

# **The Surface Temperatures of the Earth: Steps towards Integrated Understanding of Variability and Change**

## **A Community Position Paper arising from the first EarthTemp Network Meeting (June 2012, Edinburgh, UK)**

Prepared and reviewed by: EarthTemp Network investigators and Steering Group, and Chairs and Notetakers of Discussion Sessions at the first EarthTemp Network workshop (listed below)

Endorsed by: EarthTemp Network attendees (listed below)

### **Executive Summary**

Surface temperature is a key aspect of weather and climate, relevant to human health, agriculture and leisure, ecosystem services, infrastructure development and economic activity. The term “surface temperature” encompasses several distinct temperatures that differently characterise even a single place and time on Earth’s surface, as well as encompassing different domains of Earth’s surface (surface air, sea, land, lakes and ice).

Different surface temperatures play inter-connected yet distinct roles in the Earth’s surface system, and are observed with different complementary techniques. To better meet the needs of various applications and users communities, creative exploitation of the strengths of different observing system components is needed. Co-operation between scientific communities who focus on particular domains of Earth’s surface and on different components of the observing system is essential to accelerate scientific understanding and multiply the benefits of this understanding for society. A “whole-Earth” perspective on surface temperature is required.

With this in mind, the EarthTemp Network held its inaugural meeting in June 2012 (Edinburgh, UK). The 55 participants convened from 5 continents with expertise on all of Earth’s surfaces and a full range of relevant techniques. The workshop identified the following needs for progress towards meeting societal needs for surface temperature understanding and information:

1. Develop more integrated, collaborative approaches to observing and understanding Earth’s various surface temperatures
2. Build understanding of the relationships of different surface temperatures, where presently inadequate
3. Demonstrate novel underpinning applications of various surface temperature datasets in meteorology and climate

4. Make surface temperature datasets easier to obtain and exploit, for a wide constituency of users
5. Consistently provide realistic uncertainty information with surface temperature datasets
6. Undertake large-scale systematic intercomparisons of surface temperature data and their uncertainties
7. Communicate differences and complementarities of different types of surface temperature datasets in readily understood terms
8. Rescue, curate and make available valuable surface temperature data that are presently inaccessible
9. Maintain and/or develop observing systems for surface temperature data
10. Build capacities to accelerate progress in the accuracy and usability of surface temperature datasets

The needs are broadly expressed above. 28 specific ambitious steps, relevant to these objectives, are recommended in the remainder of this community position paper. These recommendations are in bold face, and can therefore be reviewed with or without reading the full text.

### **Introduction: A whole-Earth perspective**

The temperature at a location on Earth's surface is profoundly important. Surface temperature is a basic environmental/meteorological parameter that: directly affects human life and well-being; influences the function and viability of ecosystems, including agriculture; exercises controls on surface-atmosphere exchanges of energy, water, gases and aerosols; and is a primary variable of climatology and indicator of climate change. For these reasons and more, the scientific and societal importance of surface temperature has long been obvious, and surface air temperature has been observed and investigated quantitatively for several hundred years.

Surface temperature is not only profoundly important: it is complex. There are in fact several "surface temperatures" that can characterise a given place at a given time (see below). These distinct surface temperatures inter-relate and interact; they partially co-vary (albeit with distinct time constants); they play distinct geophysical and ecological roles, and often vary rapidly with time and distance.

We live in an era of operational numerical weather prediction (NWP), Earth Observation and rapid data communications. Measurements, indirect estimates and information that constrains surface temperatures are available. The availability of different types of surface temperature observation-differs enormously in frequency, spatial density, spatial completeness and length and consistency of record. In some ways, we are simultaneously data rich and data poor with regards to surface temperature observations.

**(1) We recommend the scientific communities, agencies and programmes involved in surface temperature research and applications develop more integrated, collaborative approaches to observing and understanding Earth's various surface temperatures, in order to accelerate progress in this area and multiply the benefits to society. This**

whole-Earth perspective aims to understand and exploit all forms of surface temperature observation across all domains, to develop clearer, more integrated and more informative knowledge of the surface temperatures of Earth, how they vary and how they may be changing. To multiply benefits and services to science and society, this activity needs to be supplemented by knowledge exchange, both to communicate comprehensive data and insight conveniently to users, and to draw in improved understanding and refined requirements from users.

**(1.1) The surface temperature observations included in this comprehensive perspective are:**

- land surface air temperature (LSAT) measured at ~2 m height in meteorological stations
- land surface temperature (LST) estimated from satellite thermal and passive microwave sensors measurements
- marine air temperatures (MAT) measured from ships and buoys
- sea surface temperatures measured at depth from ships, buoys, etc (SST-depth)
- sea surface temperature estimated from satellite thermal sensors (SST-skin) and passive microwave sensors (SST-subskin) measurements
- lake surface water temperature (LSWT, skin and depth), both measured in situ and estimated from satellites, and including inland seas, reservoirs, etc
- ice surface temperatures (IST), both measured in situ and estimated from satellites
- various more specialist surface temperature measurements (in situ thermal radiometry, ice-buoy thermistor chains, micrometeorological measurements, etc)

The remainder of this white paper identifies broad consensus objectives and specific ambitious steps towards those objectives.

**Build understanding of the relationships of different surface temperatures, where presently inadequate**

While there is understanding of the relationships of different surface temperatures, research is required in several areas to reach a level where we can effectively “exploit all forms of surface temperature observation across all domains, to develop clearer, more integrated and more informative knowledge of the surface temperatures of Earth, how they vary and how they may be changing”.

**(2) We recommend work to build understanding of the relationships of different surface temperatures, where presently inadequate**

**(2.1) Satellite IST and field measurements over ice sheets and sea ice show discrepancies that aren't fully explained. We recommend continuation of intensive efforts to reconcile these.** Strategic efforts are required here, and recommendation 9.4 on dedicated reference sites is relevant.

**(2.2) We recommend closer dialogue between the surface temperature and NWP re-analysis communities, to clarify the correspondence between model and observed surface temperatures, and to maximise their mutual exploitation.**

**(2.3) We recommend global systematic analysis of LSAT vs. LST relationships.** The programme of research should encompass: statistical relationships and how these vary with

meteorological, micro-meteorological, geographical and land-cover context; model/process studies and experiments designed to account for observed relationships; assessment of observed relationships in comparison to those present in major re-analysis products. Such a programme would support developments such as merged LSAT/LST datasets and use of LST in validating interpolated/gridded LSAT datasets.

**(2.4) We recommend research to elucidate the inter-relationships of surface temperature along 'edge-lands': the marginal ice zone (SST, IST, MAT), coastal zones (SST, LSAT, LST, MAT), and suburbs (heat island fringes).** There are complex issues around representation of surface temperature in the vicinity of boundaries and transition zones between domains. Datasets straddling such boundaries can disagree markedly depending on the assumptions made about how to combine data. Basic observational challenges for remote sensing are often even more complex because of the heterogeneity of 'edge-lands', and LST, SST and/or IST may be less accurate. Moreover, the true surface temperatures we seek to quantify and understand may be spatially variable (e.g., the land/sea temperature contrast) and interact (e.g., the land/sea breeze).

(Recommendations 2.3 and 2.4 are fundamental also to Recommendation 6 below.)  
Demonstrate new underpinning applications of various surface temperature datasets in meteorology and climate

The recommendations made in this paper are justifiable only because of the significant benefits foreseen from better, more accessible, more consistent surface temperature datasets. Applications in areas as diverse as crop modelling, volcano monitoring, water management, emergency responses to heat waves, lake ecology, sea-ice forecasting for shipping and many more will benefit downstream. EarthTemp Network participants recommend some particular goals in the area of meteorology and climate. Weather forecasting and climate services exploit understanding of various forms of surface temperature, and progress here underpins a wide range of benefits to society.

**(3) We recommend demonstration of new underpinning applications of various surface temperature datasets in meteorology and climate**

**(3.1) The exploitation of improved LST, LSWT and IST within numerical weather prediction and re-analysis should be further demonstrated.**

**(3.2) Climate-quality, >10-year-long timeseries of LST, LSWT, SST and IST should be systematically developed from satellite observations (some exist), assessed against in situ based trends, and exploited in climate model evaluation.**

**(3.3) The use of LST in understanding urban and suburban temperature distributions (heat island effects) should be advanced.**

**(3.4) There should be large-scale trials of the use of LSTs to help validate step-change detection and adjustments applied to LSAT timeseries from weather stations.**

**(3.5) The use of LSTs in informing interpolation of LSAT across areas without meteorological stations should be developed. This includes historical reconstruction using spatially complete modes of variability.**

Development of LSWT (see 3.2) in particular is rendered difficult by lack of accessible *in situ* validation data for many major lakes outside of N. America and Europe.

### **Make surface temperature datasets easier to obtain and exploit, for a wide constituency of users**

Users of surface temperature information are varied, and no single type of surface temperature dataset or spatio-temporal resolution will meet all their requirements. Users vary in their capacity to identify and obtain suitable environmental datasets and in their capacity to handle varied data formats. There are probably many potential non-specialist surface temperature data users in areas of health, planning, agriculture, etc. Measures such as the adoption of common surface temperature file contents and a common format may greatly expand the user base.

At the same time, the current diverse formats and contents are often driven by the interests of specific target communities with their own norms. For example, some communities expect datasets to be readily understood by Geographical Information Systems, whereas the climate community would expect the same data in netCDF files compliant with the climate and forecasting (CF) convention. A solution is a common standard across all domains, formats tailored to specific communities, and tools to convert data between standards.

**(4) We recommend that surface temperature datasets of all types be made easier to obtain and exploit, for a wide constituency of users. Specific steps towards this need to be undertaken with extensive consultation of potential users.**

**(4.1) Regarding satellite datasets, we recommend creating and sustaining a global data assembly centre (GDAC) and long-term stewardship facility (LTSF) that collect, curate and disseminate datasets, in common, self-describing formats, with free and open data access.**

This concept and nomenclature derives from the Group for High Resolution SST (GHRSSST), who have developed over several years a system including these elements for SST, by sharing tasks multi-laterally across several agencies. This proposal therefore applies to datasets other than SST. The idea is to create an equivalent capability for other domains, that can interact with and develop in tandem with GHRSSST. As well as the principles, it will be efficient to adopt and adapt applicable GHRSSST precedents in detail to ensure compatibility and avoid duplication of effort.

This is an ambitious recommendation, and smaller steps towards increasing accessibility and ease-of-use of surface temperature datasets should be pursued to build the user communities that would ultimately demand and exploit a GDAC/LTSF. Such steps include common portals or websites with links to satellite surface temperature datasets, accompanied by reliable, high level dataset descriptions and references.

An existing common-format initiative of this sort is the obs4MIPS programme, to create datasets readily usable by climate modellers and distributed via the Earth System Grid.

**(4.2) We recommend that surface temperature data providers with datasets relevant to climate modelling applications should participate in obs4MIPS where this is not already the case.**

**(4.3) We recommend expanding and simplifying access to the fundamental data holdings for *in situ* surface temperature records of all types.** This recommendation seeks to build on the progress of the International Surface Temperatures Initiative (ISTI) in rescuing, standardising and serving free and open meteorological station data from a single portal. In principle, it is attractive to integrate records from ISTI, the International Comprehensive Ocean-Atmosphere Dataset (ICOADS), and the International Arctic Buoy Program (IABP) into a shared access point. This would not supersede the need for ISTI, ICOADS, IABP and similar programmes, but would rather depend on such programmes, and arguably would augment their reach into surface temperature user communities. A useful interim step is a single location where links are maintained to freely available datasets (e.g., GHCN-daily, ECA&D and many national data sets).

### **Consistently provide realistic uncertainty information with surface temperature datasets**

Uncertainty information provided with surface temperature datasets needs to be consistently provided in two senses. First, uncertainty information should always be provided. Second, uncertainty information provided in different datasets needs to be comparable, certainly for different instances of the same sort of dataset, and ideally across different domains and types of observation.

Uncertainty is easily underestimated, and good practice needs to be developed and adopted to make uncertainty information realistic. This will make it usable in contexts where relative uncertainty in different datasets is crucial, such as statistical and assimilation-based applications of surface temperature data. Following Einstein's famous dictum, uncertainty information needs to be as simple as possible -- but not simpler. Uncertainties need to be appropriately propagated when data are aggregated into higher-level products, in order to ascribe realistic, consistent uncertainties to these higher-level datasets. This implies at least some representation of uncertainty components with differing degrees of spatial and temporal correlation. Equi-probable ensemble approaches are also attractive for capturing the complexities of uncertainties, where practicable. Users' needs regarding uncertainty information will need to be surveyed. Perhaps less obviously, users' exploitation of improved uncertainty information will need to be actively facilitated.

**(5) We recommend that all surface temperature measurements or estimates be provided with a realistic estimate of surface temperature uncertainty.** Uncertainty varies within products, from location to location. Much of this variation is usually amenable to quantification. Uncertainty information specific to each surface temperature measurement or estimate is preferable to generic estimates, but this is not universal practice. The surface temperature community should develop shared vocabulary and objectives about what forms of uncertainty information to provide. Probably, it is a necessary minimum to distinguish and

quantify random, partially correlated and systematic components of uncertainty. Where components cannot be estimated and are missing from uncertainty estimates, this needs to be clear to give a fair picture to users. Providing uncertainty estimates does not supersede the need for quality and/or confidence flags in datasets.

We note that this is a challenging area. Measurement uncertainty (which may have spatio-temporal correlation), parametric uncertainty and structural uncertainty may all be present in a dataset. The propagation of uncertainty from individual measurements through to end products can be complex. Interactions with metrologists and statistical experts can help define appropriate approaches to these challenges.

**(5.1) We recommend that uncertainty information associated with surface temperatures-measurements or estimates is itself subject to validation.** For confidence in the realism and comparability of surface temperature uncertainty estimates, the surface temperature community should develop shared approaches and good practice for validation of uncertainty information. It is important to minimise underestimation of uncertainty, avoiding situations where surface temperature products disagree by more than their supposed uncertainties plausibly explain. Relevant techniques will include inference from distributions of discrepancy between measurements from different components of the observing system, and triple collocation (multi-sensor) approaches. It will sometimes be necessary to develop better understanding of the true geophysical discrepancies between the different measurements. For structural components of uncertainty in creating datasets, the benchmarking approach can be informative. (Benchmarking quantifies the impacts of different choices and methods of dataset generation using test-cases that are synthetic, and thus perfectly known, and realistic.)

**(5.2) We recommend that a common uncertainty vocabulary be developed and adopted by the surface temperature community, building where possible on agreed usage from the metrological community.** This will facilitate communication on uncertainty and quality issues within the surface temperature community, with metrologists, and informed users. The vocabulary needs to be intellectually rigorous, and consistent with metrological usage where applicable. The vocabulary also needs to address all the types of uncertainty inherent in measuring or estimating surface temperature using satellite or in situ sensors and in creating and using such datasets, including those related to spatiotemporal sampling and correlation.

**(5.3) We identify the need for improved interactions on the topic of uncertainty characterisation, across the surface temperature science community and with users. We recommend workshops involving producers and users, testing of different approaches to uncertainty information with use cases, and similar measures.**

### **Undertake large-scale systematic intercomparisons of surface temperature datasets and their uncertainties**

Users require guidance about the suitability of different surface temperature datasets for different applications, and information about how and why surface temperature datasets differ (see also Recommendations 2.3, 2.4 and 6). Surface temperature data providers need

to be able to summarize and interpret differences for users, and in part this depends on doing systematic intercomparisons of diverse surface temperature datasets.

Systematic intercomparison between different types of surface temperature datasets will be fruitful both in communicating the differences between different temperatures, and in challenging and developing our understanding of the physics underlying differences.

Systematic intercomparison between datasets of nominally the same sort of surface temperature is crucial in communicating the full degree of discrepancies across the choice of products that a user faces in selecting datasets for their application. For example, in the case of satellite LST, surface heterogeneity, geolocation uncertainty, spectral dependencies and view-angle dependencies produce relatively large, complex, localised differences in LSTs from different sensors. For a given sensor, LSTs generated using different methods and assumptions can likewise differ significantly.

Systematic comparison of differences between datasets with the corresponding estimated uncertainties may well reveal the need to uncover and estimate additional components of uncertainty that are sometimes neglected, but are nonetheless relevant to potential users.

Satellite, gridded and blended surface temperature datasets are created by a complex sequence of steps in relation to data screening, aggregation and/or interpolation. These steps often involve detailed choices that, while based on reasoning and testing, are not fully objective. For example, when aggregating data, the weights of different inputs may depend on assumptions used to model various sources of uncertainty. Intercomparison of the consequences of such decisions can be fruitful at these intermediate stages, in addition to intercomparison of surface temperature and surface temperature uncertainty information. Benchmarking approaches are useful here. These are exercises in which common, sometimes idealised, inputs are subjected to a variety of approaches for synthesising datasets. The comparison of the resulting datasets is informative about the structural uncertainty arising from the choices made and methods used.

**(6) We recommend that all projects to develop and extend surface temperature datasets include resources dedicated to large-scale systematic intercomparisons (of both surface temperatures and their uncertainties).** The intercomparisons need to include but extend well beyond comparison to proximate datasets (such as previous versions or alternative products derived from the same raw observations), in order to expose the full range of dataset differences relevant to potential users.

**(6.1) We recommend more systematic intercomparison of the effects of different observing and recording practices between meteorological services on the surface air temperature record.** Measurement and recording practices for LSAT from weather stations are only partly standardised across meteorological services by the World Meteorological Organisation. Different practices significantly affect the absolute timeseries and climatology obtained, with more subtle impacts on anomaly timeseries. It is important to understand properly the effects of variations in practice on important surface temperature timeseries and on the relationships between different types of surface temperature (Recommendation 2). There is also a need



for more systematic assessment of the impacts of different methods of homogenising LSAT records.

**(6.2) We recommend development of a multi-product ensemble of directly-comparable representations of different surface temperature datasets.** The GHRSSST multi-product ensemble (GMPE) provides a useful precedent here. Surface temperature datasets may have, for good reasons, a range of spatial resolutions and binning/averaging in time. Large-scale intercomparison can be addressed by creating consistent representations of different datasets on a common time and space grid. These representations can then be readily manipulated to explore commonalities and differences. A web service providing on-the-fly visualisations of the ensemble and differences between members over time is a powerful way of allowing users to explore differences and build their understanding of surface temperature datasets.

### **Communicate differences and complementarities of surface temperature datasets in readily understood terms**

**(7) We recommend improved communication of the differences and complementarities of surface temperature datasets in readily understood terms.** In some cases, this needs to be underpinned by a firmer understanding of physical relationships between measurands (Recommendation 2). Recommendation 6.2 (for a surface temperature multiproduct ensemble) is also relevant and needs to be augmented by a range of written information.

**(7.1) We identify the need for a review paper, adopting a whole-Earth surface temperature perspective, explaining to general scientific users the range of surface temperature measurands, their physical significance, their inter-relationships, and the status of their corresponding measurements.** Several useful precursors for this exist covering certain domains, and the EarthTemp Network can co-ordinate this comprehensive publication.

**(7.2) We recommend adoption by surface temperature dataset producers of a common approach to providing briefing notes (~5 pages) for users.** Models for this exist and ideally an existing approach already in use within the surface temperature community should be adopted. It may be necessary to supplement an existing approach -- for example, with a structured discussion of how the surface temperature is different to and complements other types of surface temperature.

### **Rescue, curate and make available valuable surface temperature data that are presently inaccessible**

**(8) We recommend co-ordinated efforts to rescue, curate and make available valuable surface temperature data that are presently inaccessible.**

**(8.1) We support data rescue and curation initiatives related to historical meteorological observations, and recommend these include free and open access to digitized data.** Data rescue and curation is scientifically critical and an issue of inter-generational responsibility. We strongly support initiatives such as the All-Russia Research Institute of Hydrometeorological Information World Data Centre Baseline Datasets, Old Weather,

Atmospheric Circulation Reconstructions over the Earth (ACRE), ISTI, ICOADS (including the “value added” initiative) and Mediterranean Data Recovery (MEDARE). (There may be many more of which we are not aware.) Necessary elements of the most useful initiatives are: digitization; free-and-open access online; convenient integration of new data within already-available datasets; maintenance of datasets including migration to new storage media. “Citizen science” approaches to digitization can be scientifically effective and cost effective, and can have benefits relating to public engagement with science. Other data recorded with surface temperature records (e.g., precipitation, pressure) should be digitized as part of a single effort, for reasons of cost effectiveness and because they help to interpret the temperature records. Recent significant progress made in meteorological data rescue is welcomed, yet there is more that can be done.

**(8.2) We recommend that space and other agencies with responsibility for Earth-observation data relevant to surface temperature (and climate in general) are pro-active in data rescue and stewardship. This includes recovery and curation of the satellite observations (at all data processing levels) and of all pre-flight and in-flight calibration information.** Full calibration information is critical to future reprocessing of satellite observations and should be readily accessible and curated along with mission data. This will support satellite reprocessing initiatives using best techniques (arising from improved radiative transfer including advances in understanding surface emissivity, improved input data from satellite data rescue and recalibration efforts, and theoretical advances in image classification and retrieval). The GHRSST community includes an initiative to rescue full resolution (locally downlinked) NOAA meteorological satellite data, and co-operation with this initiative is recommended to all relevant holders of such data. There is relevant effort within the ERA-CLIM project and the NOAA climate data records programme.

**(8.3) We recommend international co-ordination of a programme of data rescue and curation related to research campaign data that includes meteorological observations, including surface temperature.** Research campaign data with surface temperature information is often not publicly accessible, and can provide especially valuable data from sparsely observed regions and epochs. Such data can independently test satellite retrievals, merged datasets, re-analysis fields and/or historical reconstructions. We recommend a systematic effort to collect these data with all necessary metadata, internationally, engaging research councils and institutes internationally. The rescued data should be transformed to a standard form and made freely and openly accessible. Good precedents exist that can be followed and extended, such as the open data access to observations of the Shipboard Automated Meteorological and Oceanographic System programme.

**Maintain and/or develop observing systems for surface temperature data**

**(9) Observing systems for surface temperature need to be maintained and/or developed.**

As regards satellite-based observations of surface temperature, the requirements for observations across all domains can be based on those articulated for the operational SST satellite constellation, with some additional requirements.

**(9.1) We recommend maintenance of a satellite constellation in line with GHRSSST recommendations for SST, as the baseline for a constellation for observing all surface temperatures.** The SST constellation comprises complementary observations: ~1 km resolution polar-orbiting visible and thermal imagery; frequent geostationary imagery for diurnal cycle observation; high-accuracy, low-noise, two-point calibrated dual-view thermal imagery; passive microwave for low-resolution all-weather capacity with a channel suitable for high latitude SST estimation. A GHRSSST position paper from 2009 foresaw the risk of lack of continuity and overlap of the passive microwave and dual-view thermal components of the system, which unfortunately came to pass in 2011 and 2012. The importance of appropriate redundancy of observation to maintain continuity is re-affirmed here.

From the whole-Earth perspective, additional elements in a satellite constellation are required to maximise the utility of LST.

**(9.2) In addition to the baseline from Recommendation 9.1, the whole-Earth surface temperature constellation requires development and maintenance of global multi-band thermal imagery with high spatial resolution (objective ~10 m),** Progress can be made by improving fundamental knowledge of spatial heterogeneity in surface temperature and surface emissivity at scales smaller than resolved by the meteorological-style sensors (as demonstrated in some circumstances with ASTER). The high resolution is particularly required for understanding urban areas, which are extremely heterogeneous and of great societal relevance. We note that maintenance of a stable local observation time is more crucial for LST than for SST because of the larger diurnal cycle of the former.

**(9.3) We recommend more LSAT sites specifically designed for long-term climate reference purposes at strategic locations globally, with access to specifications and metadata.** A model for this is the US climate research network ([www.ncdc.noaa.gov/uscrn](http://www.ncdc.noaa.gov/uscrn)).

**(9.4) We recommend new long-term sites suitable for radiometric validation of satellite surface temperature and traceability to SI standards. Some should be co-located with LSAT climate reference observations.** Long-term radiometric sites are required for land and ice surfaces spanning a wide range of climate regimes globally. No radiometric reference sites currently exist for SST, and this should be rectified. All these sites should be maintained with quantified, high levels of stability.

### **Build capacities to accelerate progress in the accuracy and usability of surface temperature datasets**

**(10) We recommend broad-impact building of capacity to accelerate progress in the accuracy and usability of surface temperature datasets.** Specific examples follow below.

Significant errors in satellite LSWT, LST, IST and (to a lesser degree) SST arise, still, from image classification errors. Accurate surface temperature retrieval using thermal sensors depends on cloud-free conditions. Clear-sky over water, land, ice and snow need to be distinguished from cloud-affected conditions, which is particularly challenging when the surface is highly reflective. Classification / cloud detection problems are also more acute

along boundaries; e.g., SSTs are routinely absent for the coastal pixels in many satellite datasets.

A key to rapid and consistent progress here is the capacity to estimate a priori, with known error covariance, the plausible radiances for each possible class given the observational situation (atmospheric state and surface characterisation). The necessary radiative transfer knowledge and models exist, but are not integrated and easy-to-use across domains. Therefore:

**(10.1) We recommend building integrated capacity for radiative transfer simulation across all surface temperature-relevant sensors (all wavelengths/channels, surface domains, view and illumination conditions), in support of mitigating cloud detection errors in satellite surface temperature datasets.** Relationships between varied in situ and satellite surface temperatures can be powerfully elucidated using matched multi-sensor data augmented by auxiliary information. Multi-sensor matching also supports improvement in surface temperature estimates, development of uncertainty information, validation of uncertainty information, interpretation of differences in surface temperatures, inter-comparison of sensors and algorithms, and design of quality control. Systems to provide multi-sensor match-up datasets are difficult to design and create. Some precedent exists with the SST community developed under ESA funding.

**(10.2) We recommend building shared capability for multi-sensor matched-data techniques across all domains of Earth's surface.** Reference sites (recommendations 9.3 and 9.4) would be an appropriate focus for initial developments of a multi-sensor match-up system.

### Concluding remarks

Significant benefits are foreseen to arise from better, more accessible, more consistent surface temperature datasets and these justify the considerable effort that our recommendations require. The whole-Earth perspective adopted here will, we consider, accelerate progress and multiply benefits to society from investments in meteorological and Earth observation. This will happen because of the efficiency of shared capacity building, the willingness of the surface temperature community to share ideas and agree common approaches, and because of increased quality, accessibility and usability of surface temperature datasets. Improved dialogue with users will be required and is necessary to ensure the most effective translation of the improved ST data into applications.



## About the EarthTemp Network and the writing of this position paper

The EarthTemp Network ([www.earthtemp.net](http://www.earthtemp.net)) is a funded research network, sponsored by the UK Natural Environment Research Council with the aim of increasing international co-operation and progress in quantifying and understanding variability and change in surface temperature across all domains of Earth's surface. The initiative does not aim to replace or supersede any existing programmes or activities, but rather to build collaboration.

The EarthTemp Network hosted its first workshop in Edinburgh in June 2012. Fifty-five participants gathered from 5 continents attended, with almost all of the desired range of expertise represented: scientists working on every domain of Earth's surface, making or using in situ measurements, satellite products and re-analysis.

The meeting included networking activities to build relationships across the new community, overviews of the state of the art in the field, and a series of 20 intensive small-group discussions on current gaps in our knowledge and scientific priorities on 5 to 10 year timescales across a number of themes. This position paper captures, as concretely as possible, the community conclusions of these discussion groups. The chairs of each discussion group, aided by notetakers, presented the outcomes of each group in plenary at the end of the workshop, with further opportunity to discuss and refine the points captured.

The PI of the network took these presentations as the starting point to draft this discussion paper. The next draft captured the comments and amendments of the project's co-Is and international steering group and the chairs and notetakers of the discussion sessions. Finally, the draft was sent to all participants for their comment and final approval. This process was intended to ensure that the final version is truly a consensus white paper from the EarthTemp Network membership.

This version of the white paper is for broad, rapid communication of the workshop's outcomes. It is intended that an extended version, with more detailed scientific justification and citations, will be prepared for peer-reviewed publication.

## Authorship and endorsement

**Lead author:** Christopher J. Merchant

**Co-authors:** Nick A. Rayner, Prof. John J. Remedios, Stephan Matthiesen, Prof. Phil Jones, Folke Olesen, Blair Trewin, Peter Thorne, Renate Auchmann, Gary K. Corlett, Pierre Guillevic, Glynn Hulley.

**Endorsed by:** Lisa Alexander, David Berry, Manola Brunet, Claire Bulgin, Katarzyna Dąbrowska-Zielińska, Emma Dodd, Claude Duguay, Owen Embury, Eirik Førland, Darren Ghent, Frank Göttsche, Lizzie Good, Yatian Guo, Dorothy Hall, Jacob L. Høyer, Maria A. Jiménez, Juan Carlos Jimenez-Muñoz, Alexey Kaplan, John Kennedy, Elizabeth Kent, Albert Klein, Jean-Pierre Lagouarde, Aisling Layden, Michele Lazzarini, David Llewellyn-Jones, Giuseppina Lopardo, Stuart MacCallum, Cristian Mattar, Mark McCarthy, Matt Menne, Colin Morice, Simon Pinnock, Fred Prata, Viatcheslav Razuvaev, Ignatius Rigor, Hervé Roquet, Matilde Rusticucci, Prashant Sardeshmukh, Philipp Schneider, Kay B. Smith, Jose Sobrino, Karen Veal, Yunyue Yu

**Lead author contact and affiliation:** Christopher J. Merchant ([c.merchant@ed.ac.uk](mailto:c.merchant@ed.ac.uk)), School of GeoSciences, University of Edinburgh, King's Buildings, Edinburgh EH9 3JN, UK