matchup datasets for GlobTemperature Matchup Database (GT_MDB) in harmonised format*

To facilitate detailed analysis of the differences between satellite LST data from matchups in terms of orography or land cover for example, a static / semi-dynamic (yearly updated) datafile is to be available to maintain such global information (Table 30).

Table 30: Static / semi-dynamic variables to facilitate analysis of satellite vs. satellite intercomparison differences

Dimensions	Name
	lcc_id

	time			
	lat			
	lon			
	lc_length			
Variables	**Name**	**Dimensions**	**Units**	**Comment**
	lcc_id	lc_length, lcc_id	unitless	Name of land cover classification system
	time	time	years	Year land cover classification is valid for
	Lat	lat	degrees_north	Centre latitude in decimal degrees north
	Lon	lon	degrees_east	Centre longitude in decimal degrees east
	elevation	lat, lon	m	Surface elevation
	lcc	lcc_id, time, lat, lon	unitless	Land cover classification (biome)

6.5.4. Quality control

Table 31 details the quality control variable which is mandatory in the Level-2 harmonised format and both the GT_MDB input satellite LST format and the GT_MDB in situ measurements format. Bits 0 to 5 are mandatory, bits 6 to 15 optional. These will all be documented in the accompanying Product User Guide (PUG).

It is also the intention to assign Quality Flags to the LST products at a per-pixel level similar to those used for SST in the GHRSST convention to enable users to be more informed when filtering data. This agreement for these Quality Flags needs to be made in consultation with the ILSTE-WG so as to set a community standard that can be adopted by other data providers.

*Addresses user feedback **GT-UF-16**: Assign quality flags of values agreed with the community to give consistency with other products (such as SST)*

Table 31: Quality control bits

Bit	Flag
0	Day / Night flag (day = 0, night = 1)

1	Consolidated cloud flag (0 = no cloud, 1 = cloud)
2	Consolidated confidence flag (0 = good confidence, 1 = low confidence)
3	Aerosol information available (1 = yes)
4	Aerosol detected (1 = yes)
5	Spare bit for potential future evolution
6 – 15	Optional flags included by the Data Provider. These may be for example individual detailed cloud or confidence flags carried forward from the Level-1b source data. They are to be described in the `flag_meanings` and `flag_masks` variable attributes.

***GT-TS-38**: Provide flags on the data quality in the harmonised format datafiles*

*Addresses user feedback **GT-UF-15**: Provide enhanced QC information with a comprehensive description of the flags and how to use them in the Product User Guide (PUG), and the ability to filter in the extraction tool*

6.5.5. Metadata and product resolutions

Global Metadata

***GT-TS-30**: All harmonised formats to adhere to common metadata compliant with CF conventions*

The Global metadata describe the whole file with regard to general information about conventions, data producer, contact information etc. Examples for the information provided in each of the used attributes can be found in Appendix C – Harmonised Format Examples. Table 32 details the global attributes proposed to be provided with each file.

Table 32: Global metadata for GlobTemperature products in netCDF-4 harmonised format.

Name	Comment
`conventions`	Refers to the metadata convention used in the file. For the harmonised format the Climate and Forecasting (CF) metadata convention version number.
`title`	Title of the LST data product
`summary`	Summarizes the primary content of the data product
`references`	Provides a reference to cite for data users
`institution`	Name of Institution responsible for developing the dataset
`history`	Provides information about how the product was created

Name	Comment
comment	Provides additional information that does not fit any of the other attributes
license	Provides guidance on the data use policy
id	The identification name of the product
date_created	Gives the date on which the product was created. Given as DD-MM-YYYY HH:MM:SS±HHMM, where ±HHMM is the time zone relative to UTC
product_version	Provides the version of the data product
netcdf_version_id	Gives the version of the used netCDF format and its creation date
spatial_resolution	Spatial resolution of data in datafile (eg: 1 km)
start_time	Provides the start time of the product; this relates to an orbit, start of a day or start of a month. Given as YYYY-MM-DD HH:MM:SSZ. Z is the time zone relative to UTC
time_coverage_start	Provides the start time of the total coverage of the data for the Product. Given as YYYY-MM-DD HH:MM:SSZ. Z is the time zone relative to UTC
stop_time	Provides the end time of the product; this relates to an orbit, end of a day or end of a month. Given as YYYY-MM-DD HH:MM:SSZ. Z is the time zone relative to UTC
time_coverage_end	Provides the end time of the total coverage of the data for the Product. Given as YYYY-MM-DD HH:MM:SSZ. Z is the time zone relative to UTC
northernmost_latitude	Provides the northernmost geographical extent of the data in the datafile. Given as decimal degrees, positive numbers are north of the equator
southernmost_latitude	Provides the southernmost geographical extent of the data in the datafile. Given as decimal degrees, positive numbers are north of the equator
easternmost_longitude	Provides the easternmost geographical extent of the data in the datafile. Given as decimal degrees, positive numbers are east of the Greenwich meridian
westernmost_longitude	Provides the westernmost geographical extent of the data in the datafile. Given as decimal degrees, positive numbers are east of the Greenwich meridian
source	Provides information about the source data on which the product is based on (eg: L1b identifier)
platform	Provides the name of the orbiting platform/satellite
sensor	Provides the name of the used sensor/instrument

Name	Comment
processing_level	Product processing Level (eg. L2, L3, L4)
keywords	Comma separated list of GCMD Science Keywords from http://gcmd.nasa.gov/learn/keyword_list.html
keywords_vocabulary	Provides vocabulary, typical form is "NASA Global change Master Directory (GCMD) Science Keywords"
geospatial_lat_units	Units of the latitudinal resolution. Typically “degrees_north”
geospatial_lat_resolution	Latitude Resolution in units matching geospatial_lat_units
geospatial_lon_units	Units of the longitudinal resolution. Typically “degrees_east”
geospatial_lon_resolution	Longitude Resolution in units matching geospatial_lon_units
acknowledgment	Acknowledgement of ESA as the funding agency
creator_name	Name of Project Partner responsible for developing the dataset
creator_email	Email address of Project Partner responsible for developing the dataset
creator_url	URL of GlobTemperature Website

Variable Metadata

Each individual variable in the GlobTemperature harmonised format has its own metadata. Table 33 details the attributes which are common for most variables (unless not applicable for a particular variable).

Table 33: Variable metadata for GlobTemperature products in netCDF-4 harmonised format.

Name	Comment
long_name	A free-text descriptive name for the variable
standard_name	The standard name for the variable as defined by CF conventions
units	Text description of the units the data is stored in.
_FillValue	A value used to indicate array elements which contain invalid or missing data
scale_factor	Used to pack data into a smaller datatype. The original data can be recovered using: value = (scale_factor * packed_data) + add_offset
add_offset	
valid_min	The minimum valid value for the variable in its packed

Name	Comment
	form
`valid_max`	The maximum valid value for the variable in its packed form
`Coordinates`	Describes the coordinate system in which the data is given
`source`	Published or web-based reference describing the origins of any third-party auxiliary data

Some variables contain additional metadata attributes that are only relevant for the specific variable (Table 34).

Table 34: Additional variable metadata for GlobTemperature products in netCDF-4 harmonised format.

Name	Comment
`Flag_meanings`	Describes the scientific meaning behind any flags given in the variable
`Flag_values`	Used for variables which describe a classification (eg: land cover classification). These correspond to the equivalent flag meanings.
`Flag_masks`	Used for variables which describe individual bit masks within a word flag (eg: Quality Control). These correspond to the equivalent flag meanings.

For each GlobTemperature product the variables and metadata will be documented within the Product User Guide (PUG). Furthermore, a recommended approach to utilisation of the individual variables will also be documented in the accompanying PUG (**addresses requirement REQ-20-TR**).

<u>Spatial / temporal resolutions</u>

For Level-3 single sensor datasets the proposed standard spatial resolution is 0.05° equal-angle and the temporal resolution daily; each average is resolved for day / night retrievals (**addresses requirement REQ-24-TR**). Table 35 details the potential spatial and temporal resolutions for which GlobTemperature single-sensor LST Products could be averaged and disseminated via the Data Portal given sufficient user demand. For the Level-4 GlobTemperature merged LST product the proposed spatial / temporal resolutions are detailed in Section 4.2.12.

GT-TS-10*: Standard spatial resolution of Level-3 and -4 datasets to be 0.05° unless designated otherwise*

GT-TS-39*: Standard temporal resolution of Level-3 datasets to be day / night*

Table 35: Potential additional spatial / temporal resolutions of the GlobTemperature single-sensor LST Products given sufficient user demand.

	Daily	Monthly
0.05° x 0.05°	•	•
0.1° x 0.1°	•	•
0.25° x 0.25°	•	•
0.5° x 0.5°	•	•

Datasets created within GlobTemperature specifically for the high latitudes, such as IST datasets will be provided in harmonised format in equal-area projection (**addresses requirement REQ-23-TR**).

GT-TS-40*: Provide high-latitude only (polar) datasets in equal-area projection*

6.5.6. Filename conventions

The GlobTemperature output file naming convention is proposed to follow a single harmonised structure for all products:

<product_code> <"-"> <processing_level> <"-"> <primary_sensor_name> <"_"> <product_wildcard> <start_day> <"_"> <start_time> <"-"> <processing_centre> <originator_ID> <"-"> <geospatial_lat_resolution> <X> <geospatial_lon_resolution> <"-"> <product_version> <"."> <extension>

The file length is thus consistent between the different types of datafiles ensuring maximum ease of use for the users of harmonised format products.

Table 36 details the components of the single harmonised file naming convention with reference to the following example filenames:

- Level-2, Level-3 and -4 filename example:

  GT_SSD-L2-AATSR_LST_2P20060718_102137-CUOL-0.01X0.01-V1.0.nc

- GT_MDB satellite vs. satellite filename example:

  GT_MDB-SS-AATSR_SEVIR_20060718_102137-CUOL-0.05X0.05-V1.0.nc

- GT_MDB satellite extraction for in situ validation filename example:

  GT_MDB-SE-AATSR_GBB_W_20060718_102137-CUOL-0.01X0.01-V1.0.nc

- GT_MDB in situ measurements filename example:

GT_MDB-IS-INSIT_GBB_W_20060718_XXXXX-KKIT-0.00X0.00-V1.0.nc

- GT_MDB satellite vs. in situ filename example:

GT_MDB-SI-AATSR_GBB_W_20060718_XXXXX-KKIT-0.01X0.01-V1.0.nc

Table 36: Description of output file naming conventions

Element	Example(s)	Description
<product_code>	GT_SSD GT_MDB	6-character string identifying project (GT) and product identifier: SSD = single-sensor dataset CDR = Climate Data Record MDB = Matchup Database C1G = Combined LEO/GEO Tier-1 Gap-filled L1G = LEO Tier-1 Gap-filled G2G = GEO Tier-2 Gap-filled G2X = GEO Tier-2 not gap-filled L2X = LEO Tier-2 not gap-filled NRT = Near Real-Time demonstration product
<processing_level>	L2 SS SE IS SI	2-character string identifying sensor name: L2 = Level-2 L3 = Level-3 L4 = Level-4 SS = Satellite vs. Satellite SE = Satellite Extraction IS = In Situ SI = Satellite vs. In situ

Element	Example(s)	Description
<primary_sensor_name>	AATSR INSIT	5-character string identifying sensor name: AATSR, ATSR2, ATSR1, AVHRR, SEVIR, GOES_, MTSAT, AMSRE, SSM_I, MOD11 (Terra), MYD11 (Aqua), MERGD (Merged product), SLSTR, IASI_, INSIT (In Situ data)
<product_wildcard>	LST_2P SEVIR_ GBB_W_	6-character wildcard string following three distinct patterns: 1. <product_type> <"_"> <processing_level> For LST or auxiliary (AUX) datafiles: LST_2P, LST_3U, LST_3C, AUX_2P, AUX_3U, AUX_3C 2. <secondary_sensor_name> For GT_MDB intercomparison datafiles; options are the same as for <primary_sensor_name> 3. <site_name> For GT_MDB in situ validation input satellite datafiles; options are listed in Section 5.2
<start_day>	20060718	The start day of the product based on the start time of the first data set record. Given in YYYYMMDD. For aggregated datasets over a month for example then the DD element will be replaced by XX

Element	Example(s)	Description
<start_time>	102137 XXXXXX	The start time of the product from the UTC time of the first data set record, given in HHMMSS For aggregated datasets, the appropriate elements will be replaced by X's
<processing_centre>	C K	1-character string identifier of the production facility: A = ACRI-ST C = UK-CEMS L = LandSAF K = KIT
<originator_ID>	UOL KIT	3-character string identifier of the development facility: UOL = University of Leicester UOR = University of Reading IPM = IPMA KIT = Karlsruhe Institute of Technology EST = Estellus
<geospatial_lat_resolution>	0.01 0.05 0.00	Geospatial latitude resolution in the format F4.2 For in situ point sources use 0.00
<geospatial_lon_resolution>	0.01 0.05 0.00	Geospatial longitude resolution in the format F4.2 For in situ point sources use 0.00

Element	Example(s)	Description
<product_version>	V1.0	4-character string identifier of the product version number in the form of 1-character "V" followed by number in the format F3.1
<extension>	.nc	File name extension

GT-TS-41: *Provide all harmonised format datafiles according to a common file naming convention*

7. User Case Studies: Work Plans

Five User Case Studies (UCSs) will demonstrate the value of global LST data in diverse and important fields of application; delivering strategic advice, feedback and dataset testing of the GlobTemperature products in the following application fields:

- UCS #1: Surface temperature reconstruction for climate (Met Office Hadley Centre)
- UCS #2: Estimation of evapotranspiration (Estellus)
- UCS #3: Driving of sea-ice state in a coupled ocean model (DMI)
- UCS #4: Soil moisture assessment (University of Copenhagen)
- UCS #5: Assimilation of LST in NWP (Met Office)

GT-TS-22*: Ensure quality of GlobTemperature datasets through comprehensive validation, intercomparison, and user evaluation*

Each User Case Study will be supported by firstly, a designated core partner most directly related to their interests in terms of science and data; and secondly, by University of Reading who will maintain an overview of progress and help each group benefit from interactions across the consortium. There will be strong liaison during the period of core activity whereby monthly teleconferences will be convened to:

- review / update the detailed UCS plans
- be updated on progress in each UCS against plans
- share experiences, issues and solutions (e.g., with respect to data)
- keep UCS partners informed about the GlobTemperature progress and meetings
- ensure UCS partners are aware of the required approach to the UCS deliverables
- identify material for monthly reports

Following feedback and interactions from the 2nd User Consultation Meeting this section will be updated with a further release of the User Case Study Work Plans prior to their commencement when a more complete picture of the available GlobTemperature output datasets is known and hence the work to be carried out can thus be more accurately organised. These updated Work Plans will adhere to a common format to simplify management of the suite of User Case Studies.

7.1. UCS #1: Surface temperature reconstruction for climate

7.1.1. Objective and approach

In this User Case Study, we will explore the issues involved in using LST retrievals to augment information from meteorological stations with a view to understanding the problem at different space and time scales and identifying core issues for generating a seamless product that can be used across different space and time scales. To do this, we will make use of state of the art understanding on the relationships between LST retrievals and air temperature measurements gained from the literature and other projects. We expect this study to highlight the core issues and to inform our strategy for the exploitation of LST retrievals in our future high resolution products for climate services, amongst other applications.

7.1.2. Expected results and impact

Satellite observations of surface temperature represent area-averaged 'skin' temperatures (i.e. the temperature of the Earth's surface) at scales of several tens of metres to kilometres, whereas meteorological stations record the ambient air temperature at a height of around 2m at a specific spatial point. Climate studies have traditionally utilised the latter, usually in a gridded or interpolated form, but are geographically limited where the spatial density of stations is low. This issue is becoming increasingly apparent as users ask for data sets with higher spatial resolution and better geographical coverage. Satellite data can be used to augment station data sets, providing detailed spatial pattern information for surface temperature, and observations where in situ stations are absent. Surface temperatures from satellites may also be informative with respect to spatial and temporal discrepancies in the station records themselves, for example resolving a non-climatic temperature change that results from geographical relocation of a station. However, before any synergistic use of these different data sets can be properly developed, work must first be carried out to understand the relationships between these observation types, which although physically related, are fundamentally different. Moreover, the satellite data have a number of limitations that must be taken into consideration; for example, cloud contamination in infrared data, uncertainties in the temperature retrievals and geolocation.

There are a number of studies documented in the literature where near-surface air temperature is estimated from satellite observations and nearly all of these adopt a statistical empirical approach to predict air temperatures from observed satellite variables and auxiliary data sets [RD-105, RD-106, RD-107, RD-108]. Recently, this method has been used by the Met Office to estimate air temperatures over Europe within the framework of the European Reanalysis and Observations for Monitoring (EURO4M) project (see http://www.metoffice.gov.uk/hadobs/msg_tmaxmin/). While the results of these experiments are very promising – the uncertainties of the satellite-estimated air temperatures are typically within about 3 °C – there is clearly more to be done in terms of understanding and resolving the differences between the satellite and station data. In particular, in coastal regions where the skin-air temperature relationship is particularly complex, the effects of satellite view angle, cloud contamination, and where spatial heterogeneity is high as a result of changing topography or land use.

7.1.3. Work plan

In this user case study we will determine the effect of spatial and temporal resolution on the accuracy of relationships between the different temperature data sets, as estimated in other studies. We will do this in selected regions where there is a high-density network of stations, for example in Germany, the Netherlands, the UK and parts of the US. This will also allow us to determine the impact of varying in situ network density, by withholding station data, as well as the effect of the resolution on which information is aggregated and the resolution of the satellite retrievals. We will compare and contrast:

- satellite skin temperature;
- satellite-estimated air temperature (e.g. from EURO4M);
- gridded station air temperatures (e.g. from E-OBS, http://www.ecad.eu/download/ensembles/ensembles.php);
- individual station air temperatures;
- reanalysis skin and air temperatures (e.g. ERA-Interim or EURO4M).

The comparisons will be analysed in both space and time and in conjunction with state-of-the-art land use and topography maps, satellite cloud and view-angle information, and other meteorological data The work will make use of several of the satellite temperature products produced in GlobTemperature to fully understand the spatial aspects of the problem (e.g. ATSR vs SEVIRI vs station). Uncertainty information provided in the GlobTemperature products will also be considered in the analysis.

7.1.4. Expected value

This work will enable the identification of the core issues in combining satellite and station data for climate applications. A report will be written detailing the work undertaken, describing the issues found, with recommendations for future work. This information will then also be included in a journal article for peer review presenting the user case study and discussing its implications.

*Addresses user feedback **GT-UF-1**: Improve quantification on the relationship between observations of "all-sky" land surface air temperature (LSAT) and "clear-sky" thermal infrared (TIR) LST*

7.2. UCS #2: Estimation of evapotranspiration

7.2.1. Objective and approach

Land surface heat fluxes cannot be directly observed by remote sensing techniques, so different formulations combining measurable flux related parameters to estimate heat fluxes at global scale for climatological applications are under development [RD-109, RD-110]. LST is one of the key parameters controlling the surface heat fluxes, and a key input for some of these ET models. Here we will demonstrate the production of LST-driven evapotranspiration (ET) by running the Surface Energy Balance System (SEBS) model, [RD-111] with one of the GlobTemperature generated products (Merged GEO v0.5) over 3 regional sites representative of different biomes and climate conditions. The produced ET will be evaluated with the available in situ measurements and the estimates from other ET methodologies produced by the WACMOS-ET project (http://wacmoset.estellus.eu/), being the objective of the evaluation to signal strength and limitations of using the GlobTemperature LST to derive an ET product, compared with the other existing approaches [RD-112].

7.2.2. Expected results and impact

The main result will be one year of daily GlobTemperature LST-driven ET produced over 3 regional sites spread over 3 different continents representing different land cover and climate conditions, together with an analysis of the quality of the produced ET by comparison with other estimates. This analysis will drive discussions on the potential to produce LST-driven ET by SEBS-like methodologies, taking into account the characteristics of the GlobTemperature LST estimates and the ancillary inputs required to run the model.

7.2.3. Work plan

1. Data production

    - ❖ Coding of ET model
    - ❖ Collection of auxiliary land and meteorological inputs and homogenization to the 0.05 degrees and 3–hourly resolutions of the Merged GEO v0.5 GlobTemperature product.
    - ❖ Production of daily LST-driven ET estimates over 3 regional sites of ~ 1000 km2 . The three selected sites are:

        i. Over Europe, an area in the Rietholzbach catchment in Switzerland, corresponds to a pre-alpine region, including a sub-catchment studied for more than 30 years, to try the ET estimation over a region with pasture and coniferous forest.

        ii. Over Africa, a region with a climate dominated by the West-African monsoon around one of the savannah mesoscale sites of the African Monsoon Multidisciplinary Analysis (AMMA) Land Model Intercomparison Project Phase 2 (ALMIP-2, a GEWEX Global Land Atmosphere System Study (GLASS) initiative), to test the ET estimation over a grassland region.

        iii. Over North America, a cultivated area around the Atmospheric Radiation Measurement (ARM) Southern Great Plains site is selected in North America, to have an example of ET estimation over agricultural fields.

2. Data evaluation

   ❖ Comparison with available in situ ET estimates and ET estimates from other methodologies run during the WACMOS-ET project.

   ❖ Analysis of ET differences and discussion of the impact of the specific GlobTemperature LST product selected particularities (e.g., time and space resolution and coverage, accuracy, etc) in ET estimation.

3. Presentation of results

   ❖ Writing of report summarising the findings

   ❖ Discussion with GlobTemperature producers at the consultation meeting.

7.2.4. Expected value

This case study will result in an early application of the GlobTemperature product into the expanding field of estimating ET from satellite measurements, and links the GlobTemperature project with another ESA project, WACMOS-ET, which is currently investigating the potential to develop global long-term ET products that may exploit existing and coming European EO assets (e.g., Envisat AATSR, MERIS, and the coming Sentinel series).

7.3. UCS #3: Driving of sea-ice state in a coupled ocean model

7.3.1. Objective and approach

This proposal aims at improving the sea ice description in the model using the remote sensed sea ice/snow surface temperatures from GlobTemperature with additional Metop_A observations. This will be implemented by improving the surface boundary condition of the thermodynamic equation that is solved in the sea-ice model.

A pre-processing of the L2P sea and ice surface temperature observations from GlobTemperature will be performed, where the GlobTemperature products are blended with IST observations from Metop_A, to produce a year of daily level 4 SST + IST fields, suitable to be ingested into the HYCOM-CICE model.

7.3.2. Expected results and impact

The one year with daily SST and IST level 4 fields will cover the area shown in Figure 26. The data set will be constructed within the user case study and delivered to the project afterwards.

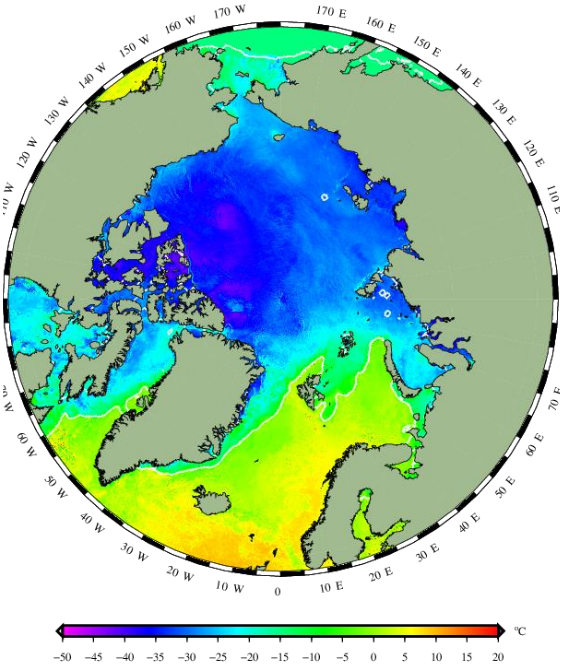


Figure 26: Example of a merged gridded level 4 SST + IST product for the Arctic. The solid white line indicates the 15% sea ice concentration contour from the Ocean and Sea Ice SAF data set.

Two ocean/sea-ice model simulations will be carried out using one year (2012) of realistic atmospheric forcing. The two simulations are:

- A simulation using the atmospheric forcing to predict the surface temperatures.
- A simulation using the chosen remote sensed ice/snow surface temperatures

DMI has vertical temperature measurements derived from 8 ice mass balance buoys that were deployed in 2012. These measurements with a thermistor every 2 cm through the ice will be used as a validation tool of the simulations. The differences in the ice cover and ice volume between the two simulations will be analyzed and the sea-ice concentration will be compared to the remote sensed sea ice concentration. In addition the sea-ice surface temperatures derived from buoys, remote sensing and atmospheric forcing will be discussed and a discussion of the effect of assimilating the IST product direct into the ocean/sea-ice model will be given as well. The results may also show spatial differences which highlights areas where the IST product is most useful. This will be combined into a scientific peer-reviewed article.

Ultimately, the assimilation of IST into the sea-ice model will reduce the error associated with the sea-ice thickness and the sea-ice cover in the operational forecasts, which is of obvious beneficial for commercial marine operators in the ice-covered seas.

7.3.3. Work plan

The experiments will start from month 12, initiated at PM2 and be carried in phase 2 of the project. The implementation of the User Case Study will be finished in Month 24 and the results will be reported at PM4. The work is split into four parts

1. Preparation of level 4 IST data set (Month 12-15)

   - The ATSR IST observations from GlobTemperature and the 1 km IST observations from Metop_A will be ingested into the DMI L4 IST processing system. Daily gap free fields of IST will be produced for a year, with auxiliary information on the daily variability, to optimize the ingestion of the IST field into the HYCOM-CICE model. The one year level 4 IST data will be validated against drifting buoy observations. The daily IST fields will be available in Netcdf format to other partners within the GlobTemperature project after generation.

2. Implementation of IST observations into model month 15-16

   - The IST observations will be assimilated into the operational Arctic model at DMI with a nudging scheme that corrects the incoming atmospheric heat flux as an additional term that converges the surface temperature of the ice/snow cover towards the observations. This will enter into the upper boundary conditions of the thermodynamic equation solved by the sea ice model. The IST has a large diurnal variability that very likely exceeds the differences between observations and modeled IST, therefore and in addition to the daily observed IST maps from GlobTemperature the diurnal variations will be used to form a series of fields that includes these variations. These fields including diurnal variations will be used for the nudging

   - The coupled ocean and sea ice model is a slightly modified version of HYCOM (HYbrid Coordinate Ocean Model) v2.2.55 [RD-113, RD-114] and CICE v4.0 (Community Ice COde) [RD-115, RD-116]. HYCOM explores a hybrid coordinate that is isopycnal in the open, stratified ocean, but smoothly reverts to a terrain-following coordinate in shallow coastal regions, and to z-level coordinates in the mixed layer and/or unstratified seas. CICE applies an elastic-viscous-plastic (EVP) sea ice rheology [RD-116, RD-117] and includes a multi-category ice thickness distribution. The thermodynamics of CICE allows for a vertical temperature profile with a vertical resolution defined by the number of thermodynamic layers (currently 4). This profile will be compared to the measurements obtained by the drifter buoys.

3. The two model simulations will be run in month 17 and 18

4. The validation of the results will be carried out in month 19-21

   - The results will be evaluated based on the following parameters:

i. The difference in of the input (ice/snow surface temperature) will be evaluated both with regards to temporal and spatial differences.

ii. The total sea-ice covered area from the two simulations will be compared to the total sea ice cover derived from OSISAF.

iii. Due to the lack of remote sensed ice volume the sea ice volume will be compared to model results from modeled sea-ice volume found by PIOMAS [RD-118].

iv. The temperature profiles from the buoys and the two simulations will be calculated and the differences will be analyzed.

5. Reporting and article writing will be carried out from month 19-24

- Results will be disseminated at progress meeting 4.

7.3.4. Expected value

The recent retreating sea-ice cover has increased the commercial interest of these remote areas during the last decade due to potential new ship routes, increased tourist cruises and oil exploration. Consequently, the need for trustworthy forecasts of atmospheric and oceanographic conditions is highly needed for safely marine operations in ice-covered seas. DMI is involved in many projects regarding ice management and marine safety in the Arctic. These uses will thus directly benefit from improvements in the performance of the ocean and sea ice models.

Numerical weather prediction models (NWP) rely on observations for their data assimilation. The amount of data in the Arctic is sparse, thus the observational control of the NWP models in Arctic is limited, which allows larger variations of the results and likely larger error bars when compared to other regions. The inclusion of IST as a control on the forcing of the sea ice model decrease these error bars and the resulting output should therefore be improved and increase the trustworthiness of the operational sea ice predictions

7.4. UCS #4: Soil moisture assessment

7.4.1. Introduction

Monitoring Soil Moisture (SM) is a key variable to determine the water fluxes between the land surface and the atmosphere. Earth Observation (EO) satellite platforms can be a powerful tool to overcome the limitations of ground sensors and spatially distribute this variable, since SM affects the emission and absorption of electromagnetic radiation in different regions of the spectrum: 1) Microwave (MW) backscattered or emitted energy from/by the ground surface allows relating the dielectric constant with SM [RD-119]; 2) When the soil is wet the energy balance of the surface is controlled by soil evaporation and vegetation transpiration and, hence, lower surface temperatures are expected in wet soils than in dryer soils during daytime hours [RD-119]. This effect can be captured in the Thermal Infra-Red (TIR) region of the electromagnetic spectrum. Additionally, if multiple observations of the land surface are taken at different times throughout the day they can be related to the soil thermal inertia [RD-120] and consequently to SM [RD-121]; and 3) In the optical domain (350-2500 nm), an increase of SM produces an overall decrease in albedo [RD-122] and specific absorption features in the Short-Wave Infrared Region (SWIR) [RD-123].

Each of these spectral regions has its own advantages and disadvantages for mapping SM [RD-124, RD-125]. MW sensors are insensitive to atmospheric disturbances, but they usually require larger pixel size (1 to 2 orders of magnitude) to be compared with sensors in the optical or thermal infrared domain, due to the lower emitted energy in this region. This is the case of Soil Moisture and Ocean Salinity (SMOS) (50 km) or the future Soil Moisture Active Passive (SMAP) (9km) missions dedicated to monitor SM.

Regarding optical and TIR sensors, they are greatly affected by the atmosphere, but, on the positive side, they allow a higher spatial and/or temporal resolution. Different methods have been proposed in the literature to combine thermal information with visible and near infrared data in order to estimate the root-zone SM. This is the case of the Temperature-Vegetation Dryness Index (TVDI) [RD-126] based on the triangle method, since it delimitates empirically the triangle formed when plotting many different cases of the Land Surface Temperature (LST) versus a Vegetation Index (VI) [RD-126, RD-127, RD-128, RD-129, RD-130]. The triangle method was first used by [RD-131] based on the different thermal properties of soil and vegetation: for equal weather forcing conditions soil and vegetation temperatures differ and this fact explains why the LST-VI scatter plot shows a typical triangular shape [RD-126]. The different ranges of moisture availability and fractional vegetation cover within the LST-VI spatial window affects its shape [RD-127]. The upper boundary is called "dry edge" that represents dry soils and stressed vegetation where evapotranspiration (ET) does not occur and hence surface temperature is maximum. The "wet edge" establishes the lower boundary that corresponds with wet soils and unstressed vegetation where ET occurs near its potential rate and thus surface temperature is minimum and close to the air temperature. Between the two edges, all intermediate conditions occur, and all SM conditions can consequently be represented within the LST-VI triangle space.

Several assumptions and prerequisites need to be taken into account when applying the triangle method: 1) Uniform atmospheric forcing together with the presence of all moisture and vegetation cover conditions are needed within the spatial domain applied [RD-132]; 2) The dimensions of this spatial domain have to be large enough to collect a sufficient amount of LST-VI cases to adequately define the triangle shape; and 3) Factors like land cover type and topography should also be taken into account to ensure the applicability of the method [RD-133].

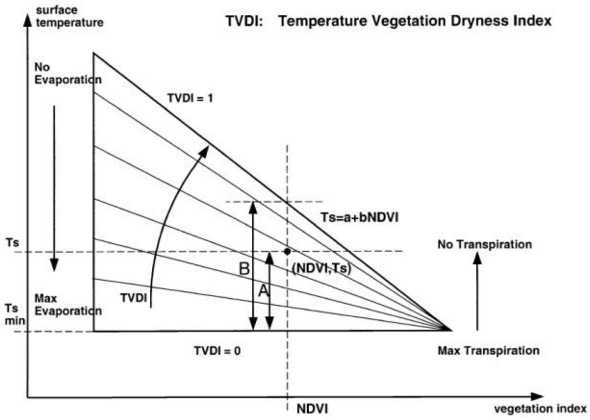


Figure 27: The Temperature Vegetation Dryness Index concept. The baseline boundary represents the wet edge. Source: [RD-126]

7.4.2. Objectives

In this study case study we propose to produce long time series of TVDI using GlobTemperature datasets for SEVIRI (~4km) and AATSR (1km). In a second step, the produced TVDI will be used for downscale the SMOS soil moisture retrievals to the SEVIRI and AATSR spatial resolutions according to the method of [RD-134]

7.4.3. Methods

Data acquisition

LST data from SEVIRI and AATSR, produced by GlobTemperature, will be used. The area of interest will be West Africa (upper left coordinates 28.0°N, 27.0°W, lower right 3.0°N 26.0°E) as this area presents the optimal conditions for applying the triangle method. Particularly interesting is the Sahel region with semi-arid environments, a big sensitivity to drought spells as well as the availability of in situ soil moisture data in several sites.

In addition, optical data for computing vegetation indices required in the triangle method will be acquired. SEVIRI level 1.5 data (0.6, 0.8 and 1.6 µm) is systematically received at the UoC-EUMETCAST processing system. MERIS reduced resolution level 2 and AATSR data (1km) will be also acquired from the ESA's MERCI online servers. Finally SMOS reprocessed L2 SM will be downloaded from am EOLI-SA/Category 1 access, currently granted at U. Copenhagen.

In situ soil moisture data aimed for product validation will be utilized for currently operated sites in Senegal (U. Copenhagen), Namibia (KIT), and the AMMA supersites in Mali, Niger and Burkina Faso, the latest ones in collaboration with AGRHYMET thanks to a DANIDA (Denmark's development cooperation) funded project.

Satellite processing

In a first step, from the 15 minute SEVIRI LST, we will estimate the daily thermal inertia at SEVIRI scale as the morning temperature rise (δTs), expressed as the slope of the linear regression of all cloud-free LST observations between 6 and 12 UTC [RD-135]. The use of morning temperature rise (δTs) offers some advantages compared to absolute LST measurements; it offers more information than does the single observation of LST, and is less susceptible to systematic retrieval errors as it is a relative value. Thermal inertia measures the resistance of a material to changes in temperature [RD-136]. A dry soil will present a higher value of δTs than a dry soil [RD-137]. Finally, to ensure the quality of the δTs data, we will filter out the cases where the R^2 of the linear fit of the temperature rise was lower than a given threshold.

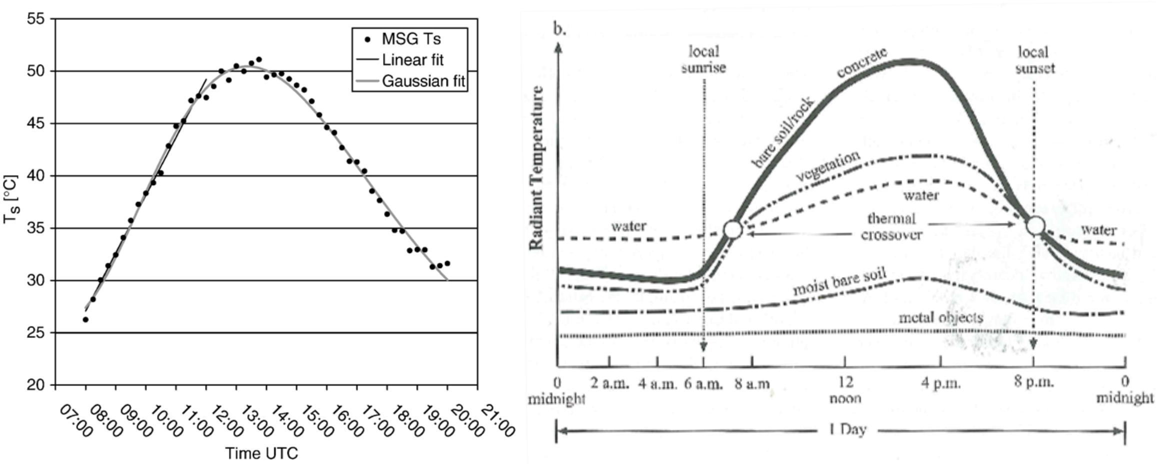


Figure 28: Left, the estimation of δTs with LST observations with SEVIRI [RD-135]. Right, daily trends of LST for different surfaces [RD-138]

Both real-time and archived optical data (since 2006 onwards) is corrected from atmospheric and BRDF effects at the UoC-EUMETCAST processing system. First, the 15-minute directional reflectances were atmospherically corrected using a modified version of the Simplified Method for Atmospheric Correction (SMAC) code [RD-139, RD-140]. As the atmospheric correction requires an estimate of the aerosol optical depth, water vapour, and ozone content, this information is fed into SMAC from the relevant MODIS atmosphere products on a daily basis (MOD08_D3/MYD08_D3). Then, a semi-empirical Bidirectional Reflectance Distribution Function (BRDF) model, inherited from the MODIS BRDF model [RD-141] is fitted using all daytime observations in a 4-days period [RD-142]. Modelled BRDF reflectances at local solar noon and observed at nadir were considered the NBAR and from those NDVI and SIWSI [RD-143] will be computed.

The Temperature Vegetation Dryness Index (TVDI) will be calculated from the thermal data and vegetation index data. The extension of the scene to be applied will be based on the conditions required for this method: it has to be large enough to represent a wide range of different soil moisture and vegetation fraction conditions, while small enough to ensure atmospheric forcing homogeneity. Additional mask might be applied to guarantee that the method is applied to both a topographically homogeneous area and to surfaces of similar aerodynamic roughness.

Once the triangles are calculated, results will be checked to remove those dates where the LST-VI triangle is not properly defined. This procedure is carried out using several different parameters extracted from the triangle calculation statistics. 1) The R^2 value of the dry edge fitting, selecting only those dates where the triangles in which this value is higher than a certain threshold. 2) The total number of pixels in the LST-VI window. 3) The number of points used to define the dry edge. 4) The range of the VI within the LST-VI window.

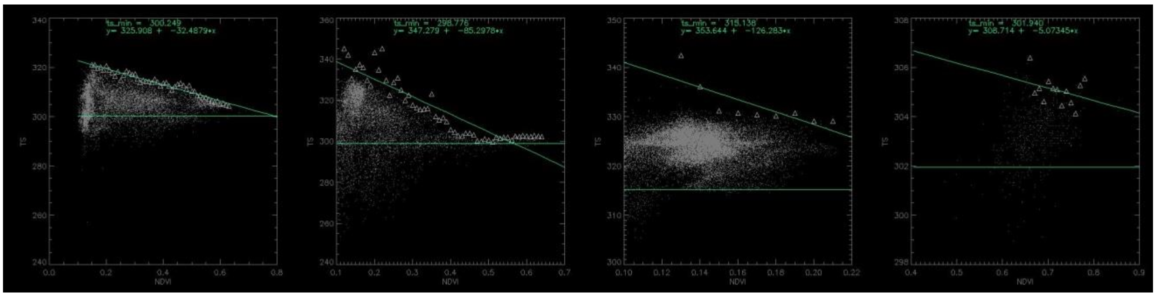


Figure 29: Shape of the LST-VI space, and estimated wet and dry edges (green lines) for different situations. White triangles represent the LST-VI pairs from where the dry edge has been estimated. Far left, ideal LST-VI space; middle-left, sub-optimal space due to noise in the dry edge definition (low R^2); images on the right side, non-valid LST-VI triangles caused by lack of enough points for the dry edge computation (middle -right) or in the LST-VI space (far-right).

Soil moisture downscaling

Based on [RD-134], the TVDI values from AATSR and SEVIRI will be used as proxy for soil evaporative efficiency (SEE) at high spatial resolution (1-4 km). The SMOS soil moisture will then be downscaled following [RD-134]

$$SM_{hi-res} = SM_{SMOS} + \frac{\partial SM_{mod}}{\partial SEE}\left(SEE_{hi-res} - \langle SEE_{hi-res}\rangle_{40km}\right)$$

Where SM_{hi-res} is the high-resolution (1-4 km) SM product, downscaled from the original SMOS data (SM_{SMOS}); $\frac{\partial SM_{mod}}{\partial SEE}$ is the partial derivative of the modeled soil model based on the soil evaporative efficiency (SEE), SEE_{hi-res} is the estimated SEE at high-resolution data, based on the TVDI, and $\langle SEE_{hi-res}\rangle_{40km}$ is its aggregated value at the SMOS scale.

Soil moisture validation

The soil moisture data will be validated with in-situ measurements. Firstly, spatio-temporal trends in TVDI values will be compared with soil moisture and rainfall data. Secondly, the SMOS SM and its downscaled product will be also validated with soil moisture measurements. Due to the linear downscaling approach, bias in SMOS SM will also be transferred to the downscaled product, nevertheless, it is expected a higher agreement of the downscaled SM than with the original SMOS resolution.

Soil and vegetation trends

Finally, changes of soil moisture will be related to vegetation dynamics by trend analysis of vegetation indices (NDVI and SIWSI) and remotely sensed Leaf Area Index. Changes in trends and seasonality will be assessed in the region over the longest time series available [RD-144]

7.5. UCS #5: Assimilation of LST in NWP

7.5.1. Objective and approach

The aim of this work package is to assess the impact of assimilation of land surface temperature (LST) retrievals from satellite observations within a land data assimilation scheme that is coupled to a numerical weather prediction model. The assessment will include both the impact on variables at the land surface (such as soil moisture and soil temperature), but also the key atmospheric forecast variables such as near surface temperature.

7.5.2. Expected results and impact

The anticipated outcome of this study will be an assessment of the quality of the LST observations from satellite through comparisons with in situ data and NWP forecasts of LST. Satellite LST observations will then be assimilated into the Met Office land data assimilation scheme and an assessment of the impact to both land surface analyses (soil moisture and temperature) and atmospheric forecasts will be made.

7.5.3. Work plan

Because of the recent improvements to both the modelling of the land surface and assimilation at the Met Office the source of the satellite data will need to be from a recent observing period. Consequently either the GlobTemperature near real time data will be used or Met Office derived LST observations from polar or geostationary platforms. It is anticipated that this work will be performed during 2015.

The work plan consists of the following packages:

1. Assessment of LST quality through comparisons with in situ and model forecasts. In situ data such as the radiometer at the Met Office Cardington site would be used and converted to an equivalent LST measurement. The GlobTemperature product will be validated against both the in situ data and against values of LST from the operational Met Office atmosphere model. The in situ data is a more accurate reference but the model data gives global coverage. The metrics examined will be standard error and bias. It is anticipated that the GlobTemperature product will contain quality flags and the impact of these flags on the comparisons will be examined. *Duration:* one month

   Outcome: a report showing the key results.

2. Adaption of existing current Met Office land DA scheme to ingest new satellite LST observations. This will include simple quality control informed from work package 1. The

current scheme is used operationally to initialise soil moisture and temperature for atmosphere models, using ASCAT soil moisture data alongside screen-level station observations of temperature and humidity. Work is needed to adapt the current software (in Fortran 2003) to ingest the GlobTemperature product, including mapping the product to forecast model gridpoints, thus ensuring uniform coverage.

It is expected there will be significant biases between GlobTemperature and the model LST fields over some surface types (e.g. desert) and so bias correction is likely to be required. This might need to be a function of both season and time of day. CDF matching (cumulative distribution function) is the preferred option for calculating the biases.

Duration: two months.

Outcome: Working software to ingest GlobTemperature data, perform QC and bias correct, meeting Met Office quality Standards, ready for use in a full NWP impact study.

3. Trials of assimilation of satellite LST within the Met Office Numerical Weather Prediction (NWP) system. A trial of the full NWP system of at least one month duration will be performed in which satellite derived LSTs are assimilated using the new software on top of the existing observations used within operational land data assimilation (screen observations, satellite derived soil moisture). The impact relative to the operational baseline will be assessed by examining the following metrics:

    - Comparisons of land surface analyses to in situ observations (such as soil temp and soil moisture).
    - Fit of existing observations to land analyses
    - Verification of atmospheric forecasts against observations, with emphasis on near surface variables over land such as 1.5 m temperature. The forecast lead time in this assessment will be from 1 to 5 days.

    Duration: two months

    Outcome: a comprehensive report examining the results of the assimilation trial.

7.5.4. Expected value

The outcome of this study will be an assessment of the impact of satellite LST within an NWP system and recommendations for the operational use of such data. At operational NWP centres the use of land measurements has focused up to now on soil moisture and this study will be an important step forward in the use of satellite derived data. The results found here will equally be applicable to reanalysis work and will help to inform use of satellite data in projects such as the EURO4M – EURRA reanalysis (of which the Met Office is a partner).

8. GlobTemperature Product Objectives

8.1. Dataset Availability

Table 37 details the GlobTemperature output products to be made available to the user community via the GlobTemperature Data Portal. Dissemination plans are provided in Table 12, and access information is provided in Section 6.1.3.

Addresses user feedback ***GT-UF-11****: Provide high quality LST data from polar-orbiting satellites with near daily global coverage spanning multiple years*

Once a dataset is released to the user community via the Data Portal evolution of the algorithm and further re-processing will be carefully managed. A minimum period of three months will be enforced between releases. The demand for a re-processed release will be governed both by user feedback, including detailed application within the User Case Studies, and any issues as identified by the ongoing Validation and Intercomparison activities. In reality it is not foreseen that progressive releases of the same dataset will occur at such a high frequency as quarterly (**addresses requirement REQ-14-TR**).

GT-TS-42*: Comply with minimum agreed period between releases of re-processed datasets*

Users will be updated via email on release of new and re-processed datasets.

GT-TS-43*: Update users on GlobTemperature Mailing List whenever new or re-processed data becomes available on the Data Portal*

For current satellite data sources the timeliness of new observations will be 7 days once the final version of the given dataset has been released to the Data Portal for user dissemination (see Table 37).

It is the intention of the Project consortium to support the Data Portal post-project. The nature of this support is maintenance of the Data Portal architecture and functionality, and provision of existing data products. There is a strong user requirement to keep products current on the Data Portal and to add new products, which is beyond the current scope of the Project, but where feasible (further funding, follow-on work, or other projects allow for this) such products can be updated.

Addresses user feedback ***GT-UF-3****: Provide ongoing support, where feasible, in the provision of LST products for mission continuity*

Table 37: Projected dataset availability for the suite of GlobTemperature products to be delivered via the Data Portal

Product	Version	Data specifics	Availability	Archive	Format
AATSR	1.0	2002 – 2012	M09	GlobTemperature	Harmonised
ATSR-2	1.0	1995 – 2003	M12	GlobTemperature	Harmonised
ATSR-1	1.0	1991 – 1997	M24	GlobTemperature	Harmonised
AMSR-E	1.0	1-year (2008, 2009 or 2010)	M24	GlobTemperature	Harmonised
	2.0	2008 – 2010	M36		
ArcLake	1.0	1991 – 2011	M12	External	NetCDF-4 external format
GOES	1.0	2009 onwards	M36	GlobTemperature	Harmonised
Metop-AVHRR	1.0	2012 – 2013 (depending on implementation of LandSAF processing chain may need to process at UK-CEMS)	M24	GlobTemperature	Harmonised
	2.0	2007 onwards	M36		
GlobTemperature MODIS	1.0	2000 - 2014 (Terra)	M24	GlobTemperature	Harmonised
	2.0	2015 onwards (Terra – if available) 2002 onwards (Aqua)	M36		
MTSAT	1.0	2010 onwards	M36	GlobTemperature	Harmonised
SEVIRI	1.0	2012 – 2013	M09	GlobTemperature	Harmonised
	2.0	2010 – 2011	M12		
	3.0	2003 – 2009	M24		
	4.0	2014 onwards	M36		
SLSTR	1.0	2016 onwards (if data available)	M36	GlobTemperature	Harmonised
SSM/I	1.0	2003	M09	GlobTemperature	Harmonised
(A)ATSR CDR	1.0	1995 – 2012 (Prototype)	M12	GlobTemperature	Harmonised

Product	Version	Data specifics	Availability	Archive	Format
	2.0	1991 – 2012	M24		
Metop-AVHRR IST	1.0	2007 onwards	M36	GlobTemperature	Harmonised
Matchup DB	1.0	For datasets available at M12	M12	GlobTemperature	Harmonised
	2.0	For datasets available at M24	M24		
	3.0	For datasets available at M36	M36		
Merged LST	1.0	Tier 1 merged GEO/LEO Prototype (not gap filled): 1-year (2010, 2011 or 2012) Tier 2 merged LEO: 1-year (2010, 2011, or 2012) + 2003 Tier 2 merged GEO: 1-year (2010, 2011 or 2012)	M12	GlobTemperature	Harmonised
	2.0	Tier 1 merged GEO/LEO LST: 2010 – 2014 Tier-1 merged LEO: 2003 - 2009 Tier 2 merged GEO: 2010 – 2014	M24		
	3.0	Tier 1 merged GEO/LEO: 2010 – 2014 Tier-1 merged LEO: 2003 – 2009 Continental GEO tiles: 2003 - 2009 NRT demonstration	M36		

Product	Version	Data specifics	Availability	Archive	Format
		product			
MODIS MOD21 / MYD21	B-version	Select test scenes / periods	M09	External	HDF-EOS external format
	1.0	2000 onwards	M24		
VIIRS (standard EDR)	1.0	2012 onwards	M36	External	HDF-5 external format
ASTER Global Emissivity Database	1.0	Seasonal climatology database	M09	External	HDF-5 external format

8.2. Publications

Each version of the Technical Specifications will include a list of publications directly related to the work carried out under the framework of the GlobTemperature Project. It is expected that each User Case Study will generate publishable material in addition to an overall publication on the Project itself. Additional publications will also be encouraged; it is expected that each scientific Work Package in this project will produce at least one such publication. The publication of results in international peer-reviewed journals will be the responsibility of the lead Project Partner for each activity. Each publication will explicitly acknowledge the support of the ESA DUE GlobTemperature project. Table 38 provides a list of cumulative GlobTemperature publications which will be maintained throughout the Project.

Table 38: Cumulative list of GlobTemperature publications

Title	WP	Authors	Date	Journal
Advancing the AATSR land surface temperature retrieval with higher resolution auxiliary datasets: Part A - product specification	3.2	Ghent, Remedios et al		In preparation
Advancing the AATSR land surface temperature retrieval with higher resolution auxiliary datasets: Part B - validation	3.2	Ghent, Remedios, Göttsche, Olesen et al		In Preparation

8.3. Users

A high level vision of the GlobTemperature objectives to meet the user needs can be defined as follow:

- To promote the uptake of LST data by the user community
- To ensure all data disseminated by the GlobTemperature project is consistently documented
- To supply users with LST data from all major datasets with consistently generated uncertainty budgets
- To provide the first global LST dataset which resolves the diurnal cycle
- To provide the first long-term LST dataset of climate quality
- To challenge the LST developer community to confront the user demand for better cloud clearing
- To challenge the next generation of satellite LST products to better meet the requirements of the users
- To engage with the user community and respond to feedback

Specifically, detailed user input into the specifications of the GlobTemperature Products; user involvement in testing the data (particularly through both the User Case Studies, and the Champion User setup); and a core programme in building the LST community globally, involving both data producers and users, through association with the EarthTemp network and the GlobTemperature UCMs will achieve a coherence and openness in facilitating the use of satellite LST data.

Provision of products which meet the needs of the user community is thus the very core of the GlobTemperature Project. As evident in the Baseline Requirements Document users of LST data are from a broad spectrum of disciplines, and vary in their capacity both to identify and access available datasets and to handle varied data formats. Guidance is frequently required by users of LST data about the suitability of different datasets for different applications, together with quantification as to why individual datasets differ amongst themselves. The agreed common nomenclature (Section 2.1) for uncertainty and accuracy needs to be disseminated to the users so they are able to compare different datasets with knowledge that these are consistent in their information. The objective is to provide comprehensive user-friendly to support to the user community, and where necessary to educate the user community in the optimum exploitation of satellite LST / IST and LSWT products. This will be achieved via a mixture of personal communication via email / phone, information provided via the Website, GlobTemperature Newsletters [AD-4], peer-reviewed publications, GlobTemperature reports for public dissemination, conference / workshop presentations, and UCMs. A schematic of the communication lines with the user community is shown in Figure 30.

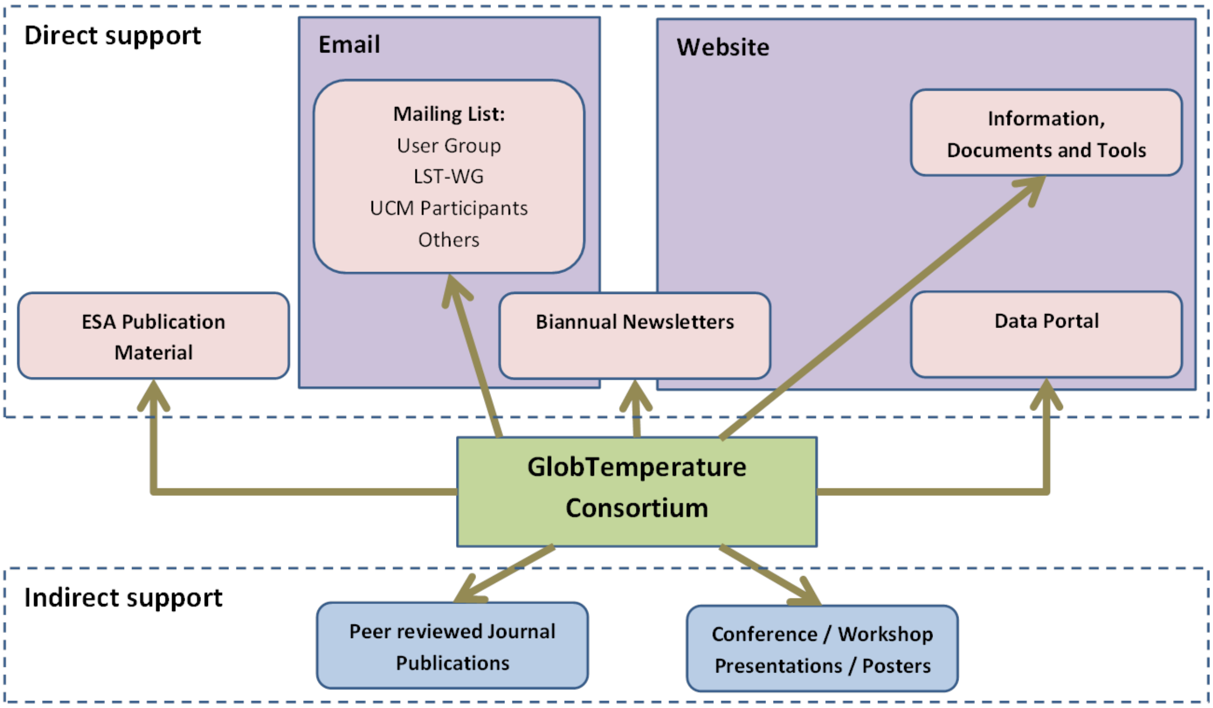


Figure 30: Schematic of the lines of communication with the user community.

GT-TS-44: *Provide multiple information pathways to ensure users are kept updated on GlobTemperature news and events: Website, email, newsletters, publications, conference / workshop presentations and posters*

The strategy for user support also includes a commitment to sustained operation of GlobTemperature from all consortium members beyond the lifetime of the project; and particularly, from ACRI-ST who host the Website and Data Portal, the University of Leicester who lead the project, and IPMA who operate the NRT LST services of the LandSAF for EUMETSAT.

Ongoing communication with the users is also a crucial activity for the consortium. The GlobTemperature User Mailing List is constantly evolving and regular emails are sent out to the users informing them of upcoming events, GlobTemperature news, Website and Data Portal developments such as the availability datasets and their documentation, which is also supplemented for "Champion Users" with more personal email updates. This intensive level of communication with the users will continue throughout the Project lifetime and beyond, where for example notification of the availability of new datasets / re-processing of existing datasets will be announced in a timely manner (**addresses requirement REQ-15-TR**). The full GlobTemperature User Mailing List is available to all Project Partners via the GlobTemperature Website. Statistics on individual user exploitation of the datasets on the Data Portal will be maintained as will the User Registrations on the Website and Data Portal with additional information on other interactions logged in the mailing list, such as attendance at User Consultation Meetings, participation in the User Requirements Survey. Such level of detail, whereby types of users are categorised, is required to enable a more tailored approach to interacting with the user community.

GT-TS-45*: Maintain the GlobTemperature Mailing List through Project networking and Website / Data Portal registrations*

GT-TS-46*: Maintain statistics on Website / Data Portal access and downloads*

8.4. International Contacts and Conferences

Building partnerships across the community will be very important, and much of this networking will be done within the framework of the ILSTE-WG:

- A key element of the ILSTE-WG work will be to build partnerships with international bodies (e.g. WMO, CEOS, IPCC), scientific programmes (e.g. GCOS, GEWEX, GEOSS), and user agencies (e.g. meteorological offices, environment agencies) to harmonise international efforts and advance LST science and applications

- Specific activities will be needed to work with GCOS to promote the case for LST & E to be classified as an Essential Climate Variable (ECV), with CEOS to promote virtual constellations for LST and standardised data protocols, and with GEO to build new user communities.

- The ILSTE-WG will need to link to other international groups in technical practice, such as CEOS and its Land Product Validation (LPV) working group.

- The ILSTE-WG will need to link to existing networks such as the EarthTemp network; alignment of meetings is already planned.

- The ILSTE-WG will manage Technical Advisory Groups to support the development and use of satellite LST information, to promote scientific insight and innovation, to identify best-practices, and to facilitate the transfer of new science into user's applications. These groups will seek to develop partnerships with international bodies identified above.

The ILSTE-WG in particular will cement relationships with the external activities / agencies listed in Table 39; but, also members of the GlobTemperature Project Team will also play key individual roles in fostering formal links with these entities.

Table 39: International external contacts

Title	Reference	Rationale
EUMETSAT's Land SAF	[RD-145]	EUMETSAT's LandSAF includes the operational production of SEVIRI LST
MyOcean project	[RD-146]	The primary collaboration is in sea ice temperatures
GCOS	[RD-147]	The Global Climate Observing System coordinates global efforts to provide long-term comprehensive observations for monitoring of climate. GCOS Essential Climate Variables (ECVs) are required to support the work of the UNFCCC and

Title	Reference	Rationale
		the IPCC. Although LST is not identified as an independent ECV, the work on the LST CDR and use of LST as a secondary ECV need to feed into GCOS.
GloboLakes	[RD-148]	The GloboLakes project extends the ARC-Lake LSWT database, including quantifying retrieval uncertainty and applying retrieval methods to other sensors.
ISCCP	[RD-149]	ISCCP provides almost 30 years of global land surface temperature data from a combinations of polar and geostationary satellites.
CEOS-LPV	[RD-150]	The CEOS Land Product Validation sub-group on LST and Emissivity aims to guide the community on validation protocols and working with users to define validation objectives.
EarthTemp Network	[RD-151]	The EarthTemp network aims to encourage and improve quantification and scientific understanding of surface temperature from meteorological stations and Earth Observation through sharing of knowledge and data.
GHRSST	[RD-152]	The Group for High Resolution Sea Surface Temperatures coordinates the provision of state-of-the-art global high-resolution SST products to the operational oceanographic, meteorological, and climate communities.
ESA Data User Element Projects	[RD-153]	The Data User Element (DUE) is a programmatic component of the Earth Observation Envelope Programme (EOEP), with a mission is to favour the establishment of a long-term relationship between the User communities and Earth Observation
ESA Climate Change Initiative Projects	[RD-154]	Common theme of cloud detection being investigated with Cloud-CCI and Aerosol-CCI groups, with objective of their participation in Cloud Clearing Round Robin
AVHRR Polar Pathfinder	[RD-155]	The development of the long time series of AVHRR datasets will provide guidance particularly on the development of the GlobTemperature Climate Data Record
MODIS Snow/Ice Project	[RD-156]	This project provides sea-ice and ice sheet surface temperature from MODIS.
Sentinel-3 Validation Team	[RD-157]	The Sentinel-3 Validation Team has an LST component in the Land sub-group.

Title	Reference	Rationale
IPCC	[RD-158]	The Intergovernmental Panel on Climate Change (IPCC) is the leading international body for the assessment of climate change. Creation of a LST Climate Data Record designed to satisfy the GCOS climate observation requirements for LST would be relevant.
WMO	[RD-159]	The WMO's Space Programme aims to promote availability and utilization of satellite data and products for weather, climate, water and related applications. The open provision of global multi-sensor LST data via the GlobTemperature Data Portal in harmonised format is in accordance with this aim.
GEWEX	[RD-160]	The Global Energy and Water Cycle Exchanges Project (GEWEX) is an integrated program of research, observations, and science activities that focuses on the atmospheric, terrestrial, radiative, hydrological, coupled processes, and interactions that determine the global and regional hydrological cycle, radiation and energy transitions, and their involvement in climate change
GEOSS	[RD-161]	The Group on Earth Observations (GEO) is coordinating efforts to build a Global Earth Observation System of Systems (GEOSS).
Eumetsat Ocean and Sea Ice SAF	[RD-162]	The Ocean and Sea Ice Satellite Application Facility (OSI SAF) manages the common requirements of meteorology and oceanography for a comprehensive information on the ocean-atmosphere interface
NOAA-NCDC	[RD-163]	NOAA are responsible for data archiving and dissemination of VIIRS Land Surface Temperature standard EDR.

The ILSTE-WG will also be a key guiding hand facilitating improved communications with the LST data providers and the user community (Figure 31).

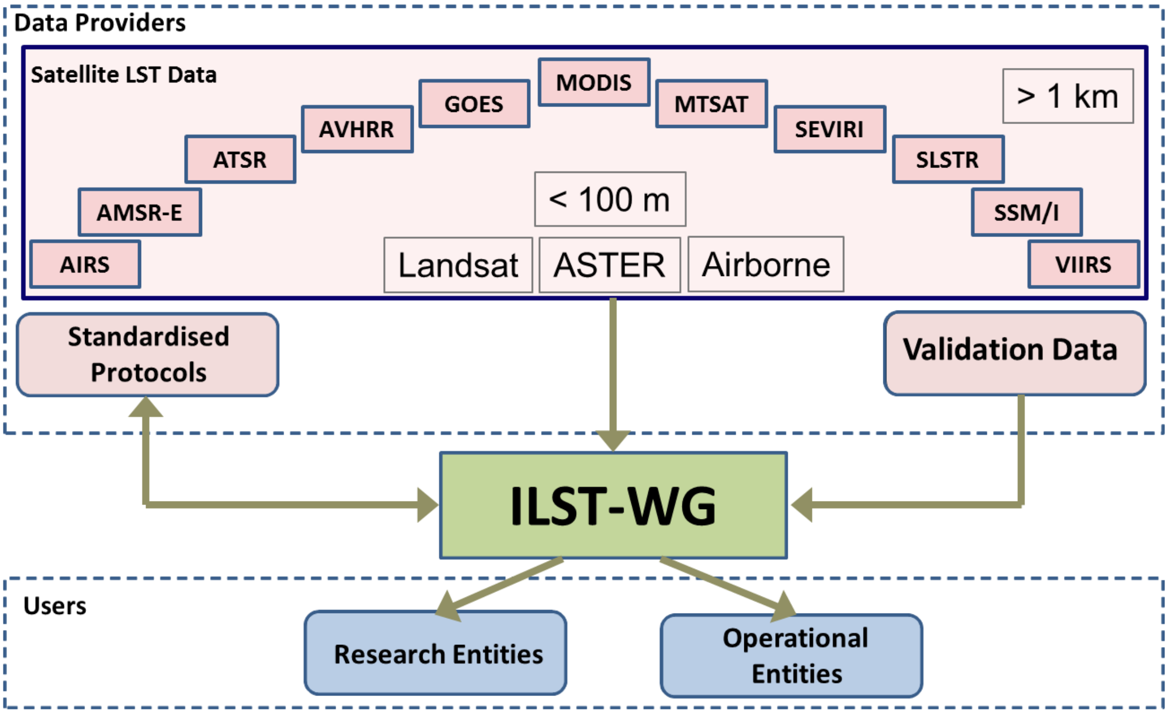


Figure 31: Position of the International LST Working Group as the forum for improved communications between the LST data providers and user community

Conferences and workshops are an important forum for dissemination of user information through presentations to a wider audience. A presentation pack is available on the GlobTemperature Website as a resource for Project Partners to utilise when preparing conference / workshop presentations. It is anticipated that each Work Package will result in at least one presentation at a conference. Table 40 shows a cumulative list of GlobTemperature presentation delivered at such events. Table 41 shows a list of potential events identified as pertinent for the dissemination of ongoing GlobTemperature information and results to the wider scientific audience.

Table 40: Cumulative list of GlobTemperature presentations.

Title	WP	Speaker	Date	Event
A framework for global diurnally-resolved observations of Land Surface Temperature	6	D. Ghent, ULeic	12-Dec-13	AGU 2013
Validation of Land Surface Temperature products in arid climate regions with permanent in-situ	4	F. Goettsche, KIT	12-Dec-13	AGU 2013
Application of a Land Surface Temperature Validation Protocol	4	D. Ghent, ULeic	29-Jan-14	LPVE

Title	WP	Speaker	Date	Event
to AATSR data				
ESA DUE GlobTemperature	All	D. Ghent, ULeic	29-Apr-14	EGU 2014
A framework for global diurnally-resolved observations of Land Surface Temperature	6	D. Ghent, ULeic	29-Apr-14	EGU 2014

Table 41: Currently identified events for potential GlobTemperature presentations.

Event	Location	Date(s)
RAQRS (4th International Symposium on Recent Advances in Quantitative Remote Sensing)	Valencia	Sep-14
The Climate Symposium	Darmstadt	Oct-14
AGU	San Francisco	Dec-14, Dec-15, Dec-16
EGU	Vienna	Apr-15, Apr-16

8.5. Technical Specifications and GlobTemperature Deliverables

The technical specifications presented in detail in this document can summarised and enumerated (Table 42) to provide traceability from the enumerated User Requirements (The User **Requirements defined from the results of the User Survey have been augmented with updates following mini-questionnaires carried out during breakout sessions.**

Table 4 and Table 6) through to the GlobTemperature deliverables (Table 43).

Table 42: Enumerated Technical Specifications for the GlobTemperature Project linking to the User Requirements and Deliverables. Updates are highlighted in red.

Technical Specification Number	Description	Relevant User Requirement Numbers	Relevant Deliverables
GT-TS-1	Provide definitions of physical nomenclature available for public dissemination	REQ-28-TR	DEL-10 DEL-25 DEL-28
GT-TS-2	Organise and chair an international committee to provide an independent source of advice and appraisal for GlobTemperature (and related	REQ-28-TR	DEL-14

Technical Specification Number	Description	Relevant User Requirement Numbers	Relevant Deliverables
	projects), and to act as a forum for user / expert interaction		DEL-15 DEL16 DEL-28
GT-TS-3	The basis for the GlobTemperature harmonised formats will be CF-compliant netCDF-4 with individual file sizes < 200 Mb	REQ-16-TR REQ-34-TR	DEL-09
GT-TS-4	Ensure User Requirements are updated with feedback from the International LST & E Working Group (ILSTE-WG) and the User Consultation Meetings (UCMs)	REQ-39-TR	DEL-05 DEL-20 DEL-21
GT-TS-5	Provide Level-2 single-sensor datasets in harmonised format	REQ-1-TR REQ-3-TR REQ-5-TR REQ-6-TR REQ-8-TR REQ-22-TR REQ-27-TR REQ-34-TR REQ-40-TR	DEL-09
GT-TS-6	Provide Level-3 and Level-4 datasets in harmonised format to be disseminated as 10° x 10° tiles	REQ-2-TR REQ-3-TR REQ-8-TR REQ-16-TR REQ-21-TR REQ-22-TR REQ-27-TR REQ-34-TR	DEL-09

Technical Specification Number	Description	Relevant User Requirement Numbers	Relevant Deliverables
		REQ-40-TR REQ-44-TR	
GT-TS-7	Provide single-sensor GEO datasets at temporal resolutions of 1-hour or less	REQ-21-TR REQ-22-TR REQ-23-TR REQ-25-TR REQ-26-TR REQ-2-BR	DEL-09
GT-TS-8	Provide links from the Data Portal to external data centres, including information on metadata, for datasets not directly disseminated by GlobTemperature	REQ-19-TR REQ-37-TR REQ-1-BR	DEL-04
GT-TS-9	Primary (Tier-1) merged LST datasets to be gap-filled	REQ-21-TR REQ-22-TR REQ-23-TR REQ-27-TR REQ-36-TR REQ-40-TR REQ-41-TR	DEL-17 DEL-29
GT-TS-10	Standard spatial resolution of Level-3 and -4 datasets to be 0.05° unless designated otherwise	REQ-17-TR REQ-22-TR REQ-23-TR	DEL-09 DEL-17 DEL-29
GT-TS-11	Standard temporal resolution of primary (Tier-1) merged LST datasets to be 3-hourly	REQ-18-TR REQ-25-TR REQ-2-BR	DEL-17 DEL-29
GT-TS-12	Secondary (Tier-2) merged LST datasets to not be	REQ-21-TR	DEL-17

Technical Specification Number	Description	Relevant User Requirement Numbers	Relevant Deliverables
	gap-filled, with priority of 10-year datasets	REQ-22-TR REQ-23-TR REQ-27-TR REQ-36-TR REQ-40-TR REQ-41-TR	DEL-29
GT-TS-13	Secondary (Tier-2) continental tiles to be gap-filled	REQ-21-TR REQ-22-TR REQ-23-TR REQ-41-TR	DEL-17 DEL-29
GT-TS-14	Develop Climate Data Record of over 10-years for (A)ATSR in harmonised format with low bias, high precision, and high stability. Targets: 1.0 K, 1.0 K and 0.3 K respectively	REQ-3-TR REQ-5-TR REQ-6-TR REQ-7-TR REQ-22-TR REQ-23-TR REQ-27-TR REQ-40-TR REQ-3-BR REQ-4-BR REQ-5-BR	DEL-08 DEL-18 DEL-24 DEL-32
GT-TS-15	Determine the optimal cloud clearing methods over land for LST retrieval	REQ-8-TR	DEL-19 DEL-22 DEL-24 DEL-32

Technical Specification Number	Description	Relevant User Requirement Numbers	Relevant Deliverables
			DEL-33 DEL-34
GT-TS-16	Provide input satellite datasets for GlobTemperature Matchup Database (GT_MDB) in harmonised format	REQ-16-TR REQ-34-TR	DEL-09
GT-TS-17	Provide in situ matchup datasets for GlobTemperature Matchup Database (GT_MDB) in harmonised format	REQ-16-TR REQ-34-TR	DEL-09
GT-TS-18	Provide validation and intercomparison matchup datasets derived according to a consistent protocol	REQ-31-TR REQ-35-TR	DEL-12 DEL-13
GT-TS-19	Provide satellite vs. satellite matchup datasets for GlobTemperature Matchup Database (GT_MDB) in harmonised format	REQ-16-TR REQ-34-TR	DEL-09
GT-TS-20	Provide NRT merged LST demonstration product with standard timeliness of less than 24 hours (target 99% coverage); maximum timeliness to be no more than 48 hours; target to be 12 hours	REQ-12a-TR REQ-13-TR	DEL-29
GT-TS-21	Validate the LST uncertainty estimates provided in the harmonised datafiles	REQ-35-TR	DEL-12 DEL-13
GT-TS-22	Ensure quality of GlobTemperature datasets through comprehensive validation, intercomparison, and user evaluation	REQ-35-TR REQ-38-TR REQ-39-TR	DEL-12 DEL-13 DEL-28 DEL-30 DEL-31
GT-TS-23	Data Portal to provide visualisation tools and statistics for LST data, LST anomalies, validation information and intercomparison data	REQ-31-TR REQ-38-TR REQ-39-TR	DEL-04 DEL-26
GT-TS-24	Provide information and documentation, including news and events, to the users via the	REQ-20-TR	DEL-04

Technical Specification Number	Description	Relevant User Requirement Numbers	Relevant Deliverables
	GlobTemperature Website		
GT-TS-25	Data portal to provide information page on metadata, and links to validation reports and Products User Guide (PUG) for each disseminated dataset	REQ-20-TR REQ-37-TR REQ-38-TR	DEL-04 DEL-11
GT-TS-26	Ensure straightforward user access to the GlobTemperature Website and Data Portal with minimal required information for registration	REQ-38-TR	DEL-04
GT-TS-27	Provide access to data archived and disseminated by GlobTemperature via FTP client, command line utilities, and interactive web browser	REQ-11-TR REQ-37-TR REQ-38-TR REQ-39-TR	DEL-04
GT-TS-28	Develop platform independent tools for reading and sub-setting datasets provided in the harmonised formats, and cloud filtered time series extraction	REQ-39-TR	DEL-27
GT-TS-29	Evaluate retrieval methods for optimisation of the LST products from Sentinel-3	REQ-40-TR	DEL-23 DEL-35 DEL-36
GT-TS-30	All harmonised formats to adhere to common metadata compliant with CF conventions	REQ-16-TR REQ-34-TR	DEL-09
GT-TS-31	As default datafiles to be disseminated with mandatory variables only. User functionality to be provided to allow selection of optional variables from auxiliary datafiles	REQ-9-TR REQ-10-TR REQ-32-TR REQ-33-TR	DEL-04 DEL-09
GT-TS-32	Provide ancillary information as optional to users and be stored in auxiliary datafiles	REQ-9-TR REQ-10-TR REQ-32-TR	DEL-09

Technical Specification Number	Description	Relevant User Requirement Numbers	Relevant Deliverables
		REQ-33-TR	
GT-TS-33	Provide uncertainty information per pixel for Level-2 data and per grid cell for Level-3 data as mandatory	REQ-4-TR REQ-29-TR	DEL-09
GT-TS-34	Provide cloud flags in Level-2 harmonised format and information on number of cloud affected pixels in Level-3 harmonised format	REQ-8-TR	DEL-09
GT-TS-35	Where information is available provide full uncertainty breakdown for Level-2, -3 and -4 data in a consistent manner	REQ-29-TR	DEL-09
GT-TS-36	Where available provide ancillary data in harmonised format datafiles: meteorological data, emissivity, land cover classification, fractional vegetation cover, NDVI and albedo	REQ-9-TR REQ-32-TR REQ-33-TR	DEL-09
GT-TS-37	All datafiles in harmonised format to be compressed at highest level (9), with `float` variables scaled to `short` where designated and geolocation data stored to 4 decimal places	REQ-10-TR REQ-34-TR	DEL-09
GT-TS-38	Provide flags on the data quality in the harmonised format datafiles	REQ-31-TR	DEL-09
GT-TS-39	Standard temporal resolution of Level-3 datasets to be day / night	REQ-2-TR REQ-24-TR	DEL-09
GT-TS-40	Provide high-latitude only (polar) datasets in equal-area projection	REQ-23-TR	DEL-09
GT-TS-41	Provide all harmonised format datafiles according to a common file naming convention	REQ-16-TR	DEL-09
GT-TS-42	Comply with minimum agreed period between releases of re-processed datasets	REQ-14-TR	DEL-04
GT-TS-43	Update users on GlobTemperature Mailing List whenever new or re-processed data becomes available on the Data Portal	REQ-14-TR REQ-15-TR	DEL-04 DEL-38
GT-TS-44	Provide multiple information pathways to ensure users are kept updated on GlobTemperature	REQ-15-TR	DEL-38

Technical Specification Number	Description	Relevant User Requirement Numbers	Relevant Deliverables
	news and events: Website, email, newsletters, publications, conference / workshop presentations and posters		
GT-TS-45	Maintain the GlobTemperature Mailing List through Project networking and Website / Data Portal registrations	REQ-15-TR	DEL-04 DEL-38
GT-TS-46	Maintain statistics on Website / Data Portal access and downloads	REQ-15-TR	DEL-04
GT-TS-47	Provide single-sensor datasets of minimum length 10-years with a target of 30-years where new observations have a target timeliness of 1 month	REQ-3-TR REQ-12b-TR	DEL-09
GT-TS-48	Provide a data repository for users to share tools within the community	REQ-42-TR	DEL-04 DEL-27
GT-TS-49	Provide a Data Portal tool to screen data as a function of cloud cover prior to download	REQ-43-TR	DEL-04 DEL-27

The Technical Specification and User Requirements can be linked to relevant GlobTemperature Deliverables. Internal management deliverables are not linked since they do not relate specifically to the enumerated User Requirements or Technical Specifications, but are listed for completeness.

Table 43: GlobTemperature Project Deliverables linking to the Technical Specifications and the User Requirements. Update are highlighted in red.

Deliverable	Description	Relevant Technical Specification Numbers	Relevant User Requirement Numbers
DEL-01	Project Management Plan	N/A	N/A
DEL-02	Monthly Report	N/A	N/A
DEL-03	Actions database	N/A	N/A
DEL-04	GlobTemperature web portal	GT-TS-8 GT-TS-23	REQ-9-TR REQ-10-TR

Deliverable	Description	Relevant Technical Specification Numbers	Relevant User Requirement Numbers
		GT-TS-24 GT-TS-25 GT-TS-26 GT-TS-27 GT-TS-31 GT-TS-42 GT-TS-43 GT-TS-45 GT-TS-46 GT-TS-48 GT-TS-49	REQ-11-TR REQ-14-TR REQ-15-TR REQ-19-TR REQ-20-TR REQ-31-TR REQ-32-TR REQ-33-TR REQ-37-TR REQ-38-TR REQ-39-TR REQ-42-TR REQ-43-TR REQ-1-BR
DEL-05	Requirements Baseline Document	GT-TS-4	REQ-39-TR
DEL-06	Technical Specification Document	ALL	ALL
DEL-07	GlobTemperature Newsletters, including annual reporting on the LST-WG activities.	GT-TS-44	REQ-15-TR
DEL-08	LST CDR Algorithm Trade-Off Analysis	GT-TS-14	REQ-3-TR REQ-5-TR REQ-6-TR REQ-7-TR REQ-22-TR REQ-23-TR REQ-27-TR

Deliverable	Description	Relevant Technical Specification Numbers	Relevant User Requirement Numbers
			REQ-40-TR REQ-3-BR REQ-4-BR REQ-5-BR
DEL-09	Satellite LST data sets in harmonised format	GT-TS-3 GT-TS-5 GT-TS-6 GT-TS-7 GT-TS-10 GT-TS-16 GT-TS-17 GT-TS-19 GT-TS-30 GT-TS-31 GT-TS-32 GT-TS-33 GT-TS-34 GT-TS-35 GT-TS-36 GT-TS-37 GT-TS-38 GT-TS-39 GT-TS-40 GT-TS-41	REQ-1-TR REQ-2-TR REQ-3-TR REQ-4-TR REQ-5-TR REQ-6-TR REQ-8-TR REQ-9-TR REQ-10-TR REQ-12b-TR REQ-16-TR REQ-17-TR REQ-21-TR REQ-22-TR REQ-23-TR REQ-24-TR REQ-25-TR REQ-26-TR REQ-27-TR REQ-29-TR

Deliverable	Description	Relevant Technical Specification Numbers	Relevant User Requirement Numbers
		GT-TS-47	REQ-31-TR REQ-32-TR REQ-33-TR REQ-34-TR REQ-40-TR REQ-44-TR REQ-2-BR
DEL-10	Technical Note - Definition of a common nomenclature for LST	GT-TS-1	REQ-28-TR
DEL-11	Product User Guide	GT-TS-25	REQ-20-TR REQ-37-TR REQ-38-TR
DEL-12	Satellite LST Validation Report	GT-TS-18 GT-TS-21 GT-TS-22	REQ-31-TR REQ-35-TR REQ-38-TR REQ-39-TR
DEL-13	Satellite LST Intercomparison Report	GT-TS-18 GT-TS-21 GT-TS-22	REQ-31-TR REQ-35-TR REQ-38-TR REQ-39-TR
DEL-14	LST-WG Terms of Reference	GT-TS-2	REQ-28-TR
DEL-15	LST-WG Implementation Plan	GT-TS-2	REQ-28-TR
DEL-16	LST-WG Progress Report	GT-TS-2 GT-TS-4	REQ-28-TR REQ-39-TR
DEL-17	Merged LST Product Prototype	GT-TS-9	REQ-17-TR

Deliverable	Description	Relevant Technical Specification Numbers	Relevant User Requirement Numbers
		GT-TS-10 GT-TS-11 GT-TS-12 GT-TS-13	REQ-18-TR REQ-21-TR REQ-22-TR REQ-23-TR REQ-25-TR REQ-27-TR REQ-36-TR REQ-40-TR REQ-41-TR REQ-2-BR
DEL-18	Prototype (A)ATSR LST CDR data set	GT-TS-14	REQ-3-TR REQ-5-TR REQ-6-TR REQ-7-TR REQ-22-TR REQ-23-TR REQ-27-TR REQ-40-TR REQ-3-BR REQ-4-BR REQ-5-BR
DEL-19	AATSR Cloud Clearing Round Robin Protocol	GT-TS-15	REQ-8-TR
DEL-20	UCM Report	GT-TS-4	REQ-39-TR
DEL-21	Annual User Assessment Report	GT-TS-4	REQ-39-TR

Deliverable	Description	Relevant Technical Specification Numbers	Relevant User Requirement Numbers
DEL-22	AATSR Cloud Clearing Round Robin Data Package	GT-TS-15	REQ-8-TR
DEL-23	Sentinel LST Product Development Plan	GT-TS-29	REQ-40-TR
DEL-24	Full (A)ATSR LST CDR data set	GT-TS-14 GT-TS-15	REQ-3-TR REQ-5-TR REQ-6-TR REQ-7-TR REQ-8-TR REQ-22-TR REQ-23-TR REQ-27-TR REQ-40-TR REQ-3-BR REQ-4-BR REQ-5-BR
DEL-25	LST Handbook	GT-TS-1	REQ-28-TR
DEL-26	Online LST data analysis tools	GT-TS-23	REQ-31-TR REQ-38-TR REQ-39-TR
DEL-27	Downloadable LST tools	GT-TS-28 GT-TS-48 GT-TS-49	REQ-39-TR REQ-42-TR REQ-43-TR
DEL-28	White Paper on Satellite LST	GT-TS-1 GT-TS-2 GT-TS-22	REQ-28-TR REQ-35-TR REQ-38-TR

Deliverable	Description	Relevant Technical Specification Numbers	Relevant User Requirement Numbers
			REQ-39-TR
DEL-29	Merged LST Product	GT-TS-9 GT-TS-10 GT-TS-11 GT-TS-12 GT-TS-13 GT-TS-20	REQ-12a-TR REQ-13-TR REQ-17-TR REQ-18-TR REQ-21-TR REQ-22-TR REQ-23-TR REQ-25-TR REQ-27-TR REQ-36-TR REQ-40-TR REQ-41-TR REQ-2-BR
DEL-30	User Case Study Final Reports	GT-TS-22	REQ-35-TR REQ-38-TR REQ-39-TR
DEL-31	User Case Study paper submissions to peer reviewed scientific journals	GT-TS-22	REQ-35-TR REQ-38-TR REQ-39-TR
DEL-32	Technical Note on the Development of a Multi-Sensor LST CDR	GT-TS-14 GT-TS-15	REQ-3-TR REQ-5-TR REQ-6-TR REQ-7-TR

Deliverable	Description	Relevant Technical Specification Numbers	Relevant User Requirement Numbers
			REQ-8-TR REQ-22-TR REQ-23-TR REQ-27-TR REQ-40-TR REQ-3-BR REQ-4-BR REQ-5-BR
DEL-33	AATSR Cloud Clearing Round Robin Report	GT-TS-15	REQ-8-TR
DEL-34	AATSR Cloud Clearing Round Robin – paper submission to a scientific journal	GT-TS-15	REQ-8-TR
DEL-35	Sentinel LST Products	GT-TS-29	REQ-40-TR
DEL-36	Sentinel LST Product Development Report	GT-TS-29	REQ-40-TR
DEL-37	Final Report	ALL	ALL
DEL-38	GlobTemperature User List	GT-TS-43 GT-TS-44 GT-TS-45	REQ-14-TR REQ-15-TR

8.6. Evolution of Technical Specifications for GlobTemperature Products

The Technical Specifications have been updated following mini-questionnaires carried out during breakout sessions thus satisfying the technical requirement **GT-TS-4**; these updates are in response to the updates to the User Requirements (Table 6). The updates to the Technical Specifications are summarised in Table 44.

Table 44: Updates to GlobTemperature Technical Specifications. Text highlighted indicate updates following both UCM#2 (blue) and UCM#3 (green)

Technical Specification Number	Description
GT-TS-6	Provide Level-3 and Level-4 datasets in harmonised format to be disseminated as 10° x 10° tiles
GT-TS-14	Develop Climate Data Record of 20-years for (A)ATSR in harmonised format with low bias, high precision, and high stability. Targets: 1.0 K, 1.0 K and 0.3 K respectively.
GT-TS-20	Investigate NRT merged LST demonstration product with standard timeliness of less than 24 hours (target 99% coverage); maximum timeliness to be no more than 48 hours; target timeliness of 12 hours
GT-TS-23	Data Portal to provide visualisation tools and statistics for LST data, LST anomalies, validation information and intercomparison data. Where possible a mechanism will be explored through the ILSTE-WG for data providers and users to share visualisation and analysis tools.
GT-TS-28	Develop platform independent tools for reading and sub-setting datasets provided in the harmonised formats, and cloud filtered time series extraction. Where possible a mechanism will be explored for data providers and users to share reading and sub-setting tools.
GT-TS-31	As default datafiles to be disseminated with mandatory variables only. User functionality to be provided to allow selection of optional variables from auxiliary datafiles, and Data Portal tools to allow sub-setting of data.
GT-TS-35	Where information is available provide full uncertainty breakdown for Level-2, -3 and -4 data in a consistent manner
GT-TS-42	Comply with agreed period between releases of re-processed datasets being no more frequent than quarterly
GT-TS-47	Provide single-sensor datasets of minimum length 10-years with a target of 30-years where new observations have a target timeliness of less than 1 month
GT-TS-48	Provide a data repository for users to share tools within the community
GT-TS-49	Provide a Data Portal tool to screen data as a function of cloud cover prior to download

In addition to updates to the Technical Specifications via the updates to the User Requirements following the UCMs, the project also captures the qualitative user feedback from these meetings. This feedback should influence future developments within the Project. As such, a set of User Feedback specifications has been defined; with individual items addressed in the previous sections, and a summary presented in Table 45.

Not all user feedback falls within the current scope of the Project, such as: the need for high spatial resolution data for urban studies in particular, but also for ET applications; continued updating of data products with new observations; and the provision of multi-year SSM/I data. Where these lie outside the scope of the project, they are nonetheless recorded in the GlobTemperature UCM Reports [AD-7], but not transformed into specifications.

Table 45: Enumeration of specifications to address Qualitative User Feed. Text highlighted indicate updates following both UCM#2 (blue) and UCM#3 (green)

User Feedback Number	Description
GT-UF-1	Improve quantification on the relationship between observations of “all-sky” land surface air temperature (LSAT) and “clear-sky” thermal infrared (TIR) LST
GT-UF-2	Improve quantification on the relationship between observations of TIR retrieved LST and microwave (MW) retrieved LST including the “clear-sky” bias
GT-UF-3	Provide ongoing support, where feasible, in the provision of LST products for mission continuity
GT-UF-4	Adopt a common LST terminology including a common protocol on validation and intercomparison disseminating these to the user community
GT-UF-5	Deliver consistent and accurate LST products, with unified formats (NetCDF and GIS-friendly GeoTiff) and metadata, product lists and dissemination schedules; with the provision of as much ancillary information as possible through the option of being able to customise the dataset files
GT-UF-6	Preserve information from Level-2 products in higher level products including number of data points/pixels used in averages as well as the times of the observations
GT-UF-7	Improve cloud screening, where feasible, in development of new products and updates to existing products with documented algorithms
GT-UF-8	Provide “user-friendly” uncertainties in the output LST products at a per-pixel level with sufficient metadata information
GT-UF-9	Provide extraction tools to subset datafiles with all information retained through the extraction process, and simple visualisation tools / Quick Looks to examine data at different resolutions, with a filter for cloud cover
GT-UF-10	Provide a repository on the Data Portal for users to share extraction / visualisation tools
GT-UF-11	Provide high quality LST data from polar-orbiting satellites with near daily global coverage spanning multiple years
GT-UF-12	Document emissivity approach for each algorithm in the Product User Guide (PUG)
GT-UF-13	Share information and expertise on best validation / calibration protocols

User Feedback Number	Description
GT-UF-14	Facilitate user selectable data extraction for multi-mission Level-2 and Level-3, for area (tiles, global files as single zip-files, or ROI selection) and data fields; with optimised folder structure
GT-UF-15	Provide enhanced QC information with a comprehensive description of the flags and how to use them in the Product User Guide (PUG), and the ability to filter in the extraction too
GT-UF-16	Assign quality flags of values agreed with the community to give consistency with other products (such as SST)
GT-UF-17	Enable users to send a disk and have an entire archive uploaded and posted back

9. Appendices

9.1. Appendix A – International LST & E Working Group Membership

The International LST & E Working Group (ILSTE-WG) core membership can be categorised as Steering Committee membership (Table 46) or General membership (Table 47). It is envisaged that although initial membership has been with these individuals over the course of the Project (and beyond) membership will be more fluid with additional members becoming involved. The structure and function of the ILSTE-WG may also evolve over the course of the Project (and beyond).

Table 46: GlobTemperature ILSTE-WG steering committee

Name	Institution	Role
John Remedios	U. Leicester	GlobTemperature Project Director
Darren Ghent	U. Leicester	GlobTemperature Project Scientist
Simon Pinnock	ESA	ESA representative
Simon Hook	NASA-JPL	NASA representative
Glynn Hulley	NASA-JPL	NASA MEaSUREs representative
Isabel Trigo	IPMA	LandSAF representative
Bob Yu	NOAA	NOAA representative
Lothar Schueller	EUMETSAT	EUMETSAT representative

Table 47: GlobTemperature ILSTE-WG general membership

Name	Institution	Role
Frank Göttsche	KIT	LST & E measurement team
Chris Merchant	U. Reading	
Catherine Prigent	Estellus	
Robert (Bob) Knuteson	U. Wisconsin	
Dorothy Hall	NASA-GSFC	
Jose Sobrino	U. Valencia	
Andrew French	USDA-ARS	LST & E users
Jacob Hoyer	DMI	

Name	Institution	Role
Lizzie Good	Met Office	
Hector Solana Nieto	U. Copenhagen	
Chris Taylor	CEH	
Claude Duguay	U. Waterloo	
Maria Fabrizia Buongiorno	INGV	
Martha Anderson	USDA-ARS	
Jakub Walawender	IMGW	
Marcel Urban	U. Jena	
Bob Scholes	CSIR	
Corinne Frey	DLR	
Philippe Goryl	ESA	Sentinel-3 representative

9.2. Appendix B – Detailed categorisation of the LST Validation Protocol

<u>Accuracy Criteria in Category A</u>

Here we define six classes of in situ data, describing a wide range of possibilities with respect to the data quality and expected validation accuracy as well as complexity and expense of data acquisition. In addition to proper instrumentation and calibration, a key element in defining the different levels was the availability of multi-year time series of radiometer data, since long and consistent time series are becoming increasingly valuable, not only for allowing a significantly increased number of satellite vs. in situ matchups for better statistical analysis, but also for better identification of instrumental issues such as drift.

The criteria selected for the quality classes in this category are:

- Proper instrumentation and demonstrated calibration
- Length of the data collection period (minimum 3 years)
- No or only minimal gaps in the time series (maximum 5 days/month)
- High-frequency temporal sampling (minimum 2 minutes)

- Comprehensive documentation of the validation site
- An existing uncertainty budget
- (Seasonal) in situ emissivity provided
- Measures actual BT of surface (not a proxy)

Class 1 in situ data (A1)

A class 1 in situ validation site completely fulfils all the criteria listed above. At the time of writing no such sites exist, primarily due to the lack of a comprehensive and documented uncertainty budget at the currently existing Class 2 sites.

Class 2 in situ data (A2)

Class 2 in situ data are established long-term in situ validation sites, completely equipped with one or more highly accurate and calibrated radiometers, which provide continuous observations with no or only small data gaps. The sites are either completely homogeneous over an area of ideally 3 x 3 pixels or alternatively heterogeneous with well-documented and measured heterogeneity. In addition to radiometers, these sites measure the standard meteorological parameters. All instrumentation and procedures must be well documented and the site description must be available to the LST research community. The sites in this class only lack one of the criteria listed above, in most cases this is a comprehensive uncertainty budget.

Examples of established sites that collect Class 2 in situ data are

- Gobabeb LST validation site, Namibia [RD-164, RD-165]
- Evora LST validation site, Portugal [RD-164, RD-165]
- Lake Tahoe LST validation site, California/Nevada, USA [RD-91, RD-92]

Class 3 in situ data (A3)

In situ validation sites that fail to meet two of the criteria listed above are considered Class 3 sites. In addition to the lack of an uncertainty budget, such sites typically have long (multi-year) time series but are not continuous in the sense that measurements are only taken during certain times of the year.

Examples of Class 3 in situ sites/datasets are:

- Dahra, Senegal [RD-164, RD-165]
- RMZ/Heimat, Namibia [RD-164, RD-165]

- Valencia LST validation site, Spain [RD-23]. At this site, LST measurements have been carried out with calibrated radiometers for several years, however the sampling was limited to the summer months of each year.

Class 4 in situ data (A4)

In situ validation sites that fail to meet three of the criteria listed are considered Class 4 sites. This includes stations that have potential as Class 2 (or even Class 1) stations, but that currently only have relatively short time series which may have substantial gaps due to instrument failure or cloud conditions. Furthermore this class contains station networks established for reasons other than LST validation as well as most validation campaigns that provide high-quality and reasonably well-documented data but only for a very short time period.

Examples of Class 4 in situ sites/datasets are:

- Sites of the Atmospheric Radiation Measurement (ARM) Climate Research Facility (Stokes and Schwartz, 1994)
- Most short-term LST validation campaigns

Class 5 in situ data (A5)

Class 5 in situ sites violate four of the listed criteria. An example of Class 5 in situ data includes measurements made by the United States Climate Reference Network (USCRN) (NOAA/NESDIS, 2007). This network provides continuous surface temperature data at 114 stations located within the continental United States and is planned to be operated for many decades in order to provide consistent datasets for climate research. However, while the stations provide data on infrared ground surface temperature, the calibration level of the instruments and thus the data quality is currently unknown. In addition, the data are currently only recorded at hourly intervals. Further research needs to be undertaken to determine the feasibility of using USCRN data for LST validation. If the outcome of such an analysis is positive, it is likely that USCRN data can be classified in one of the higher classes in future.

Class 6 in situ data (A6)

Class 6 in situ observations violate at least five of the listed criteria. This lowest level of complexity and validation quality is generally provided by in situ measurements of LST proxies, such as air temperature. It has been shown that the air temperature and ground surface temperature are almost the same during certain hours of the night and that air temperature can thus be used as a surrogate dataset to validate LST as a first approximation if the satellite overpass occurs temporally close to those times (Prata, 2003). While this technique obviously only allows for rough comparisons, air temperature is ubiquitously observed at a large number of meteorological stations worldwide, so this class potentially includes a multitude of stations that can be used for providing general guidance on LST quality at a global scale. Such an approach has for example been used in Greenland [RD-166].

Accuracy Criteria in Category B

The accuracy classes for this category are established based upon the expected accuracy of both the radiative transfer code and the atmospheric profiles. The two key criteria used for classifying the types of radiance-based validation of LST were

1. Atmospheric profile of temperature and water vapour content obtained from radiosonde launches at the validation site
2. Radiative transfer model based on line-by-line radiative transfer code rather than band transmission

Three classes have been defined, ranging from highest to lowest expected accuracy of the validation.

Class 1 radiance-based validation (B1)

A Class 1 radiance-based validation fulfils both of the criteria listed above, i.e. it uses line-by-line radiative transfer code in conjunction with atmospheric profiles of air temperature and water vapour observed directly at the validation site during the time of the satellite overpass. The combination of a line-by-line radiative transfer code together with a radiosonde-based atmospheric profile provides the highest possible level of accuracy for this type of LST validation.

Class 2 radiance-based validation (B2)

A Class 2 radiance-based validation is performed very similar to a Class 1 radiance-based validation; however one of the two classification criteria is not met. Therefore, a Class 2 radiance-based validation uses either a band-transmission radiative transfer model in conjunction with radiosonde-based atmospheric profiles observed directly at the validation site during the time of the satellite overpass or a line-by-line radiative transfer model in conjunction with atmospheric profiles obtained from a less accurate source such as from a reanalysis dataset.

Class 3 radiance-based validation (B3)

A Class 3 radiance-based validation relaxes both of the classification criteria necessary for a Class 1 validation: It uses a broad-band radiative transfer model together with atmospheric profiles obtained from an atmospheric model. As such, this validation class is expected to provide the lowest level of validation accuracy; however it is still a very valuable validation method when no ground LST measurements are available.

<u>Accuracy Criteria in Category C</u>

The key criteria selected for a Category C validation are:

1. Matchup times must be within a specified threshold – a recommendation being ±10 minutes.
2. The reference dataset must be operationally available

Class 1 inter-comparison (C1)

A Class 1 inter-comparison is considered the most accurate type of inter-comparison. It fulfils the criteria listed above. Such an inter-comparison can for example be accomplished by using data from two instruments onboard of the same satellite platform or alternatively from similar instruments flying successively along a similar orbit (such as the A-Train group of satellites).

Class 2 inter-comparison (C2)

A Class 2 inter-comparison relaxes one of the criteria established above. As such, this accuracy class encompasses LST inter-comparisons of datasets that deviate in their respective matchup times by more than the recommended threshold.

A special case of Class 2 inter-comparisons are airborne LST observations. Aircraft equipped with radiometers are a powerful tool for validating both TOA radiances and LST derived from spaceborne instruments, as they provide much higher spatial detail than satellite data. They further allow detailed observations of the atmospheric conditions. The primary advantage of the airborne platform is that it allows coverage over a much larger area than could normally be achieved with field measurements and provides significantly more spatial detail than satellite observations can deliver. However, it is a requirement that the instrument is well calibrated. Airborne TIR instruments are generally flown in dedicated validation campaigns and as such are specifically set up to match the satellite instrument to be validated in terms of overpass time and viewing angle. However, due to the episodic nature of such campaigns and the resulting lack of operational availability, data acquired in airborne LST campaigns does not fulfil one of the criteria listed above and thus is classified as a Class 2 inter-comparison.

Class 3 inter-comparison (C3)

The third accuracy class within the inter-comparison category encompasses the inter-comparison of satellite-derived LST data with spatially distributed LST proxy data, such as reanalysis data as provided by the ECMWF [RD-96, RD-167] or NCEP [RD-168].

Accuracy Criteria in Category D

In contrast to the other three validation categories, no specific key criteria were defined for category D. While criteria such as the length of time series, the number and size of gaps in the time series, and the temporal sampling could be used to define classes, such requirements are highly dependent on the goal of the time series analysis and vary widely.

Instead, accuracy classes for this category were established simply based on the geographical scale over which the time series are computed. This follows the idea that localized time series will be able to be interpreted more easily than global time series, as the latter usually combine a whole number of artificial and natural issues and thus make the identification of individual instrument problems or similar validation issues very challenging.

Class 1 time series analysis (D1)

A Class 1 time series analysis is performed at the single pixel level (or an average over a small number of neighbouring pixels). Plotting and studying reasonably long time series of such a small area can be very valuable for identifying algorithm and instrument issues, such as increased noise or calibration drift.

Class 2 time series analysis (D2)

A Class 2 time series analysis is performed at for a geographically invariant scene. For most instruments on low earth orbit platforms this means areas at a scale on the order of a few hundred kilometres.

Class 3 time series analysis (D3)

A Class 3 time series analysis is performed at the regional scale. This could be on the scale of a country, a continent, or a certain land cover type. While not as powerful as Class 1 and 2, this type of time series analysis can still provide valuable information about problems in the data. For biome based retrieval algorithms this may uncover biome-specific retrieval issues.

Class 4 time series analysis (D4)

A Class 4 time series analysis is computed at the global scale. While this type of analysis is not as useful for validation purposes as the other three classes, it can still provide interesting information. Furthermore, after establishing their accuracy, global time series are extremely relevant for global change research.

9.3. Appendix C – Harmonised Format Examples

9.3.1. Level-2 Product Example

Primary LST Product (LST)

```
netcdf GT_SSD-L2-MOD11_LST_2-20070618_162500-CUOL-0.01X0.01-V1.0.nc {

dimensions:

        time = 1 ;

        nj = 2030 ;

        ni = 1354 ;

variables:

        double jul_date(time) ;

                jul_date:long_name = "julian date" ;

                jul_date:units = "d" ;

                jul_date:_FillValue = -32768. ;
```

```
        jul_date:comment = "reference time in julian days at start of orbit" ;
    float lat(nj, ni) ;
        lat:long_name = "centre latitude" ;
        lat:standard_name = "latitude" ;
        lat:units = "degrees_north" ;
        lat:_FillValue = -32768.f ;
        lat:valid_min = -90.f ;
        lat:valid_max = 90.f ;
        lat:coordinates = "lon lat" ;
        lat:comment = "latitude coordinate of pixel centre" ;
    float lon(nj, ni) ;
        lon:long_name = "centre longitude" ;
        lon:standard_name = "longitude" ;
        lon:units = "degrees_east" ;
        lon:_FillValue = -32768.f ;
        lon:valid_min = -180.f ;
        lon:valid_max = 180.f ;
        lon:coordinates = "lon lat" ;
        lon:comment = "longitude coordinate of pixel centre" ;
    int dtime(nj, ni) ;
        dtime:long_name = "time difference from reference time" ;
        dtime:standard_name = "time" ;
        dtime:units = "seconds" ;
        dtime:_FillValue = -32768 ;
        dtime:valid_min = 0 ;
        dtime:valid_max = 300000 ;
        dtime:coordinates = "lon lat" ;
        dtime:comment = "time difference from start of orbit in seconds" ;
```

```
short LST(nj, ni) ;
        LST:long_name = "land surface temperature" ;
        LST:standard_name = "surface_temperature" ;
        LST:units = "K" ;
        LST:_FillValue = -32768s ;
        LST:add_offset = 273.15f ;
        LST:scale_factor = 0.01f ;
        LST:valid_min = -7315s ;
        LST:valid_max = 6685s ;
        LST:coordinates = "lon lat" ;
        LST:comment = "MOD11 pixel land surface temperature product" ;
short LST_uncertainty(nj, ni) ;
        LST_uncertainty:long_name = "land surface temperature uncertainty" ;
        LST_uncertainty:units = "K" ;
        LST_uncertainty:_FillValue = -32768s ;
        LST_uncertainty:add_offset = 0.f ;
        LST_uncertainty:scale_factor = 0.001f ;
        LST_uncertainty:valid_min = 0s ;
        LST_uncertainty:valid_max = 10000s ;
        LST_uncertainty:coordinates = "lat lon" ;
        LST_uncertainty:comment = "MOD11 land surface temperature pixel uncertainty" ;
int QC(nj, ni) ;
        QC:long_name = "quality control flags" ;
        QC:units = "1" ;
        QC:_FillValue = -32768 ;
        QC:valid_min = 0 ;
        QC:valid_max = 65535 ;
        QC:coordinates = "lat lon" ;
```

```
		QC:comment = "quality control flags " ;
		QC:flag_meanings = "night cloud poor_confidence aerosol_information aerosol" ;
		QC:flag_masks = 1, 2, 4, 8, 16 ;
	short satze(nj, ni) ;
		satze:long_name = "satellite zenith angle" ;
		satze:units = "degree" ;
		satze:_FillValue = -32768s ;
		satze:add_offset = 0.f ;
		satze:scale_factor = 0.01f ;
		satze:valid_min = 0s ;
		satze:valid_max = 18000s ;
		satze:coordinates = "lat lon" ;
		satze:comment = "MOD11 pixel satellite zenith angle" ;
	short sataz(nj, ni) ;
		sataz:long_name = "satellite azimuth angle" ;
		sataz:units = "degree" ;
		sataz:_FillValue = -32768s ;
		sataz:add_offset = 0.f ;
		sataz:scale_factor = 0.01f ;
		sataz:valid_min = -18000s ;
		sataz:valid_max = 18000s ;
		sataz:coordinates = "lat lon" ;
		sataz:comment = "MOD11 pixel satellite azimuth angle" ;
// global attributes:
		:Conventions = "CF-1.4" ;
		:title = "Land Surface Temperature from Moderate Resolution Imaging Spectroradiometer" ;
		:summary = "This file contains land surface temperature (LST) data in a harmonised format from operational Moderate Resolution Imaging Spectroradiometer (MODIS) Level-2 observations. By using these data, you agree to cite the papers given in the references metadata field in any publications derived from them" ;
```

:references = "NASA Land Processes Distributed Active Archive Center (LP DAAC). MODIS L2. USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota. 2001" ;

:institution = "University of Leicester" ;

:history = "Created using software developed at University of Leicester" ;

:comment = "These data were reformatted at the UK CEMS facility using software developed at The University of Leicester" ;

:license = "Data use is free and open" ;

:id = " GT_SSD-L2-MOD11_LST_2" ;

:date_created = "24-03-2014 15:05:53+0000" ;

:product_version = "1.0" ;

:netcdf_version_id = "4.1.3 of Sep 2 2013 10:18:28 $" ;

:spatial_resolution = "1 km" ;

:start_time = "2007-06-18 16:24:59Z" ;

:time_coverage_start = "2007-06-18 16:24:59Z" ;

:stop_time = "2007-06-18 16:29:59Z" ;

:time_coverage_end = "2007-06-18 16:29:59Z" ;

:northernmost_latitude = -68.25106f ;

:southernmost_latitude = -89.99261f ;

:easternmost_longitude = -0.003457065f ;

:westernmost_longitude = 0.005445458f ;

:source = "MOD11_L2" ;

:platform = "Terra" ;

:sensor = "MODIS" ;

:processing_level = " L2" ;

:keywords = "Earth Science, Land Surface, Land Temperature, Land Surface Temperature " ;

:keywords_vocabulary = "NASA Global change Master Directory (GCMD) Science Keywords " ;

:geospatial_lat_untis = "degrees_north" ;

:geospatial_lat_resolution = 0.01f ;

:geospatial_lon_untis = "degrees_east" ;

```
                :geospatial_lon_resolution = 0.01f ;
                :acknowledgment = "Development of the data was funded by ESA and NCEO" ;
                :creator_name = "Darren Ghent" ;
                :creator_email = "djg20@le.ac.uk" ;
                :creator_url = "http://www.globtemperature.info/" ;
}
```

Auxiliary LST Product (AUX)

```
netcdf GT_SSD-L2-MOD11_AUX_2-20070618_162500-CUOL-0.01X0.01-V1.0.nc {
dimensions:
        channel = 2 ;
        nj = 2030 ;
        ni = 1354 ;
        ch_length = 2
variables:
        char channel(ch_length,channel) ;
                channel:long_name = "channel_name" ;
                channel:units = "1" ;
                channel:_FillValue = -32768s ;
                channel:comment = "MOD11 channel name" ;
        short emis(channel,time, nj, ni) ;
                emis:long_name = "surface emissivity" ;
                emis:standard_name = "surface_longwave_emissivity" ;
                emis:units = "1" ;
                emis:_FillValue = -32768s ;
                emis:add_offset = 0.f ;
                emis:scale_factor = 0.004f ;
                emis:valid_min = 0s ;
                emis:valid_max = 250s ;
```

emis:coordinates = "lat lon" ;

emis:comment = "MOD11 channel emissivity" ;

short solze(time, nj, ni) ;

solze:long_name = "solar zenith angle" ;

solze:standard_name = "solar_zenith_angle" ;

solze:units = "degree" ;

solze:_FillValue = -32768s ;

solze:add_offset = 0.f ;

solze:scale_factor = 0.01f ;

solze:valid_min = 0s ;

solze:valid_max = 18000s ;

solze:coordinates = "lat lon" ;

solze:comment = "MOD11 pixel solar zenith angle" ;

short solaz(time, nj, ni) ;

solaz:long_name = "solar azimuth angle" ;

solaz:standard_name = "solar_azimuth_angle" ;

solaz:units = "degree" ;

solaz:_FillValue = -32768s ;

solaz:add_offset = 0.f ;

solaz:scale_factor = 0.01f ;

solaz:valid_min = -18000s ;

solaz:valid_max = 18000s ;

solaz:coordinates = "lat lon" ;

solaz:comment = "MOD11 pixel solar azimuth angle" ;

short lwm(time, nj, ni) ;

lwm:long_name = "land/water mask" ;

lwm:units = "1" ;

lwm:_FillValue = -32768s ;

lwm:valid_min = 0 ;

lwm:valid_max = 7 ;

lwm:coordinates = "lon lat" ;

lwm:comment = "MOD11 pixel land water mask" ;

lwm:flag_meanings = "Shallow Ocean (Ocean <5k from coast OR <50m deep), Land (not anything else), Ocean Coastlines and Lake Shorelines, Shallow Inland Water (Inland Water < 5km from shore OR < 50m deep), Ephemeral (intermittent) Water, Deep Inland Water (Inland water > 5km from shoreline AND > 50m deep), Moderate or Continental Ocean (Ocean > 5km from coast AND > 50m deep AND < 500m deep), Deep Ocean (Ocean > 500m deep)" ;

lwm:flag_values = 0s, 1s, 2s, 3s, 4s, 5s, 6s, 7s ;

short LST_unc_ran(nj, ni) ;

LST_unc_ran:long_name = "land surface temperature random uncertainty" ;

LST_unc_ran:units = "K" ;

LST_unc_ran:_FillValue = -32768s ;

LST_unc_ran:add_offset = 0.f ;

LST_unc_ran:scale_factor = 0.001f ;

LST_unc_ran:valid_min = 0s ;

LST_unc_ran:valid_max = 10000s ;

LST_unc_ran:coordinates = "lat lon" ;

LST_unc_ran:comment = "Moderate Resolution Imaging Spectroradiometer land surface temperature random uncertainty" ;

short LST_unc_loc(nj, ni) ;

LST_unc_loc:long_name = "land surface temperature locally correlated uncertainty" ;

LST_unc_loc:units = "K" ;

LST_unc_loc:_FillValue = -32768s ;

LST_unc_loc:add_offset = 0.f ;

LST_unc_loc:scale_factor = 0.001f ;

LST_unc_loc:valid_min = 0s ;

LST_unc_loc:valid_max = 10000s ;

LST_unc_loc:coordinates = "lat lon" ;

LST_unc_loc:comment = "Moderate Resolution Imaging Spectroradiometer land surface temperature locally correlated uncertainty" ;

short LST_unc_sys(systematic) ;

LST_unc_sys:long_name = "land surface temperature large scale systematic uncertainty" ;

LST_unc_sys:units = "K" ;

LST_unc_sys:_FillValue = -32768s ;

LST_unc_sys:add_offset = 0.f ;

LST_unc_sys:scale_factor = 0.001f ;

LST_unc_sys:valid_min = 0s ;

LST_unc_sys:valid_max = 10000s ;

LST_unc_sys:comment = "Moderate Resolution Imaging Spectroradiometer land surface temperature large scale systematic uncertainty" ;

// global attributes:

:Conventions = "CF-1.4" ;

:title = "Land Surface Temperature from Moderate Resolution Imaging Spectroradiometer" ;

:summary = "This file contains land surface temperature (LST) auxiliary (AUX) data in a harmonised format from operational Moderate Resolution Imaging Spectroradiometer (MODIS) Level-2 observations. By using these data, you agree to cite the papers given in the references metadata field in any publications derived from them" ;

:references = "NASA Land Processes Distributed Active Archive Center (LP DAAC). MODIS L2. USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota. 2001" ;

:institution = "University of Leicester" ;

:history = "Created using software developed at University of Leicester" ;

:comment = "These data were reformatted at the UK CEMS facility using software developed at The University of Leicester" ;

:license = "Data use is free and open" ;

:id = " GT_SSD-L2-MOD11_AUX_2" ;

:date_created = "24-03-2014 15:05:53+0000" ;

:product_version = "1.0" ;

:netcdf_version_id = "4.1.3 of Sep 2 2013 10:18:28 $" ;

:spatial_resolution = "1 km" ;

```
:start_time = "2007-06-18 16:24:59Z" ;
:time_coverage_start = "2007-06-18 16:24:59Z" ;
:stop_time = "2007-06-18 16:29:59Z" ;
:time_coverage_end = "2007-06-18 16:29:59Z" ;
:northernmost_latitude = -68.25106f ;
:southernmost_latitude = -89.99261f ;
:easternmost_longitude = -0.003457065f ;
:westernmost_longitude = 0.005445458f ;
:source = "MOD11_L2" ;
:platform = "Terra" ;
:sensor = "MODIS" ;
:processing_level = " L2" ;
:keywords = "Earth Science, Land Surface, Land Temperature, Land Surface Temperature "  ;
:keywords_vocabulary = "NASA Global change Master Directory (GCMD) Science Keywords " ;
:geospatial_lat_untis = "degrees_north" ;
:geospatial_lat_resolution = 0.01f ;
:geospatial_lon_untis = "degrees_east" ;
:geospatial_lon_resolution = 0.01f ;
:acknowledgment = "Development of the data was funded by ESA and NCEO" ;
:creator_name = "Darren Ghent" ;
:creator_email = "djg20@le.ac.uk" ;
:creator_url = "http://www.globtemperature.info/" ;
}
```

9.3.2. Level-3 product example

<u>Primary LST Product (LST)</u>

```
netcdf GT_SSD-L3-AATSR_LST_3-200706XX_XXXXX-CUOL-0.05X0.05-V1.0.nc {
dimensions:
```

```
        time = 2 ;
        lon = 7200 ;
        lat = 3600 ;
variables:
        short time(time) ;
                time:long_name = "diurnal index" ;
                time:standard_name = "time" ;
                time:units = "1" ;
                time:comment = "Day or night indicator" ;
                time:flag_meanings = "day night" ;
                time:flag_values = 0, 1 ;
        float lon(lon) ;
                lon:long_name = "centre longitude" ;
                lon:standard_name = "longitude" ;
                lon:units = "degrees_east" ;
                lon:_FillValue = -32768.f ;
                lon:valid_min = -180.f ;
                lon:valid_max = 180.f ;
                lon:coordinates = "lon lat" ;
                lon:comment = "longitude coordinate of grid cell centre" ;
        float lat(lat) ;
                lat:long_name = "centre latitude" ;
                lat:standard_name = "latitude" ;
                lat:units = "degrees_north" ;
                lat:_FillValue = -32768.f ;
                lat:valid_min = -90.f ;
                lat:valid_max = 90.f ;
                lat:coordinates = "lon lat" ;
```

lat:comment = "latitude coordinate of grid cell centre" ;

short LST(time, lon, lat) ;

LST:long_name = "land surface temperature" ;

LST:standard_name = "surface_temperature" ;

LST:units = "K" ;

LST:_FillValue = -32768s ;

LST:add_offset = 273.15f ;

LST:scale_factor = 0.01f ;

LST:valid_min = -7315s ;

LST:valid_max = 6685s ;

LST:coordinates = "lon lat" ;

LST:comment = "Advanced Along Track Scanning Radiometer mean land surface temperature product" ;

short LST_uncertainty(time, lon, lat) ;

LST_uncertainty:long_name = "land surface temperature uncertainty" ;

LST_uncertainty:units = "K" ;

LST_uncertainty:_FillValue = -32768s ;

LST_uncertainty:add_offset = 0.f ;

LST_uncertainty:scale_factor = 0.001f ;

LST_uncertainty:valid_min = 0s ;

LST_uncertainty:valid_max = 10000s ;

LST_uncertainty:coordinates = "lon lat" ;

LST_uncertainty:comment = "Advanced Along Track Scanning Radiometer cell surface temperature pixel uncertainty" ;

int n(time, lon, lat) ;

n:long_name = "total number of pixels" ;

n:units = "1" ;

n:_FillValue = -32768 ;

n:coordinates = "lon lat" ;

n:comment = "Advanced Along Track Scanning Radiometer cell pixel count" ;

int ncld(time, lon, lat) ;

ncld:long_name = "number of cloudy pixels" ;

ncld:units = "1" ;

ncld:_FillValue = -32768 ;

ncld:coordinates = "lon lat" ;

ncld:comment = "Advanced Along Track Scanning Radiometer cell cloudy pixel count" ;

short LST_variance(time, lon, lat) ;

LST_variance:long_name = "land surface temperature variance" ;

LST_variance:units = "K" ;

LST_variance:_FillValue = -32768s ;

LST_variance:add_offset = 0.f ;

LST_variance:scale_factor = 0.001f ;

LST_variance:valid_min = 0s ;

LST_variance:valid_max = 10000s ;

LST_variance:coordinates = "lon lat" ;

LST_variance:comment = "Advanced Along Track Scanning Radiometer variance of cell surface temperatures from pixels" ;

short satze(time, lon, lat) ;

satze:long_name = "satellite zenith angle" ;

satze:units = "degree" ;

satze:_FillValue = -32768s ;

satze:add_offset = 0.f ;

satze:scale_factor = 0.01f ;

satze:valid_min = 0s ;

satze:valid_max = 18000s ;

satze:coordinates = "lat lon" ;

satze:comment = " Advanced Along Track Scanning Radiometer mean zenith viewing angle within cell " ;

short sataz(time, lon, lat) ;

sataz:long_name = "satellite azimuth angle" ;

sataz:units = "degree" ;

sataz:_FillValue = -32768s ;

sataz:add_offset = 0.f ;

sataz:scale_factor = 0.01f ;

sataz:valid_min = -18000s ;

sataz:valid_max = 18000s ;

sataz:coordinates = "lat lon" ;

sataz:comment = " Advanced Along Track Scanning Radiometer mean azimuth viewing angle within cell " ;

// global attributes:

:Conventions = "CF-1.4" ;

:title = "Gridded Land Surface Temperature from Advanced Along Track Scanning Radiometer" ;

:summary = "This file contains land surface temperature (LST) data estimated from Advanced Along Track Scanning Radiometer (AATSR) observations and gridded onto a regular latitude / longitude grid. By using these data, you agree to cite the papers given in the references metadata field in any publications derived from them" ;

:references = "Ghent D., Land Surface Temperature Validation and Algorithm Verification (Report to European Space Agency). 2012(UL-NILU-ESA-LST-VAV)" ;

:institution = "University of Leicester" ;

:history = "Created using software developed at University of Leicester" ;

:comment = "These data were produced at the UK CEMS facility using software developed at The University of Leicester" ;

:license = "Data use is free and open" ;

:id = " GT_SSD-L3-AATSR_LST_3" ;

:date_created = "30-05-2014 11:38:38+0000" ;

:product_version = "1.0" ;

:netcdf_version_id = "4.1.3 of Sep 2 2013 10:18:28 $" ;

:spatial_resolution = "0.05X0.05" ;

:start_time = "2006-07-01 00:00:00Z" ;

:time_coverage_start = "2002-07-22 23:37:42Z" ;

:stop_time = "2006-07-31 23:59:59Z" ;

:time_coverage_end = "2012-04-08 10:58:27Z" ;

:northernmost_latitude = 90.f ;

:southernmost_latitude = -90.f ;

:easternmost_longitude = 180.f ;

:westernmost_longitude = -180.f ;

:source = " GT_SSD-L2-AATSR_LST_2 " ;

:platform = "Envisat" ;

:sensor = "AATSR" ;

:processing_level = " L3" ;

:keywords = "Earth Science, Land Surface, Land Temperature, Land Surface Temperature " ;

:keywords_vocabulary = "NASA Global change Master Directory (GCMD) Science Keywords " ;

:geospatial_lat_untis = "degrees_north" ;

:geospatial_lat_resolution = 0.05f ;

:geospatial_lon_untis = "degrees_east" ;

:geospatial_lon_resolution = 0.05f ;

:acknowledgment = "Development of the data was funded by ESA and NCEO" ;

:creator_name = "Darren Ghent" ;

:creator_email = "djg20@le.ac.uk" ;

:creator_url = "http://www.globtemperature.info/" ;

}

Auxiliary LST Product (AUX)

netcdf GT_SSD-L3-AATSR_AUX_3-200706XX_XXXXX-CUOL-0.05X0.05-V1.0.nc {

dimensions:

time = 2 ;

lon = 7200 ;

```
        lat = 3600 ;
variables:
        short lwm(time, lon, lat) ;
                LSM:long_name = "land proportion" ;
                LSM:units = "1" ;
                LSM:_FillValue = -128s ;
                LSM:add_offset = 0.f ;
                LSM:scale_factor = 0.004f ;
                LSM:valid_min = 0s ;
                LSM:valid_max = 250s ;
                LSM:coordinates = "lon lat" ;
                LSM:comment = "fraction of grid cell that is designated land by the AATSR land sea mask" ;
        short solze(time, lon, lat) ;
                solze:long_name = "solar zenith angle" ;
                solze:standard_name = "solar_zenith_angle" ;
                solze:units = "degree" ;
                solze:_FillValue = -32768s ;
                solze:add_offset = 0.f ;
                solze:scale_factor = 0.01f ;
                solze:valid_min = 0s ;
                solze:valid_max = 18000s ;
                solze:coordinates = "lat lon" ;
                solze:comment = " Advanced Along Track Scanning Radiometer mean solar zenith angle within
cell " ;
        short solaz(time, lon, lat) ;
                solaz:long_name = "solar azimuth angle" ;
                solaz:standard_name = "solar_azimuth_angle" ;
                solaz:units = "degree" ;
```

solaz:_FillValue = -32768s ;

solaz:add_offset = 0.f ;

solaz:scale_factor = 0.01f ;

solaz:valid_min = -18000s ;

solaz:valid_max = 18000s ;

solaz:coordinates = "lat lon" ;

solaz:comment = " Advanced Along Track Scanning Radiometer mean solar azimuth angle within cell " ;

short LST_unc_ran(nj, ni) ;

LST_unc_ran:long_name = "land surface temperature random uncertainty" ;

LST_unc_ran:units = "K" ;

LST_unc_ran:_FillValue = -32768s ;

LST_unc_ran:add_offset = 0.f ;

LST_unc_ran:scale_factor = 0.001f ;

LST_unc_ran:valid_min = 0s ;

LST_unc_ran:valid_max = 10000s ;

LST_unc_ran:coordinates = "lat lon" ;

LST_unc_ran:comment = " Advanced Along Track Scanning Radiometer land surface temperature random uncertainty" ;

short LST_unc_loc(nj, ni) ;

LST_unc_loc:long_name = "land surface temperature locally correlated uncertainty" ;

LST_unc_loc:units = "K" ;

LST_unc_loc:_FillValue = -32768s ;

LST_unc_loc:add_offset = 0.f ;

LST_unc_loc:scale_factor = 0.001f ;

LST_unc_loc:valid_min = 0s ;

LST_unc_loc:valid_max = 10000s ;

LST_unc_loc:coordinates = "lat lon" ;

LST_unc_loc:comment = " Advanced Along Track Scanning Radiometer land surface temperature locally correlated uncertainty" ;

short LST_unc_sys(systematic) ;

LST_unc_sys:long_name = "land surface temperature large scale systematic uncertainty" ;

LST_unc_sys:units = "K" ;

LST_unc_sys:_FillValue = -32768s ;

LST_unc_sys:add_offset = 0.f ;

LST_unc_sys:scale_factor = 0.001f ;

LST_unc_sys:valid_min = 0s ;

LST_unc_sys:valid_max = 10000s ;

LST_unc_sys:comment = " Advanced Along Track Scanning Radiometer land surface temperature large scale systematic uncertainty" ;

short NDVI(time, lon, lat) ;

NDVI:long_name = "normalised difference vegetation index" ;

NDVI:standard_name = "normalized_difference_vegetation_index" ;

NDVI:units = "1" ;

NDVI:_FillValue = -32768s ;

NDVI:add_offset = 0.f ;

NDVI:scale_factor = 0.004f ;

NDVI:valid_min = 0s ;

NDVI:valid_max = 250s ;

NDVI:coordinates = "lon lat" ;

NDVI:comment = "Advanced Along Track Scanning Radiometer cell normalised difference vegetation index" ;

// global attributes:

:Conventions = "CF-1.4" ;

:title = "Gridded Land Surface Temperature from Advanced Along Track Scanning Radiometer" ;

:summary = "This file contains land surface temperature (LST) auxiliary (AUX) data estimated from Advanced Along Track Scanning Radiometer (AATSR) observations and gridded onto a regular latitude /

longitude grid. By using these data, you agree to cite the papers given in the references metadata field in any publications derived from them" ;

:references = "Ghent D., Land Surface Temperature Validation and Algorithm Verification (Report to European Space Agency). 2012(UL-NILU-ESA-LST-VAV)" ;

:institution = "University of Leicester" ;

:history = "Created using software developed at University of Leicester" ;

:comment = "These data were produced at the UK CEMS facility using software developed at The University of Leicester" ;

:license = "Data use is free and open" ;

:id = " GT_SSD-L3-AATSR_AUX_3" ;

:date_created = "30-05-2014 11:38:38+0000" ;

:product_version = "1.0" ;

:netcdf_version_id = "4.1.3 of Sep 2 2013 10:18:28 $" ;

:spatial_resolution = "0.05X0.05" ;

:start_time = "2006-07-01 00:00:00Z" ;

:time_coverage_start = "2002-07-22 23:37:42Z" ;

:stop_time = "2006-07-31 23:59:59Z" ;

:time_coverage_end = "2012-04-08 10:58:27Z" ;

:northernmost_latitude = 90.f ;

:southernmost_latitude = -90.f ;

:easternmost_longitude = 180.f ;

:westernmost_longitude = -180.f ;

:source = " GT_SSD-L2-AATSR_AUX_2 " ;

:platform = "Envisat" ;

:sensor = "AATSR" ;

:processing_level = " L3" ;

:keywords = "Earth Science, Land Surface, Land Temperature, Land Surface Temperature " ;

:keywords_vocabulary = "NASA Global change Master Directory (GCMD) Science Keywords " ;

:geospatial_lat_untis = "degrees_north" ;

```
                :geospatial_lat_resolution = 0.05f ;
                :geospatial_lon_untis = "degrees_east" ;
                :geospatial_lon_resolution = 0.05f ;
                :acknowledgment = "Development of the data was funded by ESA and NCEO" ;
                :creator_name = "Darren Ghent" ;
                :creator_email = "djg20@le.ac.uk" ;
                :creator_url = "http://www.globtemperature.info/" ;
}
```

9.3.3. GlobTemperature Matchup Database examples

GT_MDB input satellite LST for validation

```
netcdf GT_MDB-SE-MOD11_GBB_W-20070718_094500-CUOL-0.01X0.01-V1.0.nc {
dimensions:
        channel = 2 ;
        lat = 50 ;
        lon = 50 ;
        ch_length = 2
variables:
        float lat(lat) ;
                lat:long_name = "centre latitude" ;
                lat:standard_name = "latitude" ;
                lat:units = "degrees_north" ;
                lat:valid_min = -90.f ;
                lat:valid_max = 90.f ;
                lat:axis = "Y" ;
        float lon(lon) ;
                lon:long_name = "centre longitude" ;
                lon:standard_name = "longitude" ;
```

lon:units = "degrees_east" ;

lon:valid_min = -180.f ;

lon:valid_max = 180.f ;

lon:axis = "X" ;

double jul_date(lat, lon) ;

jul_date:long_name = "julian date" ;

jul_date:units = "d" ;

jul_date:_FillValue = -32768. ;

jul_date:coordinates = "lat lon" ;

short QC(lat, lon) ;

QC:long_name = "quality control flags" ;

QC:units = "1" ;

QC:_FillValue = -32768s ;

QC:valid_min = 0 ;

QC:valid_max = 0 ;

QC:coordinates = "lat lon" ;

QC:comment = "quality control flags corresponding to the Moderate Resolution Imaging Spectroradiometer land surface temperature product" ;

QC:flag_meanings = "night cloud_mask" ;

QC:flag_masks = 1s, 2s ;

short LST(lat, lon) ;

LST:long_name = "land surface temperature" ;

LST:standard_name = "surface_temperature" ;

LST:units = "K" ;

LST:_FillValue = -32768s ;

LST:add_offset = 273.15f ;

LST:scale_factor = 0.01f ;

LST:valid_min = -7315s ;

LST:valid_max = 6685s ;

LST:coordinates = "lat lon" ;

LST:comment = "Moderate Resolution Imaging Spectroradiometer pixel land surface temperature product" ;

short LST_uncertainty(lat, lon) ;

LST_uncertainty:long_name = "land surface temperature uncertainty" ;

LST_uncertainty:units = "K" ;

LST_uncertainty:_FillValue = -32768s ;

LST_uncertainty:add_offset = 0.f ;

LST_uncertainty:scale_factor = 0.001f ;

LST_uncertainty:valid_min = 0s ;

LST_uncertainty:valid_max = 10000s ;

LST_uncertainty:coordinates = "lat lon" ;

LST_uncertainty:comment = "Moderate Resolution Imaging Spectroradiometer land surface temperature pixel uncertainty" ;

short satze(lat, lon) ;

satze:long_name = "satellite zenith angle" ;

satze:units = "degree" ;

satze:_FillValue = -32768s ;

satze:add_offset = 0.f ;

satze:scale_factor = 0.01f ;

satze:coordinates = "lat lon" ;

short sataz(lat, lon) ;

sataz:long_name = "satellite azimuth angle" ;

sataz:units = "degree" ;

sataz:_FillValue = -32768s ;

sataz:add_offset = 0.f ;

sataz:scale_factor = 0.01f ;

sataz:coordinates = "lat lon" ;

```
char channel(ch_length,channel) ;
        channel:long_name = "channel_name" ;
        channel:units = "1" ;
        channel:_FillValue = -32768s ;
        channel:comment = "MOD11 channel name" ;
short emis(channel,lat, lon) ;
        emis:long_name = "surface emissivity" ;
        emis:standard_name = "surface_longwave_emissivity" ;
        emis:units = "1" ;
        emis:_FillValue = -32768s ;
        emis:add_offset = 0.f ;
        emis:scale_factor = 0.004f ;
        emis:valid_min = 0s ;
        emis:valid_max = 250s ;
        emis:coordinates = "lat lon" ;
        emis:comment = "MOD11 channel emissivity" ;
short solze(lat, lon) ;
        solze:long_name = "solar zenith angle" ;
        solze:standard_name = "solar_zenith_angle" ;
        solze:units = "degree" ;
        solze:_FillValue = -32768s ;
        solze:add_offset = 0.f ;
        solze:scale_factor = 0.01f ;
        solze:coordinates = "lat lon" ;
short solaz(lat, lon) ;
        solaz:long_name = "solar azimuth angle" ;
        solaz:standard_name = "solar_azimuth_angle" ;
        solaz:units = "degree" ;
```

```
                solaz:_FillValue = -32768s ;
                solaz:add_offset = 0.f ;
                solaz:scale_factor = 0.01f ;
                solaz:coordinates = "lat lon" ;
        short cld_frac(lat, lon) ;
                cld_frac:long_name = "cloud fraction" ;
                cld_frac:standard_name = "cloud_area_fraction" ;
                cld_frac:units = "1" ;
                cld_frac:_FillValue = -32768s ;
                cld_frac:add_offset = 0.f ;
                cld_frac:scale_factor = 0.004f ;
                cld_frac:valid_min = 0s ;
                cld_frac:valid_max = 250s ;
                cld_frac:coordinates = "lat lon" ;
                cld_frac:comment = "pixel cloud fraction" ;


// global attributes:
                :Conventions = "CF-1.4" ;
                :title = "Land Surface Temperature from Moderate Resolution Imaging Spectroradiometer" ;
                :summary = "This file contains land surface temperature (LST) data extracted from the Moderate Resolution Imaging Spectroradiometer product for validation within the GlobTemperature Matchup DataBase (GT_MDB). By using these data, you agree to cite the papers given in the references metadata field in any publications derived from them" ;
                :references = "Ghent D., Land Surface Temperature Validation and Algorithm Verification (Report to European Space Agency). 2012(UL-NILU-ESA-LST-VAV)" ;
                :institution = "University of Leicester" ;
                :history = "Created using software developed at University of Leicester" ;
                :comment = "These data were produced at the UK CEMS facility using software developed at The University of Leicester under the ESA DUE GlobTemperature Project" ;
                :license = "Data use is free and open" ;
```

:id = " GT_MDB-SE-MOD11_GBB_W " ;

:date_created = "24-02-2014 10:24:05+0000" ;

:product_version = "1.0" ;

:netcdf_version_id = "4.1.3 of Sep 2 2013 10:18:28 $" ;

:spatial_resolution = "0.01 degrees" ;

:start_time = "2007-07-18 09:45:31Z" ;

:time_coverage_start = "2007-07-18 09:45:31Z" ;

:stop_time = "2007-07-18 09:45:39Z" ;

:time_coverage_end = "2007-07-18 09:45:39Z" ;

:northernmost_latitude = "-23.300961" ;

:southernmost_latitude = "-23.800961" ;

:easternmost_longitude = " 15.301380" ;

:westernmost_longitude = " 14.801380" ;

:source = " GT_SSD-L2-MOD11_LST_2 " ;

:platform = "Terra" ;

:sensor = "MODIS" ;

:processing_level = " MDB" ;

:keywords = "Earth Science, Land Surface, Land Temperature, Land Surface Temperature " ;

:keywords_vocabulary = "NASA Global change Master Directory (GCMD) Science Keywords " ;

:geospatial_lat_units = "degrees_north" ;

:geospatial_lat_resolution = 0.01f ;

:geospatial_lon_units = "degrees_east" ;

:geospatial_lon_resolution = 0.01f ;

:acknowledgment = "Development of the data was funded by ESA DUE GlobTemperature" ;

:creator_name = "Darren Ghent" ;

:creator_email = "djg20@le.ac.uk" ;

:creator_url = "http://www.globtemperature.info" ;

}

GT_MDB satellite vs. in situ matchups

```
netcdf GT_MDB-SI-MOD11_GBB_W-20070718_XXXXXX-CUOL-0.01X0.01-V1.0.nc {
dimensions:
        time = 2 ;
        lat = 50 ;
        lon = 50 ;
variables:
        float insitu_lat() ;
                insitu_lat:long_name = "in situ latitude" ;
                insitu_lat:standard_name = "latitude" ;
                insitu_lat:units = "degrees_north" ;
                insitu_lat:valid_min = -90.f ;
                insitu_lat:valid_max = 90.f ;
                insitu_lat:axis = "Y" ;
        float insitu_lon() ;
                insitu_lon:long_name = "in situ longitude" ;
                insitu_lon:standard_name = "longitude" ;
                insitu_lon:units = "degrees_east" ;
                insitu_lon:valid_min = -180.f ;
                insitu_lon:valid_max = 180.f ;
                insitu_lon:axis = "X" ;
        short station_LST(time) ;
                station_LST:long_name = "station land surface temperature" ;
                station_LST:standard_name = "surface_temperature" ;
                station_LST:units = "K" ;
                station_LST:_FillValue = -32768s ;
                station_LST:add_offset = 273.15f ;
                station_LST:scale_factor = 0.01f ;
```

```
                station_LST:valid_min = -7315s ;
                station_LST:valid_max = 6685s ;
                station_LST:comment = "Land surface temperature derived from station measurements" ;
        short station_LST_unc (time) ;
                station_LST_unc:long_name = "station land surface temperature uncertainty" ;
                station_LST_unc:units = "K" ;
                station_LST_unc:_FillValue = -32768s ;
                station_LST_unc:add_offset = 0.f ;
                station_LST_unc:scale_factor = 0.001f ;
                station_LST_unc:valid_min = 0s ;
                station_LST_unc:valid_max = 10000s ;
                station_LST_unc:comment = "Land surface temperature pixel uncertainty from station derivation" ;
        float sat_lat(lat) ;
                sat_lat:long_name = "satellite centre latitude" ;
                sat_lat:standard_name = "latitude" ;
                sat_lat:units = "degrees_north" ;
                sat_lat:valid_min = -90.f ;
                sat_lat:valid_max = 90.f ;
                sat_lat:axis = "Y" ;
        float sat_lon(lon) ;
                sat_lon:long_name = "satellite centre longitude" ;
                sat_lon:standard_name = "longitude" ;
                sat_lon:units = "degrees_east" ;
                sat_lon:valid_min = -180.f ;
                sat_lon:valid_max = 180.f ;
                sat_lon:axis = "X" ;
        double jul_date(time, lat, lon) ;
```

jul_date:long_name = "julian date" ;

jul_date:units = "d" ;

jul_date:_FillValue = -32768. ;

jul_date:coordinates = "lat lon" ;

int n(time, lon, lat) ;

n:long_name = "total number of aggregated pixels" ;

n:units = "1" ;

n:_FillValue = -32768 ;

n:coordinates = "lon lat" ;

n:comment = "Grid cell pixel count" ;

short LST(time, lat, lon) ;

LST:long_name = "land surface temperature" ;

LST:standard_name = "surface_temperature" ;

LST:units = "K" ;

LST:_FillValue = -32768s ;

LST:add_offset = 273.15f ;

LST:scale_factor = 0.01f ;

LST:valid_min = -7315s ;

LST:valid_max = 6685s ;

LST:coordinates = "lat lon" ;

LST:comment = "Moderate Resolution Imaging Spectroradiometer grid cell land surface temperature product" ;

short LST_uncertainty(lat, lon) ;

LST_uncertainty:long_name = "land surface temperature uncertainty" ;

LST_uncertainty:units = "K" ;

LST_uncertainty:_FillValue = -32768s ;

LST_uncertainty:add_offset = 0.f ;

LST_uncertainty:scale_factor = 0.001f ;

LST_uncertainty:valid_min = 0s ;

LST_uncertainty:valid_max = 10000s ;

LST_uncertainty:coordinates = "lat lon" ;

LST_uncertainty:comment = "Moderate Resolution Imaging Spectroradiometer land surface temperature grid cell uncertainty" ;

short satze(time, lat, lon) ;

satze:long_name = "satellite zenith angle" ;

satze:units = "degree" ;

satze:_FillValue = -32768s ;

satze:add_offset = 0.f ;

satze:scale_factor = 0.01f ;

satze:coordinates = "lat lon" ;

short sataz(time, lat, lon) ;

sataz:long_name = "satellite azimuth angle" ;

sataz:units = "degree" ;

sataz:_FillValue = -32768s ;

sataz:add_offset = 0.f ;

sataz:scale_factor = 0.01f ;

sataz:coordinates = "lat lon" ;

// global attributes:

:Conventions = "CF-1.4" ;

:title = "Land Surface Temperature matchup between Moderate Resolution Imaging Spectroradiometer and Gobabeb in situ measurements" ;

:summary = "This file contains land surface temperature (LST) data extracted from the Moderate Resolution Imaging Spectroradiometer product for validation within the GlobTemperature Matchup DataBase (GT_MDB) against measurements acquired from Gobabeb. By using these data, you agree to cite the papers given in the references metadata field in any publications derived from them" ;

:references = "Ghent D., Land Surface Temperature Validation and Algorithm Verification (Report to European Space Agency). 2012(UL-NILU-ESA-LST-VAV)" ;

:institution = "University of Leicester" ;

:history = "Created using software developed at University of Leicester" ;

:comment = "These data were produced at the UK CEMS facility using software developed at The University of Leicester under the ESA DUE GlobTemperature Project" ;

:license = "Data use is free and open" ;

:id = " GT_MDB-SI-MOD11_GBB_W " ;

:date_created = "24-02-2014 10:24:05+0000" ;

:product_version = "1.0" ;

:netcdf_version_id = "4.1.3 of Sep 2 2013 10:18:28 $" ;

:spatial_resolution = "0.01 degrees" ;

:start_time = "2007-07-18 09:45:31Z" ;

:time_coverage_start = "2007-07-18 09:45:31Z" ;

:stop_time = "2007-07-18 09:45:39Z" ;

:time_coverage_end = "2007-07-18 09:45:39Z" ;

:northernmost_latitude = "-23.300961" ;

:southernmost_latitude = "-23.800961" ;

:easternmost_longitude = " 15.301380" ;

:westernmost_longitude = " 14.801380" ;

:source = " GT_MDB-SE-MOD11_GBB_W, GT_MDB-IS-INSIT_GBB_W " ;

:platform = "Terra" ;

:sensor = "MODIS" ;

:processing_level = " MDB" ;

:keywords = "Earth Science, Land Surface, Land Temperature, Land Surface Temperature " ;

:keywords_vocabulary = "NASA Global change Master Directory (GCMD) Science Keywords " ;

:geospatial_lat_units = "degrees_north" ;

:geospatial_lat_resolution = 0.01f ;

:geospatial_lon_units = "degrees_east" ;

:geospatial_lon_resolution = 0.01f ;

:acknowledgment = "Development of the data was funded by ESA DUE GlobTemperature" ;

```
        :creator_name = "Darren Ghent" ;
        :creator_email = "djg20@le.ac.uk" ;
        :creator_url = "http://www.globtemperature.info" ;
}
```

GT_MDB multi-sensor satellite intercomparison matchup

```
netcdf GT_MDB-SS-AATSR_SEVIR-20070402_101249-CUOL-0.05X0.05-V1.0.nc {
dimensions:
    sensor = 2 ;
    lat = 200 ;
    lon = 200 ;
    sr_length = 5 ;
variables:
    char sensor(sr_length,sensor) ;
        sensor:long_name = "sensor name" ;
        sensor:units = "1" ;
    float lat(lat) ;
        lat:long_name = "centre latitude" ;
        lat:standard_name = "latitude" ;
        lat:units = "degrees_north" ;
        lat:_FillValue = -32768.f ;
        lat:valid_min = -90.f ;
        lat:valid_max = 90.f ;
        lat:coordinates = "lon lat" ;
        lat:comment = "latitude coordinate of pixel centre" ;
    float lon(lon) ;
        lon:long_name = "centre longitude" ;
        lon:standard_name = "longitude" ;
        lon:units = "degrees_east" ;
```

```
        lon:_FillValue = -32768.f ;
        lon:valid_min = -180.f ;
        lon:valid_max = 180.f ;
        lon:coordinates = "lon lat" ;
        lon:comment = "longitude coordinate of pixel centre" ;
short n(sensor, lat, lon) ;
        n:long_name = "pixel count" ;
        n:units = "1" ;
        n:_FillValue = -32768s ;
        n:coordinates = "lon lat" ;
        n:comment = "number of pixels averaged" ;
double jul_date(sensor, lat, lon) ;
        jul_date:long_name = "julian date" ;
        jul_date:units = "d" ;
        jul_date:_FillValue = -32768. ;
        jul_date:coordinates = "lat lon" ;
        jul_date:comment = "time of matchup in Julian Date" ;
short LST(sensor, lat, lon) ;
        LST:long_name = "land surface temperature" ;
        LST:standard_name = "surface_temperature" ;
        LST:units = "K" ;
        LST:_FillValue = -32768s ;
        LST:add_offset = 273.15f ;
        LST:scale_factor = 0.01f ;
        LST:valid_min = -7315s ;
        LST:valid_max = 6685s ;
        LST:coordinates = "lon lat" ;
        LST:comment = "land surface temperature data" ;
```

```
short LST_uncertainty(sensor, lat, lon) ;
        LST_uncertainty:long_name = "land surface temperature uncertainty" ;
        LST_uncertainty:units = "K" ;
        LST_uncertainty:_FillValue = -32768s ;
        LST_uncertainty:add_offset = 0.f ;
        LST_uncertainty:scale_factor = 0.001f ;
        LST_uncertainty:valid_min = 0s ;
        LST_uncertainty:valid_max = 10000s ;
        LST_uncertainty:coordinates = "lat lon" ;
        LST_uncertainty:comment = "land surface temperature pixel uncertainty data" ;
short satze(sensor, lat, lon) ;
        satze:long_name = "satellite zenith angle" ;
        satze:units = "degree" ;
        satze:_FillValue = -32768s ;
        satze:add_offset = 0.f ;
        satze:scale_factor = 0.01f ;
        satze:valid_min = 0s ;
        satze:valid_max = 18000s ;
        satze:coordinates = "lat lon" ;
        satze:comment = "satellite zenith angle data" ;
short sataz(sensor, lat, lon) ;
        sataz:long_name = "satellite azimuth angle" ;
        sataz:units = "degree" ;
        sataz:_FillValue = -32768s ;
        sataz:add_offset = 0.f ;
        sataz:scale_factor = 0.01f ;
        sataz:valid_min = -18000s ;
        sataz:valid_max = 18000s ;
```

sataz:coordinates = "lat lon" ;

sataz:comment = "satellite azimuth angle data" ;

short tcwv(sensor, lat, lon) ;

tcwv:long_name = "total column water vapour" ;

tcwv:standard_name = "atmosphere_mass_content_of_water_vapor" ;

tcwv:units = "kg m-2" ;

tcwv:_FillValue = -32768s ;

tcwv:add_offset = 0.f ;

tcwv:scale_factor = 0.004f ;

tcwv:valid_min = 0s ;

tcwv:valid_max = 2000s ;

tcwv:coordinates = "lon lat" ;

tcwv:comment = "total column water vapour data" ;

// global attributes:

:Conventions = "CF-1.4" ;

:title = "Land Surface Temperature intercomparison matchup data" ;

:summary = "This file contains land surface temperature (LST) intercomparison matchups in a harmonised format. By using these data, you agree to cite the papers given in the references metadata field in any publications derived from them" ;

:references = "" ;

:institution = "University of Leicester" ;

:history = "Created using software developed at University of Leicester" ;

:comment = "These data were reformatted at the UK CEMS facility using software developed at The University of Leicester" ;

:license = "Data use is free and open" ;

:id = " GT_MDB-SS-AATSR_SEVIR" ;

:date_created = "12-05-2014 14:09:05+0100" ;

:product_version = "1.0" ;

:netcdf_version_id = "4.1.3 of Sep 2 2013 10:18:28 $" ;

:spatial_resolution = 0.05f ;

:start_time = "2007-04-02 10:55:44Z" ;

:time_coverage_start = "2007-04-02 10:55:44Z" ;

:stop_time = "2007-04-02 10:54:08Z" ;

:time_coverage_end = "2007-04-02 10:54:08Z" ;

:northernmost_latitude = 40.f ;

:southernmost_latitude = 30.f ;

:easternmost_longitude = 0.f ;

:westernmost_longitude = -10.f ;

:source = " GT_SSD-L2-AATSR_LST_2, GT_SSD-L2-SEVIR_LST_2" ;

:platform = "Envisat, MSG" ;

:sensor = "AATSR, SEVIRI" ;

:processing_level = " MDB" ;

:keywords = "Earth Science, Land Surface, Land Temperature, Land Surface Temperature " ;

:keywords_vocabulary = "NASA Global change Master Directory (GCMD) Science Keywords " ;

:geospatial_lat_units = "degrees_north" ;

:geospatial_lat_resolution = 0.01f ;

:geospatial_lon_units = "degrees_east" ;

:geospatial_lon_resolution = 0.01f ;

:acknowledgment = "Development of the data was funded by ESA and NCEO" ;

:creator_name = "Darren Ghent" ;

:creator_email = "djg20@le.ac.uk" ;

:creator_url = "http://www.globtemperature.info/" ;

}

End of document