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EUSTACE

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EU Surface Temperature for All Corners of Earth

Deliverable D3.*5*

Validation report for the final in-filled EUSTACE surface air temperature product

Deliverable Title	*Validation report for the final in-filled EUSTACE surface air temperature product*		
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1) Executive Summary

Here, we report on the validation of the EUSTACE Global air temperature estimates, v1.0, alongside validation of the EUSTACE Air temperature estimates from satellite, v1.0.

The EUSTACE daily air temperature estimates were matched with reference daily air temperatures from land stations, ice stations and moored buoys and instantaneous observations of air temperature from ships and ice buoys. The reference data used for validation were excluded from both the relationship building in Work Package 1 and the inputs to the analyses produced by Work Package 2.

Over ocean the EUSTACE Global air temperature estimates, v1.0 performs well with a global median discrepancy (RSD) of +0.005 K (1.76 K) against HadNMAT2 inputs over 1995-2012 and 0.00 K (1.15 K) over 1850-2012. The highest discrepancies are found in the Southern Ocean, although matchups are sparse in this region.

The EUSTACE Global air temperature estimates, v1.0 also performs well in most land regions with a global median discrepancy (RSD) against withheld data from the EUSTACE Global Station Dataset of -0.13K (1.76K) over 2002-2015 and -0.23K (1.76 K) over 1850-2015; the negative discrepancy arises largely over some regions of Africa and the west of North America. However seasonal median discrepancies over central Asia can be high, 6-10 K in DJF at some stations. Nonetheless, comparison to the validation results of the EUSTACE Air temperature estimates from satellite v1.0 demonstrates that significant seasonal biases have successfully been removed by the analysis method over land in most locations.

Over ice domains, the EUSTACE Global air temperature estimates, v1.0 performs less well over 2001-2009, especially over Arctic land. Regional median discrepancies (RSDs) against DMI Quality Controlled ice buoy data are +0.25 K (3.17 K) in the Arctic and -0.29 K (4.14 K) in the Antarctic sea ice regions. However, these results also represent a reduction in bias compared to those seen in the EUSTACE Air temperature estimates from satellite v1.0 here (see below). The median discrepancies and RSDs for sea-ice are much larger in the years after 2009 when the satellite air temperature estimates end in these regions. The regional median discrepancies over land-ice (including the Antarctic ice-shelf) against station data are: +0.57 K (3.57 K) in the Arctic and +0.27 K (2.38 K) in the Antarctic; here a warm bias relative to withheld validation data is introduced in the analysis in the Antarctic.

Over the longer period, 1890-2015, the EUSTACE Global air temperature estimates, v1.0 shows discrepancies of +0.37 K (4.04 K) over Northern Hemisphere land ice, +0.47 K (2.68 K) over Southern Hemisphere land ice, +1.19 K (4.60 K) over Northern Hemisphere sea ice and +4.76 K (6.81 K) over Southern Hemisphere sea ice. The increase in positive bias when the whole period is considered arises from a drift in the EUSTACE Global air temperature estimates, v1.0 over the Poles prior to about 1960;

these erroneous data have not been released in these regions, as they do not provide useful information.

The EUSTACE Air temperature estimates from satellite v1.0 demonstrate a positive median discrepancy (RSD) against HadNMAT2 of +0.25 K (1.19 K) with the highest discrepancies occurring in the mid to high northern latitudes. Note there were few matchups south of 20° N and none south of 50° S.

Over land EUSTACE Air temperature estimates from satellite v1.0 provides estimates of Tmin and Tmax. Although the global median discrepancies (RSDs) against EUSTACE GSD are not large, –0.23 K (2.95 K) for Tmin and +0.21 K (3.37) for Tmax, there is considerable regional and seasonal variation in median discrepancy.

Over ice, the EUSTACE Air temperature estimates from satellite v1.0 have regional median discrepancies of +0.02 to +0.98 K and RSDs of 2.73 to 3.64 K depending on region and surface type (land or sea-ice).

The uncertainty estimates accompanying the EUSTACE Air temperature estimates from satellite v1.0 vary in quality depending on domain. Over ocean the uncertainty estimates are accurate, over land for both Tmin and Tmax the uncertainties are accurate for the smaller uncertainties but underestimated on data with higher uncertainties, and over ice the uncertainties are underestimated.

The uncertainty estimates provided with the EUSTACE Global air temperature estimates, v1.0 show little agreement with the modelled value over ocean (overestimated and show little variation with actual discrepancy), but good agreement over land, which will allow users to filter out poor quality data there. Since the EUSTACE Global air temperature estimates, v1.0 validates extremely well in comparison to withheld data over the ocean, this hopefully mitigates the impact of the less-effective uncertainty estimates here. Analysis uncertainties are underestimated over ice regions, particularly in the Northern Hemisphere and over Southern Hemisphere land ice; here, this arises from the treatment by the analysis method of the over-sampled air temperature estimates from satellite.

Results from the validation, alongside the development of other objective criteria, have been used to determine where and when EUSTACE Global air temperature estimates, v1.0 is suitable for release. The results shown here are derived from matchups with the globally-complete, pre-release fields produced by the statistical analysis. Users will find that the data which are shown here to validate particularly poorly are likely not to have been released in the final product.

2) Project Objectives

With this deliverable, the project has contributed to the achievement of the following objectives (DOA, Section B1.1):

No.	Objective	Yes	No
1	Intensively develop the hitherto immature use of Earth Observation estimates of Earth's surface **skin** temperature to enable new Climate Data Records of the surface **air** temperature Essential Climate Variable (ECV) to be created, for all locations over all surfaces of Earth (i.e. land, ocean, ice and lakes), for every day since 1850. EUSTACE will achieve this by: combining information estimated from multiple satellites with surface air temperature measurements made *in situ* and **creating complete analyses** of surface air temperature, through the application of novel statistical in-filling methods.	Yes	
2	Integrate these new daily surface air temperature Climate Data Records into a range of applications in Earth System Science and Climate Services and research, amongst others. EUSTACE will achieve this via the active and continuous engagement of trail-blazer users, and the provision of products through already-existing user community data portals and service mechanisms, in standard formats.		No
3	Undertake and report detailed research into the relationships between surface skin temperature estimated from Earth Observation satellite measurements and surface air temperature observed *in situ* by conventional measurements, over all surfaces of the Earth, including the polar regions. This is likely to provide information useful for refining coupling in Earth system models.		No
4	Create a sustainable, automated system at an appropriate level of maturity for the potential production of the products beyond the lifetime of the project. To enable this, EUSTACE will also identify Earth Observation and conventional data streams that could be used to update the surface air temperature Climate Data Records in the future, including those from Sentinel missions.		No
5	Extensively validate the new surface air temperature Climate Data Records against independent, surface-based reference data, sourced by the project for this purpose.	Yes	

6	Develop and report new, consistent, validated estimates of uncertainty both in already-existing Earth Observation surface skin temperature estimates and in the new surface air temperature Climate Data Records, at all locations and times across the Earth's surface.	Yes	
7	Develop links with related activities within Europe and beyond to help to ensure the execution of a joined-up work programme, the Copernicus Services and to enable the provision of requirements for the future surface skin temperature and surface air temperature observing system.		No
8	Other – not directly linked to one of the above objectives		

3) Detailed Report

a) Introduction

This report describes the validation against independent reference *in situ* air temperatures of the EUSTACE Global air temperature estimates, v1.0 and its uncertainty estimates. The results for the validation of the EUSTACE Air temperature estimates from satellite v1.0 are given alongside for the period when they are both available over each surface (land, ocean and ice). Since the EUSTACE Air temperature estimates from satellite are input to the EUSTACE Global air temperature estimates, v1.0 (along with station data), an assessment of these inputs can aid interpretation of the results of validation of the Global air temperature estimates. The Appendix provides equivalent results for EUSTACE Global air temperature estimates, v1.0 for the whole period, 1850-2015.

EUSTACE products provide daily temperature statistics. The Air temperature estimates from satellite provide daily minimum temperature (Tmin) and daily maximum temperature (Tmax) over land and ice domains and daily mean temperature (Tmean) over the ocean and ice domains. The EUSTACE Global air temperature estimates, v1.0 provides Tmean and covers 1850 to 2015. The time coverages of the different EUSTACE Air temperature estimates from satellite v1.0 products are given in Table 1.

Table 1: Time coverage of EUSTACE datasets

Test Dataset	Temperature variable	Time Coverage
EUSTACE Global air temperature estimates, v1.0	Tmean	1850 - 2015
EUSTACE Air temperature estimates from satellite v1.0 (ocean)	Tmean	1995 - 2012
EUSTACE Air temperature estimates from satellite v1.0 (land)	Tmin, Tmax	2002 - 2016
EUSTACE Air temperature estimates from satellite v1.0 (ice)	Tmean, Tmin, Tmax	2001 - 2009

b) Methods and data

For the validation of the EUSTACE air temperature estimates over oceans, *in situ* marine air temperatures have been obtained from two sources: a subset of observations input to the Met Office Hadley Centre and National Oceanography

Centre Night Marine Air Temperature dataset (HadNMAT2; Kent et al., 2013), bias corrected to a height of 2 m; and the Global Tropical Moored Buoy Array (GTMBA; McPhaden et al., 2009). Biases due to solar heating are known to affect data observed both from ships and the Global Tropical Moored Buoy Array, so daytime data (solar zenith angles of less than 90°) were discarded and only night-time reference data from these platforms were used. Over land, the data used as reference are taken from the EUSTACE Global Station Dataset; and the University of Leicester *in situ* database which includes data from the Atmosphere Radiation Measurement (ARM; Cadeddu et Al., 2013) network, the United States Climate Regional Network (USCRN; Diamond et al., 2013) and the Baseline Surface Radiation Network (BSRN, Ohmura et al., 1998). DMI Quality Controlled station and ice buoy data are used to validate air temperature estimates over permanent ice in the Polar Regions. The time coverage of the *in situ* reference products are given in Table 2.

With the exception of the EUSTACE Global Station Dataset which provides Tmin and Tmax, the reference *in situ* data are instantaneous observations provided at various frequencies throughout the day. In the case of data observed at stationary platforms, daily temperature statistics were calculated for comparison with the corresponding EUSTACE daily temperature. For mobile platforms such as ships and ice buoys which may move through several EUSTACE grid boxes in a 24 hour period, each reference temperature was matched to the corresponding EUSTACE daily temperature.

Table 2: Reference datasets used in validation

Reference *in situ* dataset	**Abbreviation used in text and plot titles**	**Time coverage**
HadNMAT2 inputs corrected to 2m – subset reserved for validation	HadNMAT2	1850 – 2012
Global Tropical Moored Buoy Array	GTMBA	1979 – 2017
EUSTACE Global Station Dataset – subset of stations reserved for validation	EUST2 or EUSTACE GSD	1850 – 2015
University of Leicester *in situ* database	ULMDB	1993 – 2017
DMI quality controlled station data	DMIQC	1890 - 2015
DMI quality controlled ice buoy data	DMIQC SEA	

For each matchup pair, a matchup discrepancy was calculated (test minus reference). The matchup discrepancy is modelled as the sum of the error on the test value, the error on the reference value and an uncertainty in the matchup process. The uncertainty in the matchup process here has contributions due to spatial matching

(matching a grid box value to a point platform value, and matching of air temperatures at different heights) and temporal matching (matching of instantaneous observations to daily mean temperatures).

Global or hemispheric medians and robust standard deviations of the matchup discrepancies were calculated. The matchup discrepancies were also binned to a 2° x 2° latitude-longitude seasonal climatology in order to visualize any seasonal or spatial variation.

The EUSTACE air temperature estimates are each associated with an estimate of uncertainty which itself must be validated. Here the variance of the matchup discrepancy is modelled as a sum in quadrature of the uncertainty on the reference *in situ* measurement ($\sigma_{in\,situ}$), the test EUSTACE uncertainty estimate ($\sigma_{EUSTACE}$), and a term representing the uncertainty inherent in matching a point observation at an *in situ* station with a 0.25° x 0.25° gridbox mean ($\sigma_{match-up}$):

$$\sigma^2_{discrepancy} = \sigma^2_{in\,situ} + \sigma^2_{match-up} + \sigma^2_{EUSTACE}. \qquad (1)$$

2Uncertainty estimates are provided with the HadNMAT2 and these values are used in the model. For the other *in situ* datasets where uncertainty estimates are not provided a global value is used (Table 3). The values assigned $\sigma_{match-up}$ were estimated from the variance of in situ measurements available from different platforms within a single EUSTACE grid box. Few grid boxes have more than one platform so a single global value was used (Table 3). The modelled matchup discrepancy variance is compared with the actual values.

Table 3: Values assigned to uncertainty on an in situ observation and to the matchup uncertainty in the model of matchup discrepancy variance given in Equation (1).

Dataset	$\sigma_{in\,situ}$ (K)	Reference for $\sigma_{in\,situ}$	$\sigma_{match-up}$ (K)
EUST2	0.5	ARM (2011)	1.0
ULMDB	0.5	ARM (2011)	1.0
GTMBA	0.1	https://www.pmel.noaa.gov/gtmba/sensor-specifications (accessed 18/03/2019)	0.8
HadNMAT2	Uncertainties provided		0.8
DMIQC	0.5	ARM (2011)	1.0
DMIQC SEA	1.0		1.0

The rest of this report discusses the various statistics calculated from the matchup discrepancies for the ocean, land and ice domains.

c) Results

i) Ocean

For validation of EUSTACE air temperature estimates in the ocean domain, reference data are taken from HadNMAT2 inputs (this set of withheld reference data is hereafter referred to as the HadNMAT2 subset) and GTMBA buoys. The GTMBA buoys are limited to the tropics. The HadNMAT2 subset covers a wider geographic region and also a longer time period (Table 2), however, data availability is limited south of a latitude of 40 °S.

Global statistics for matchup discrepancies by reference dataset are shown in Table 4 (and Table 5 in the Appendix). The EUSTACE Global air temperature estimates, v1.0 show zero median discrepancy against the HadNMAT2 subset (+0.005 K with an RSD of 1.76 K over 1995-2012, 0.00K (1.15 K) over 1850-2015). The EUSTACE Air temperature estimates from satellite v1.0 have higher median discrepancies against the HadNMAT2 subset and the GTMBA of between +0.22 K and +0.28 K. The RSD is higher for the EUSTACE Global air temperature estimates, v1.0 and this is likely a result of the wider geographical coverage in the matchups: matchups to the EUSTACE Air temperature estimates from satellite v1.0 are few south of 20° N. The geographical coverage of the matchups of the HadNMAT2 subset to the EUSTACE estimates is evident in the maps of seasonal median discrepancy shown in Figure 1 (see Figure 2 for maps of seasonal RSD).

In all seasons, the median discrepancies of the EUSTACE Global air temperature estimates, v1.0 (Figure 1 and Figure 16 in the Appendix) are small and more consistent geographically than those of the EUSTACE Air temperature estimates from satellite v1.0, which may indicate that the noise is reduced in the analysis. Only in the most data-sparse regions, are discrepancies below -1.0 K or above +1.0 K. There is a slight seasonal cycle seen with more negative discrepancies in DJF and SON than in MAM and JAS in Figure 1.

The EUSTACE Global air temperature estimates, v1.0 has higher RSDs in the northern mid-latitudes, where temperatures are more variable (Figure 2 and Figure 17 in the Appendix, most grid boxes are around 2-3 K), compared to the tropics where RSDs are mostly below 0.5 K. The EUSTACE Air temperature estimates from satellite v1.0 have few matchups in the tropics but again RSDs tend to be higher in the northern mid-latitudes. For both the EUSTACE Global air temperature estimates and Air temperature estimates from satellite, the RSDs are highest in the region of the Gulf Stream, in winter (> 3.0 K).

Medians and RSDs for 10° latitude bands were calculated from the matchup discrepancies (see Figure 3 and left-hand panel of Figure 18 in the Appendix). Air temperature estimates from satellite are consistent with the HadNMAT2 subset to within +/- 0.5K in all latitude bands between 60° S and 80° N. There are no matchups outside of this latitude range. The EUSTACE Global air temperature estimates, v1.0 is consistent with reference data to within +/- 0.25K in all latitudes between 70° S and 80° N, but more positive (negative) discrepancies occur above 80° N (70° S). The discrepancies with the HadNMAT2 subset are smaller still when averaged over the whole period, 1850-2012 (see left-hand panel of Figure 18 in the Appendix). The RSDs for this data set also increase towards the poles.

Time series of global annual median and RSD of matchup discrepancy for matchups to the HadNMAT2 subset are plotted in Figure 4 and the right-hand panel of Figure 18 in the Appendix. Both the EUSTACE Global air temperature estimates, v1.0 and the Air temperature estimates from satellite v1.0 are stable to within 0.25 K over time, back to 1995 for the Air temperature estimates from satellite and back to 1905 for the Global air temperature estimates (whose stability is greater overall). Before 1905, stability in the Global air temperature estimates decreases as the matchups drop below 10,000 per year (right-hand panel of Figure 18 in the Appendix). RSD increases in times of reduced data coverage, such as during the two World Wars.

The relationship between matchup discrepancy RSD and the EUSTACE uncertainty estimate is plotted for the EUSTACE Global air temperature estimates, v1.0 and the Air temperature estimates from satellite v1.0 (ocean) in Figure 5 (and Figure 19 in the Appendix). The modelled matchup discrepancy RSD (dashed line in figures) and the RSD of the matchups in each uncertainty bin (blue bars) are equal if the model is correct, the uncertainties are accurate and the median discrepancy is zero. In the case of the EUSTACE Global air temperature estimates, v1.0 the median discrepancy is near zero for most matchups. However, the matchup discrepancy RSD does not follow the model and varies little with the uncertainty estimate, indicating that the uncertainty estimates for the EUSTACE Global air temperature estimates, v1.0 will be of limited use to users over the ocean. In contrast the uncertainty estimates for the EUSTACE Air temperature estimates from satellite v1.0 characterise the uncertainty well. The matchup discrepancy RSD for each uncertainty bin matches the modelled value for uncertainties up to around 1.5 K. There is a small median bias of up to 0.1 K for air temperature estimates in these bins, which should be included in the EUSTACE uncertainty, so one would expect the bin RSD to exceed the modelled value by this much if the uncertainty estimates were accurate. Therefore the uncertainty estimates may be slightly underestimated, but it is also likely that the model error is of this order due to poor knowledge of the matchup process uncertainty ($\sigma_{matchup}$ in Equation (1)). The analysis indicates that the uncertainty estimates provided with EUSTACE Air temperature estimates from satellite (ocean) are a useful guide to data quality.

Table 4: Global matchup statistics for EUSTACE Air temperature estimates from satellite v1.0 and Global air temperature estimates, v1.0 against reference in situ data for minimum daily temperature (Tmin), maximum daily temperature (Tmax) and mean daily temperature (Tmean). Statistics for the ice domain are for the northern hemisphere (NH) and the southern hemisphere (SH) Polar Regions. Number of matchups are also given in each case.

Ocean									
	EUSTACE Global air temperature estimates, v1.0 Tmean			**EUSTACE Air temperature estimates from satellite v1.0 (ocean) Tmean**					
	Median (K)	**RSD (K)**	**Number**	**Median (K)**	**RSD (K)**	**Number**			
HadNMAT2	+0.005	1.76	877145	+0.25	1.19	73756			
GTMBA				+0.22	0.47	8137			
Land									
	EUSTACE Global air temperature estimates, v1.0 Tmean			**EUSTACE Air temperature estimates from satellite v1.0 (land) Tmin**			**EUSTACE Air temperature estimates from satellite v1.0 (land) Tmax**		
	Median (K)	**RSD (K)**	**Number**	**Median (K)**	**RSD (K)**	**Number**	**Median (K)**	**RSD (K)**	**Number**
EUSTACE GSD	-0.13	1.76	8207589	-0.23	2.95	3099752	+0.21	3.37	3191781
ULMDB				-0.23	2.71	197951	+0.49	3.37	211269
Ice									
	EUSTACE Global air temperature estimates, v1.0 Tmean			**EUSTACE Air temperature estimates from satellite v1.0 (ice) Tmean**					
	Median (K)	**RSD (K)**	**Number**	**Median (K)**	**RSD (K)**	**Number**			
DMIQC NH	+0.57	3.57	34820	+0.53	3.10	23526			
DMIQC SH	+0.27	2.38	31177	+0.02	2.73	19232			
DMIQC_SEA NH	+0.25	3.17	17625	+0.39	3.76	107519			
DMIQC_SEA SH	-0.29	4.14	214635	+0.98	3.64	5496			

EUSTACE Global air temperature estimates, v1.0	EUSTACE Air temperature estimates from satellite, v1.0 (ocean)

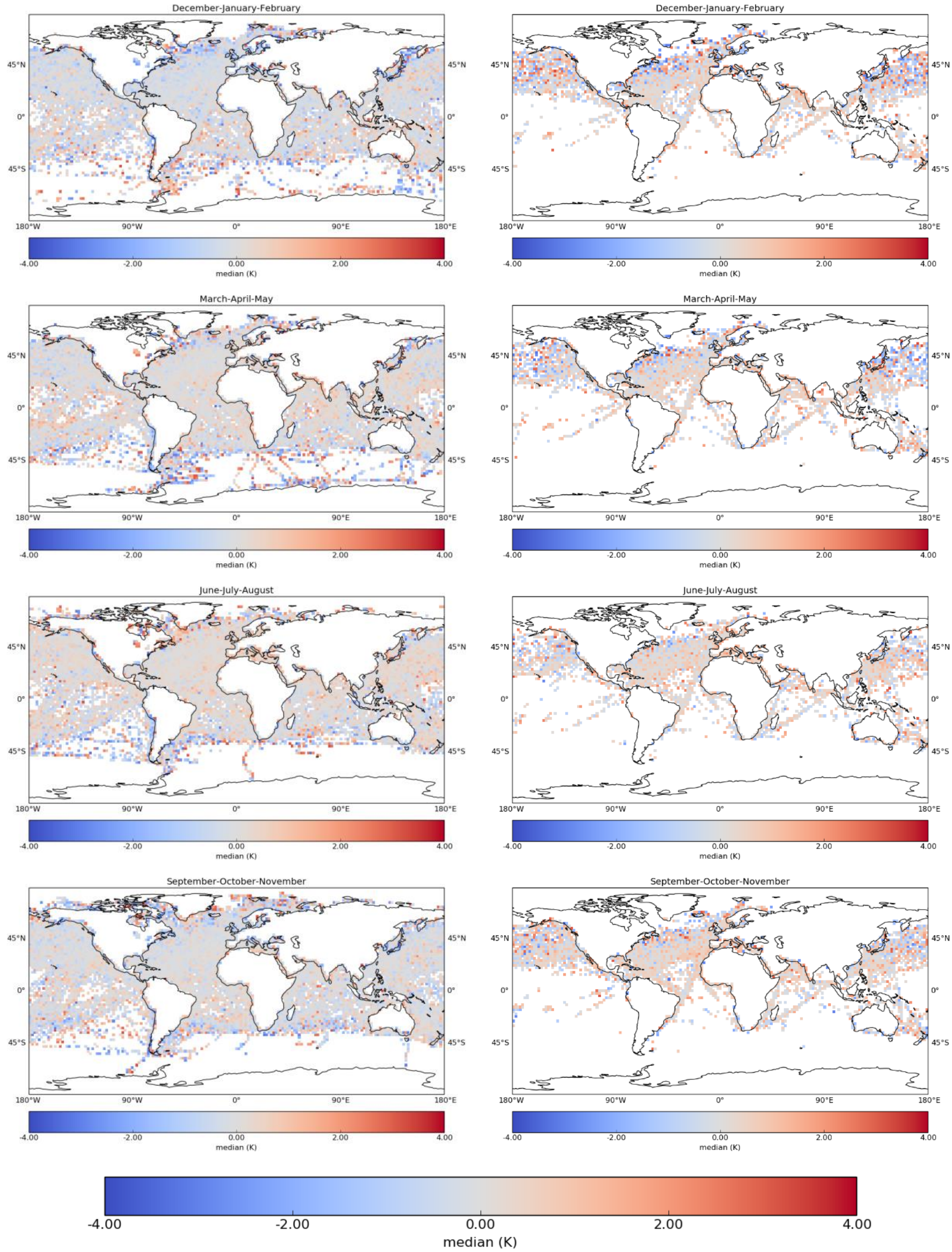


Figure 1: Maps of gridded seasonal mean discrepancy (K) for EUSTACE Products, 1995-2012, minus HadNMAT2 subset

EUSTACE Global air temperature estimates, v1.0	EUSTACE Air temperature estimates from satellite, v1.0 (ocean)

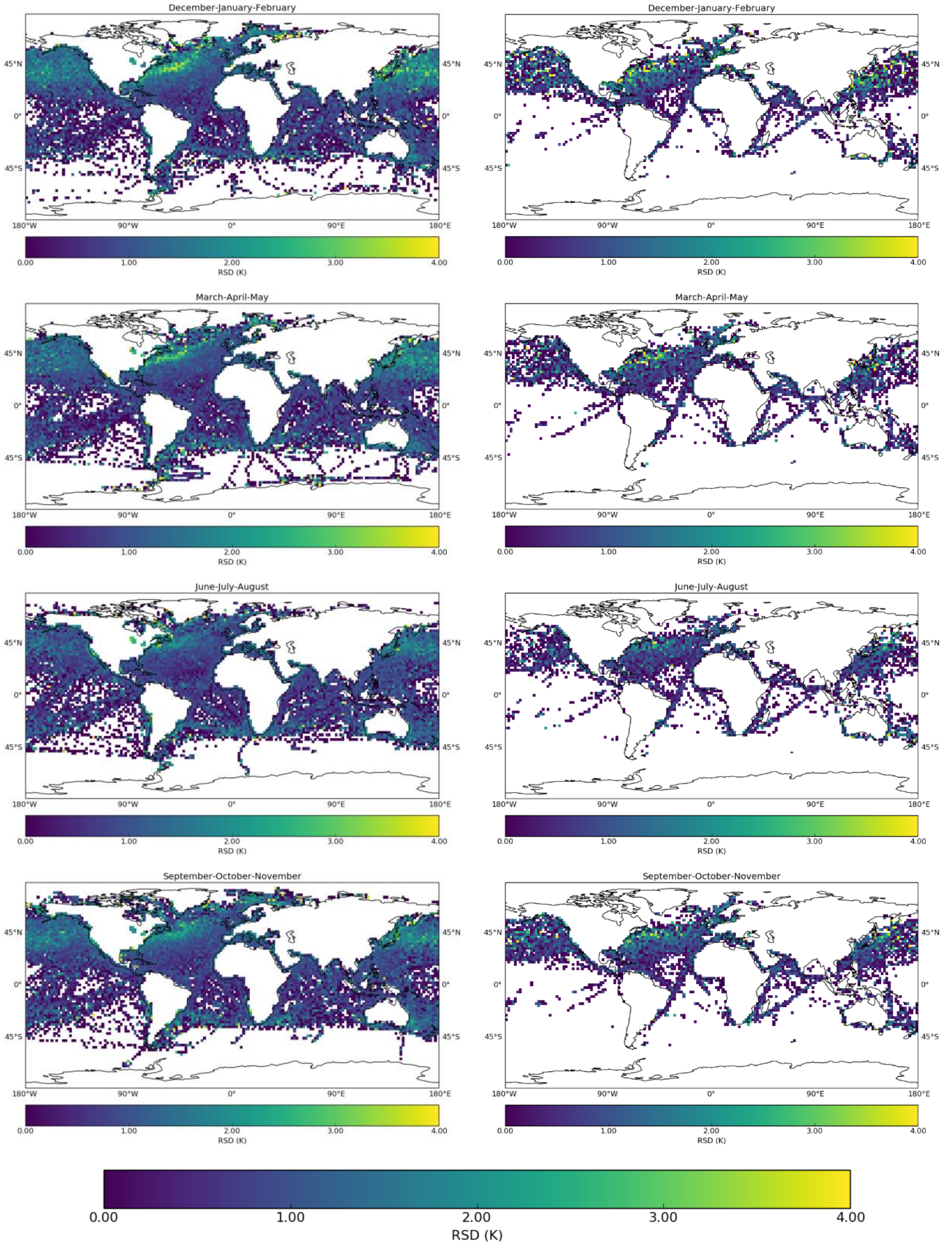


Figure 2: Maps of RSD of gridded seasonal mean discrepancy (K) for EUSTACE Products, 1995-2012, minus HadNMAT2 subset

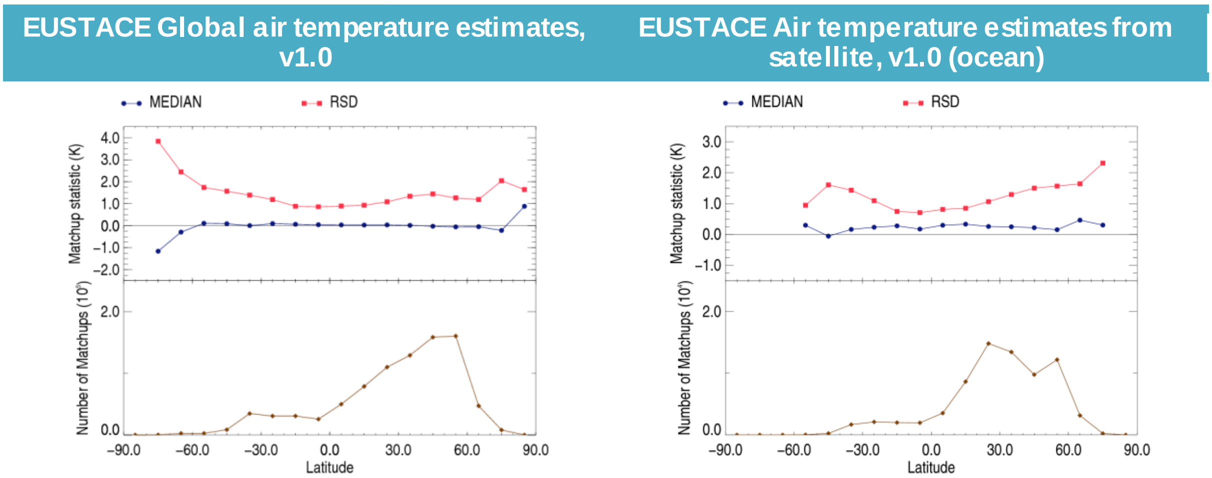


Figure 3: Matchup discrepancy and RSD (K) v. latitude for matchups to HadNMAT2 subset: EUSTACE Global air temperature estimates, v1.0 (left) and EUSTACE Air temperature estimates from satellite, v1.0 Ocean (right)

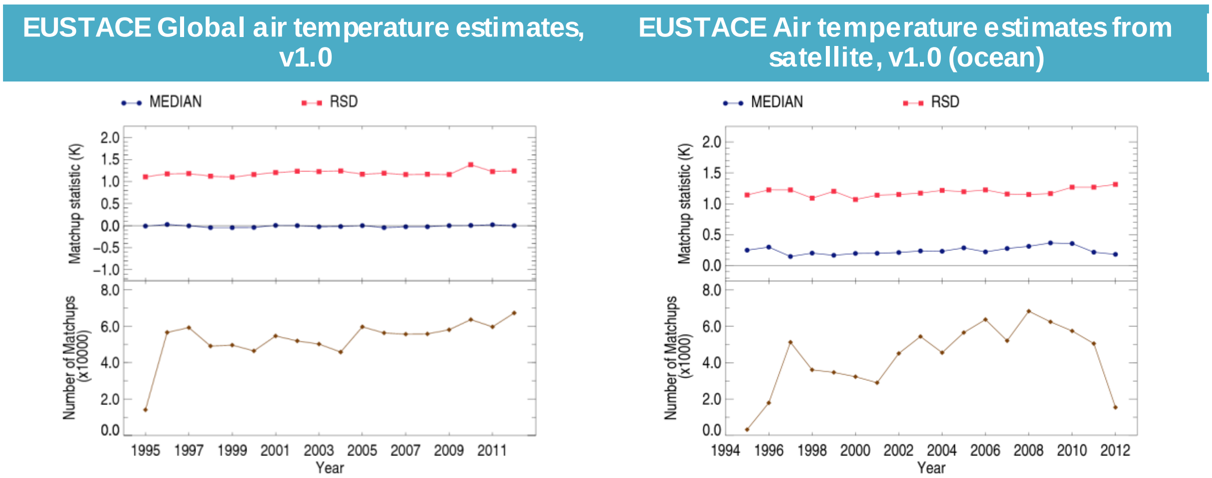


Figure 4: Time series 1995-2012 of global median matchup discrepancy (K) for the EUSTACE Global air temperature estimates, v1.0 (left) and EUSTACE Air temperature estimates from satellite v1.0 Ocean (right). Note: scales differ between plots. Annual medians have been calculated from the Air temperature estimates from satellite for 1995, 1996 and 2012 even though data were not available for several months in those years.

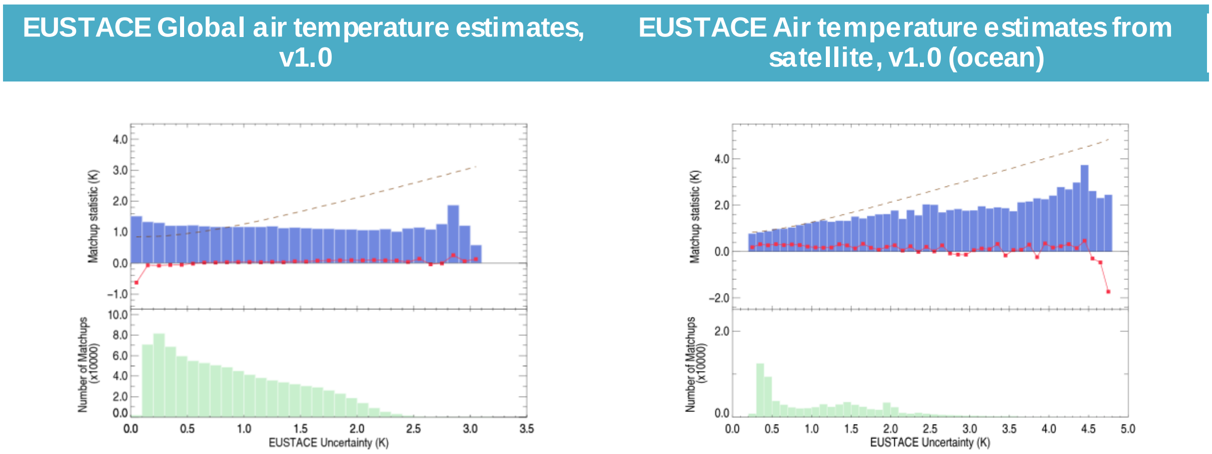


Figure 5: Matchup discrepancy RSD against EUSTACE uncertainty estimate (K) for matchups to HadNMAT2 subset 1995-2012 for the EUSTACE Global air temperature estimates, v1.0 (left) and EUSTACE Air temperature estimates from satellite v1.0 (ocean) (right). Blue bars indicate the matchup discrepancy RSD and red squares show the matchup discrepancy median. The brown dashed line shows the modelled expected relationship between the matchup discrepancy RSD and the EUSTACE uncertainty. The number of matchups in each uncertainty bin is shown by the green bars in the lower histogram.

ii) Land

For validation of the EUSTACE air temperature estimates over land, reference data were obtained from two sources. First, a subset of stations was selected from the EUSTACE Global Station Dataset (EUSTACE GSD) and reserved for validation. Data from these stations were used only for validation and not for either relationship building in Work Package 1 or as inputs to the analysis in Work Package 2. The EUSTACE GSD provides Tmin and Tmax and these data were used in the validation of the EUSTACE Air temperature estimates from satellite, v1.0. However, the EUSTACE Global air temperature estimates v1.0 provides estimates of Tmean only, so for validation of the Global air temperature estimates v1.0 the EUSTACE GSD Tmin and Tmax were averaged to obtain Tmean. The EUSTACE GDS selection has reasonable geographical coverage, although station density is much larger in the USA, central Europe and parts of Australia than elsewhere. Moreover, large parts of Africa and South America and the Indian sub-continent are poorly sampled. The second source utilized was the University of Leicester *in situ* Matchup Database which contains data collected from the ARM, BSRN and USCRN networks. These stations are often better maintained and better sited, however geographical coverage is reduced, with the majority of stations situated in the USA.

Over land, the EUSTACE Air temperature estimates from satellite v1.0 have a small negative global median discrepancy when compared to station data, -0.23 K, with RSDs between 2.71 and 2.95 K for Tmin and a global median discrepancy of +0.21 to +0.49 K with RSDs of 3.37 K for Tmax (see Table 4). In the case of the EUSTACE Global air temperature estimates v1.0 for Tmean the global median discrepancy is -0.13 K for 2000-2015 (-0.23 K over 1850-2015) with RSD of 1.76 (in both cases).

The global discrepancies are small, however the global statistics are dominated by matchups to stations in the USA. Maps of gridded discrepancies for matchups to EUSTACE GSD data demonstrating the spatial and seasonal variation are shown in Figure 6 and Figure 7 (also Figure 20 in the Appendix), with RSDs in Figure 8 and Figure 9 (and Figure 21 in the Appendix).

In all seasons the EUSTACE Global air temperature estimates v1.0 has a median discrepancy over the USA largely between -1.0 and +1.0 K, but sometimes exceeding -1.0 K (with RSDs of up to about 4 K); whereas the EUSTACE Air temperature estimates from satellite v1.0 have a larger positive median discrepancy over the eastern half of the USA in winter (December-February). This discrepancy is larger for Tmax (4-6 K) than Tmin (up to 4 K). In addition, for the Air temperature estimates from satellite v1.0 the median discrepancy changes with season. In summer (June-August), the median bias in this region is negative (down to -0.4 K for Tmin and as low as -0.6 K for Tmax). The RSDs for Tmin are highest in winter and spring, most grid boxes in the region have RSDs over 2 K whereas in summer and autumn are the RSDs are 2 K or lower. For Tmax the RSDs are again highest in winter and spring (3-5 K in the eastern half of the USA) and lower in summer and autumn (2-3 K in summer and up to 4 K in autumn). RSDs in the EUSTACE Global air temperature estimates v1.0 are higher in the western half than in the eastern half of USA. The mountainous terrain in the western USA is a likely contributing factor: the high elevation variance in a grid cell is likely associated with a higher matchup uncertainty and is also likely to impact the LST-air temperature regression model.

Large positive median discrepancies occur over much of central and northern Asia in the winter, in particular in the EUSTACE Air temperature estimates from satellite v1.0. In the case of Tmax the large discrepancies (> 6K) are more widespread and smaller positive discrepancies are also present in Europe. Smaller positive discrepancies are also present in autumn and spring (up to 4 K). In summer, in the same region, median discrepancies are negative for both Tmin and Tmax estimates from satellite whilst median discrepancies for the EUSTACE Global air temperature estimates v1.0 are relatively small (mostly between -1.0 K and +1.0 K), except in the north-eastern part of central Asia in DJF, where the analysis has not managed to fully correct the biases in the EUSTACE Air temperature estimates from satellite v1.0. The fact that these remain in the results for 1850-2015 (see Figure 20 in the Appendix) indicate that they pervade the climatology component of the EUSTACE Global air temperature estimates v1.0. As this is a region with relatively few in situ measurements, the largest biases (seen here in the globally-complete pre-release fields) are likely not to be present in the released EUSTACE Global air temperature estimates v1.0, as they will have been removed.

Matchups over South America are confined mainly to the eastern margin of that continent. In this region, the EUSTACE Air temperature estimates from satellite v1.0 have more negative median discrepancies over South America than the EUSTACE Global air temperature estimates v1.0 in all seasons.

The histogram of uncertainty estimates from the EUSTACE Global air temperature estimates v1.0 (Figure 10 and Figure 22 in the Appendix) shows the median discrepancy to be near zero for air temperature estimates with uncertainty estimates less than 1 K (the majority of the matchups). The uncertainty bin RSDs are within around 0.5 K of the modelled value showing the EUSTACE Global air temperature estimates v1.0 uncertainty estimates for land to be of useful accuracy for the whole record. For uncertainty estimates above 1 K the median discrepancy increases with uncertainty estimate; as these data have a non-zero median bias to station data, a user might wish to use the uncertainty estimates to filter out these data. (If they still remain in the released version.)

In the case of Tmin estimated from satellite, uncertainty estimates less than 3.0 K have small median discrepancies and RSDs agree with the model showing uncertainty estimates to be accurate (Figure 10). These data comprise the majority of the matchups. Above 3.0 K, the median discrepancy is negative and increases in magnitude. The associated bin RSDs are smaller than the modelled RSDs indicating that the EUSTACE uncertainty estimates are underestimated. Users may find it appropriate to discard data with an uncertainty greater than 3.0 K if it suits their application.

For Tmax, uncertainty estimates less than 3.4 K are associated with matchups with median discrepancies of near zero and bin RSDs are close to modelled values demonstrating uncertainty estimates are accurate. This is also the case for the small number of matchups where the EUSTACE uncertainty estimate is between 3.9 K and 4.1 K. For uncertainty estimates between 3.4 K and 3.9 K and above 4.1 K the median bin discrepancy is non-zero and the bin RSD is sometimes greater than the modelled value suggesting that the uncertainty is underestimated for these data.

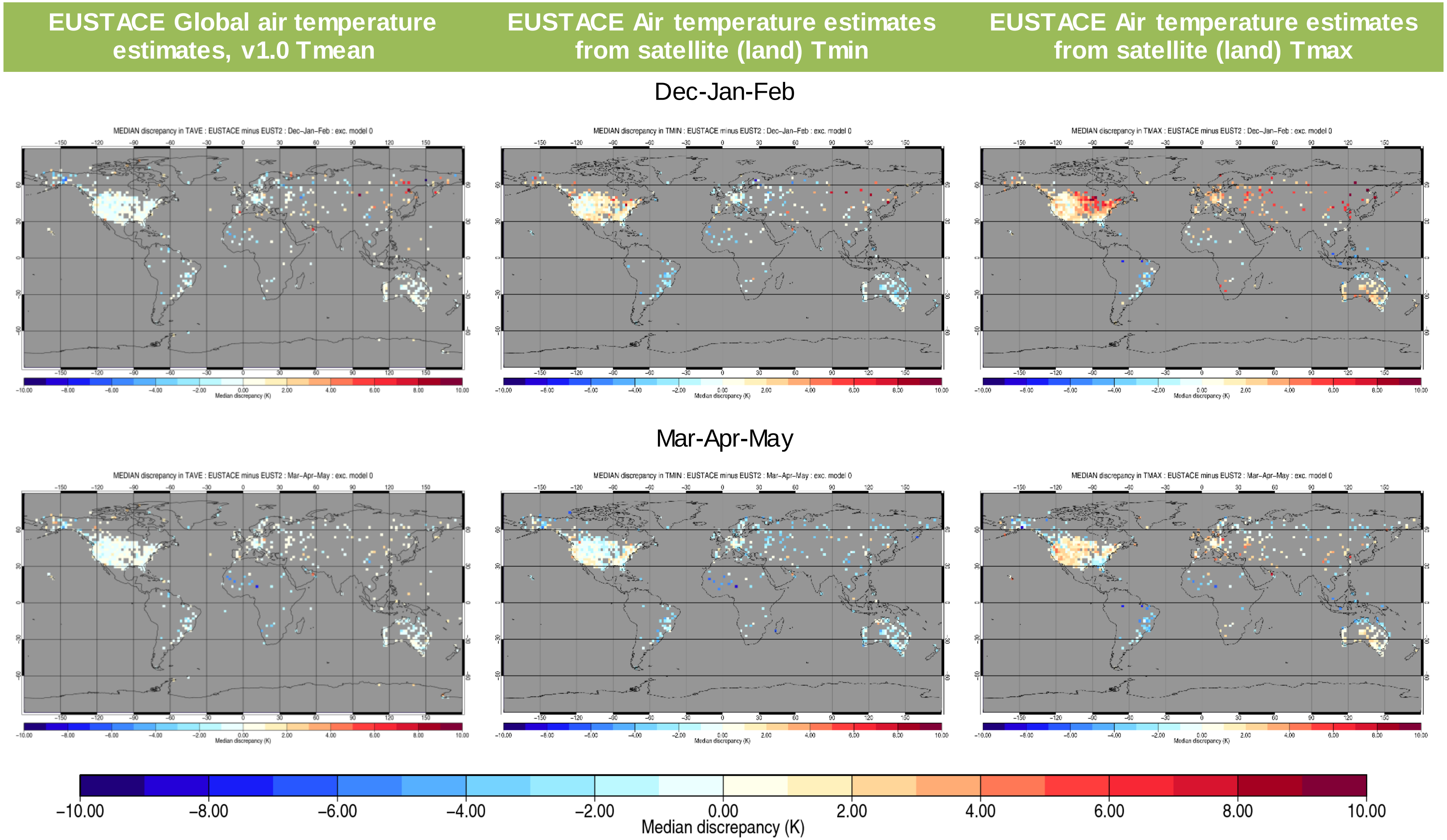
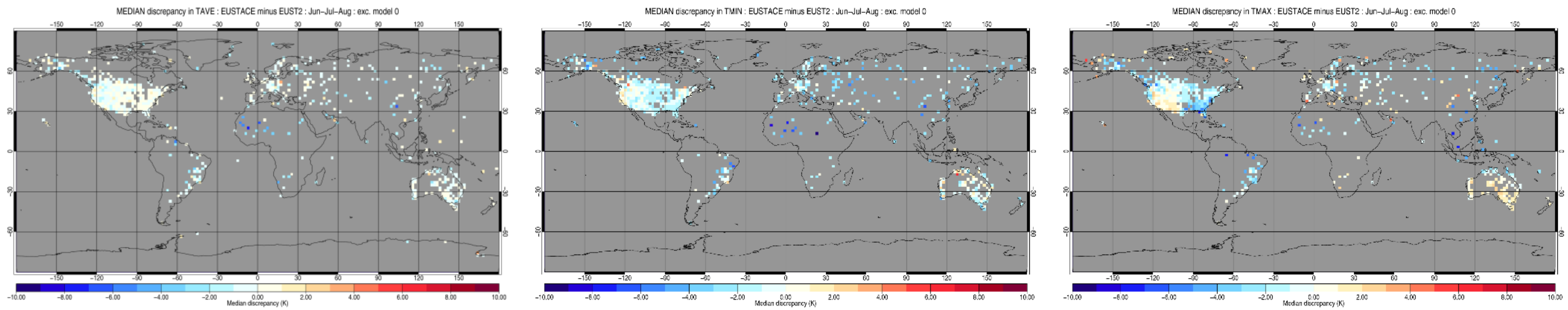


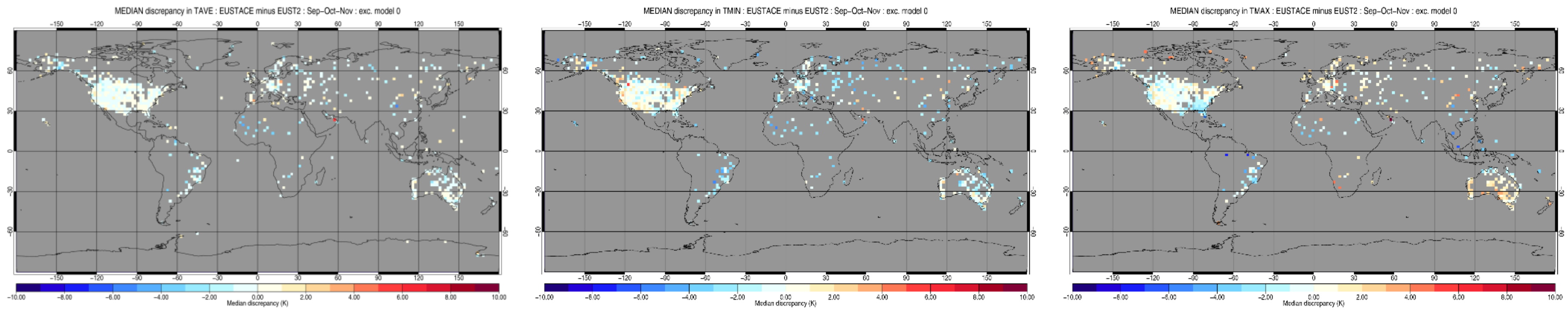
Figure 6: Maps of mean gridded seasonal median discrepancy (K) for EUSTACE Products minus EUSTACE Global Station Dataset in situ surface air temperatures for December-January-February (top row) and March-April-May (bottom row), 2000-2015.

EUSTACE Global air temperature estimates, v1.0 Tmean	EUSTACE Air temperature estimates from satellite (land) Tmin	EUSTACE Air temperature estimates from satellite (land) Tmax

Jun-Jul-Aug



Sep-Oct-Nov



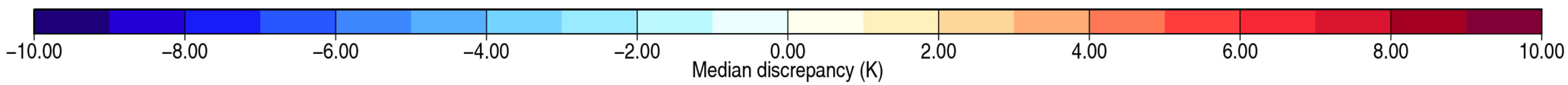


Figure 7: Maps of mean gridded seasonal median discrepancy (K) for EUSTACE Products minus EUSTACE Global Station Dataset in situ surface air temperatures for June-July-August (top row) and September-October-November (bottom row), 2000-2015.

EUSTACE Global air temperature estimates, v1.0 Tmean	EUSTACE Air temperature estimates from satellite (land) Tmin	EUSTACE Air temperature estimates from satellite (land) Tmax

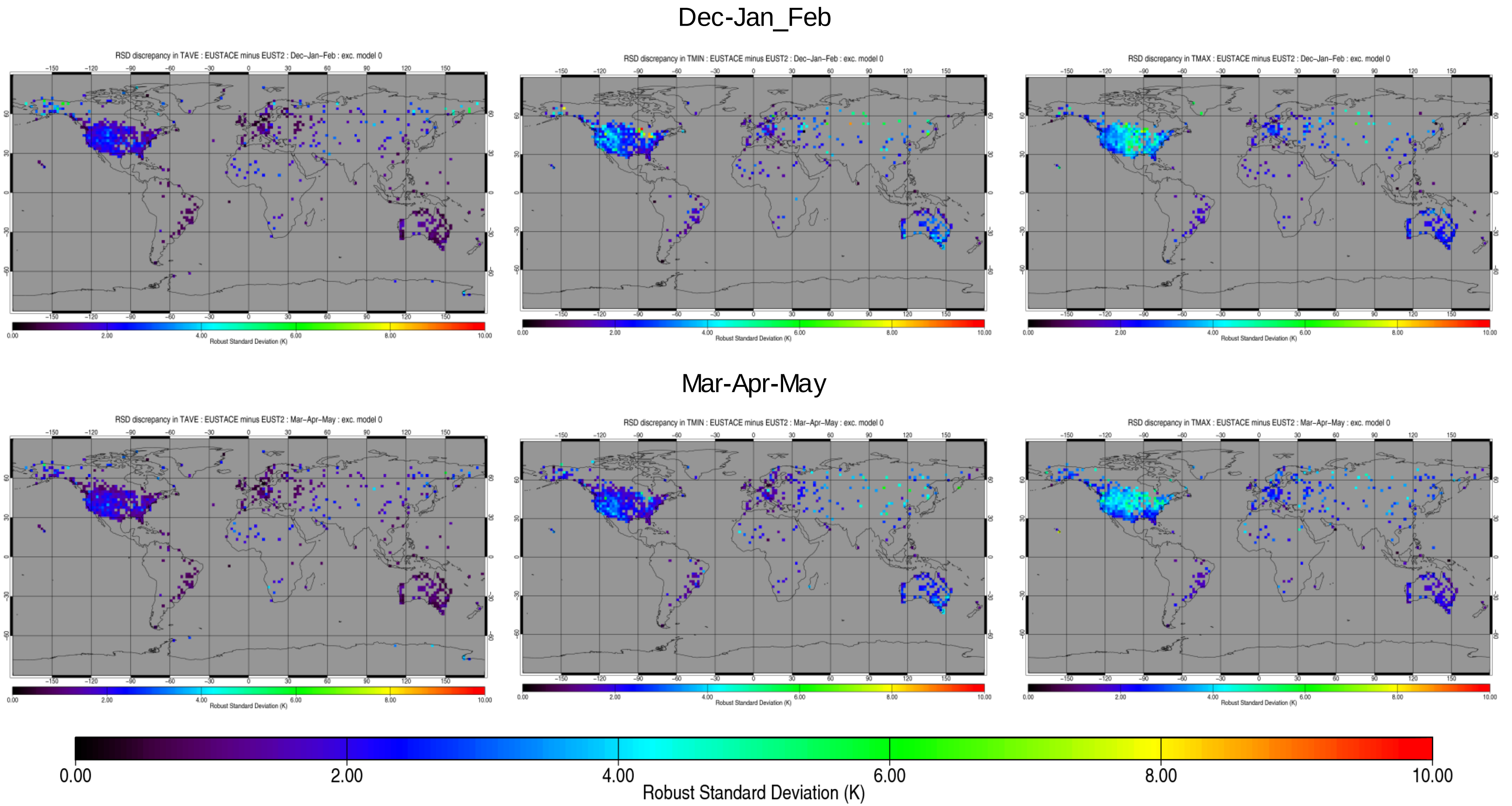


Figure 8: Maps of RSD of gridded seasonal mean discrepancy (K) for EUSTACE Products minus EUSTACE Station Dataset in situ surface air temperatures for December-January-February (top row) and March-April-May (bottom row), 2000-2015.

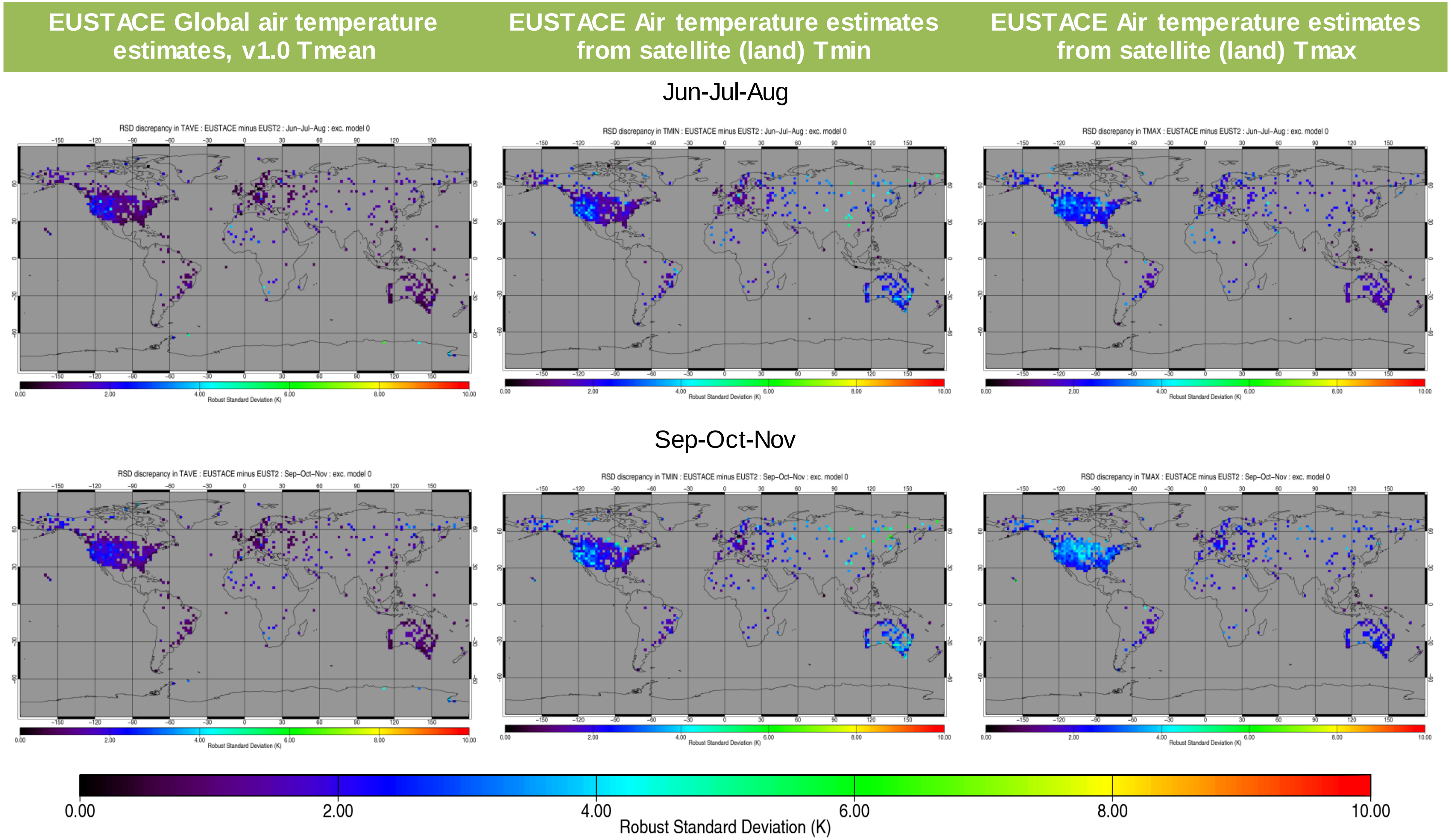


Figure 9: Maps of RSD of gridded seasonal mean discrepancy (K) for EUSTACE Products minus EUSTACE Station Dataset in situ surface air temperatures for June-July-August (top row) and September-October-November (bottom row), 2000-2015.

EUSTACE Global air temperature estimates, v1.0 Tmean	EUSTACE Air temperature estimates from satellite (land) Tmin	EUSTACE Air temperature estimates from satellite (land) Tmax

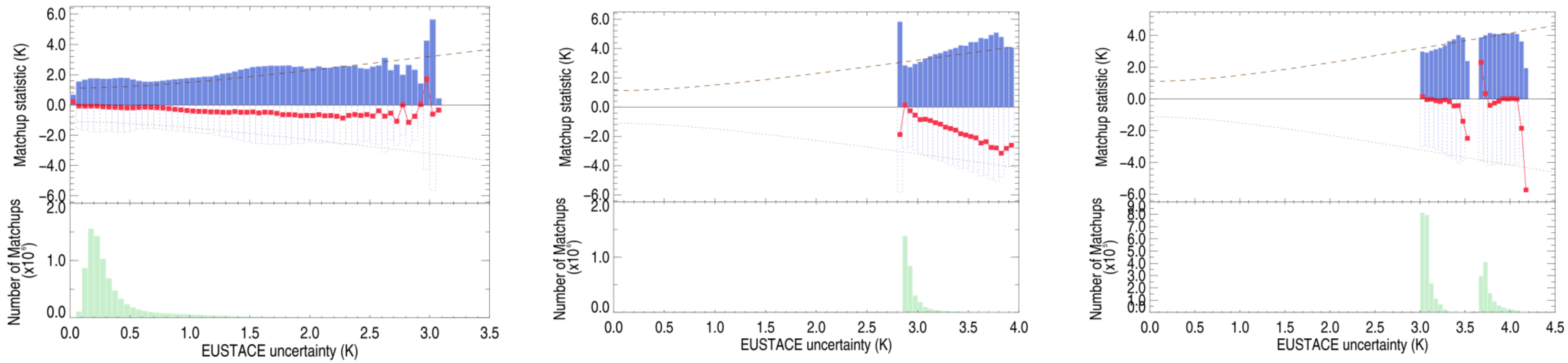


Figure 10: Matchup discrepancy against EUSTACE uncertainty estimate (K) for the EUSTACE Global air temperature estimates, v1.0 Tmean (left), EUSTACE Air temperature estimates from satellite Land Tmin (centre) and Tmax (right). See Figure 5 for details.

iii) Ice

Over the ice domain *in situ* air temperatures from stations and ice buoys have been quality controlled and provided by DMI. In the Arctic, the ice stations used for validation are situated on the Greenland ice sheet or on the northern slopes of Alaska. In Antarctica, some stations are situated on the sea-ice shelf and some on land ice. Ice buoys provide air temperatures above sea-ice in both Polar Regions. Data over regions of permanent ice are sparse and matchup numbers are necessarily low.

The regional statistics for matchups to station data and buoy data are provided in Table 4 (and Table 5 in the Appendix) and histograms of the same data are plotted in Figure 11 and Figure 12 (and Figure 23 and Figure 24 in the Appendix). In the Arctic, the EUSTACE Air temperature estimates from satellite v1.0 have positive median discrepancies (RSDs) of +0.53 K (3.10 K) for matchups to stations and +0.93 K (3.76 K) for matchups to buoys over 2000-2009, showing the EUSTACE estimates to be warmer than the reference data on average. In the Antarctic, the EUSTACE Air temperature estimates from satellite v1.0 have a low median discrepancy of +0.02 K and a RSD of 2.73 K for matchups to stations and a positive median discrepancy of +0.98 K with a RSD of 3.64 K for matchups to buoys.

The results for matchups of EUSTACE Global air temperature estimates, v1.0 with *in situ* station air temperatures in the Antarctic (Figure 11 and Figure 23) show a discrepancy of +0.27 K and relatively small RSD of 2.38 K over 2000-2009 (+0.37 K (2.68 K) over 1850-2015). In the Arctic, the median discrepancy is +0.57 K with RSD of 3.57 K over 2000-2009 (+0.47 K (4.04 K) over 1850-2015). The Arctic result is close to that for the Air temperature estimates from satellite for 2000-2009, but a relative warm bias has been introduced by the analysis in the Antarctic. For matchups against buoys (Figure 12 and Figure 24) the median discrepancies (and RSDs) are -0.29 K (4.14 K) in the Arctic and +0.25 K (3.17 K) in the Antarctic for the EUSTACE Global air temperature estimates, v1.0. In both hemispheres, the analysis has reduced a larger positive discrepancy against buoys seen above in the EUSTACE Air temperature estimates from satellite v1.0.

To explore what the impact of the loss of air temperature estimates has on the analysis after 2009, in Figure 13 the matchups against buoys are divided into two time periods: 2000-2009 and 2010-2015. The histograms for data before 2010 have a Gaussian shape and low median discrepancy whereas the histograms of later data show large positive median discrepancies and large RSDs. If we assume the reference data are good (they have undergone quality control tests) then this indicates that the EUSTACE Global air temperature estimates, v1.0 is less well-constrained in the sea-ice domains of both Polar Regions after 2009.

Histograms of matchup discrepancy statistics against EUSTACE uncertainty estimate are plotted for the matchups to station *in situ* data in Figure 14 (and Figure 25 in the Appendix) and for matchups to buoy data in Figure 15 (and Figure 26 in the Appendix). In the case of the majority of matchups of EUSTACE Air temperature estimates from satellite v1.0 to station data (Figure 14), the associated uncertainty estimate lies between 2.4 and 2.7 K. For these uncertainty bins, the total uncertainty (median discrepancy plus RSD) exceeds the modelled value by around 0.8 K indicating the EUSTACE uncertainty estimates are too small.

Against buoy data (Figure 15), the matchups of EUSTACE Air temperature estimates from satellite v1.0 show different behaviour in the Arctic and Antarctic. In the Arctic, most matchups have associated uncertainty estimates between 1.8 and 2.1K, with median discrepancies less than 1 K. The uncertainty bin RSDs are larger than the modelled values by up to 2 K implying the uncertainties are again underestimated. In the Antarctic, the majority of the matchups are associated with uncertainty estimates of 2.4 to 2.6 K and positive median discrepancies. Here, the uncertainties are underestimated by 1.0-1.5 K.

In the case of the matchups of EUSTACE Global air temperature estimates, v1.0 to station data (Figure 14 and Figure 25 in the Appendix) the uncertainty estimates are underestimated by 3K in the Arctic. In the Antarctic, matchups where the EUSTACE uncertainty estimate is below 1 K (the vast majority) are better estimated; those few matchups where the EUSTACE uncertainty estimate is above 1 K are underestimated by several kelvin. When matched to buoy data (Figure 15 and Figure 26 in the Appendix), the uncertainties in the EUSTACE Global air temperature estimates, v1.0 are roughly half the size the matchup model suggests they should be. This underestimation of uncertainties over ice covered regions arises from the treatment by the analysis system of the over-sampled air temperature estimates from polar-orbiting satellites.

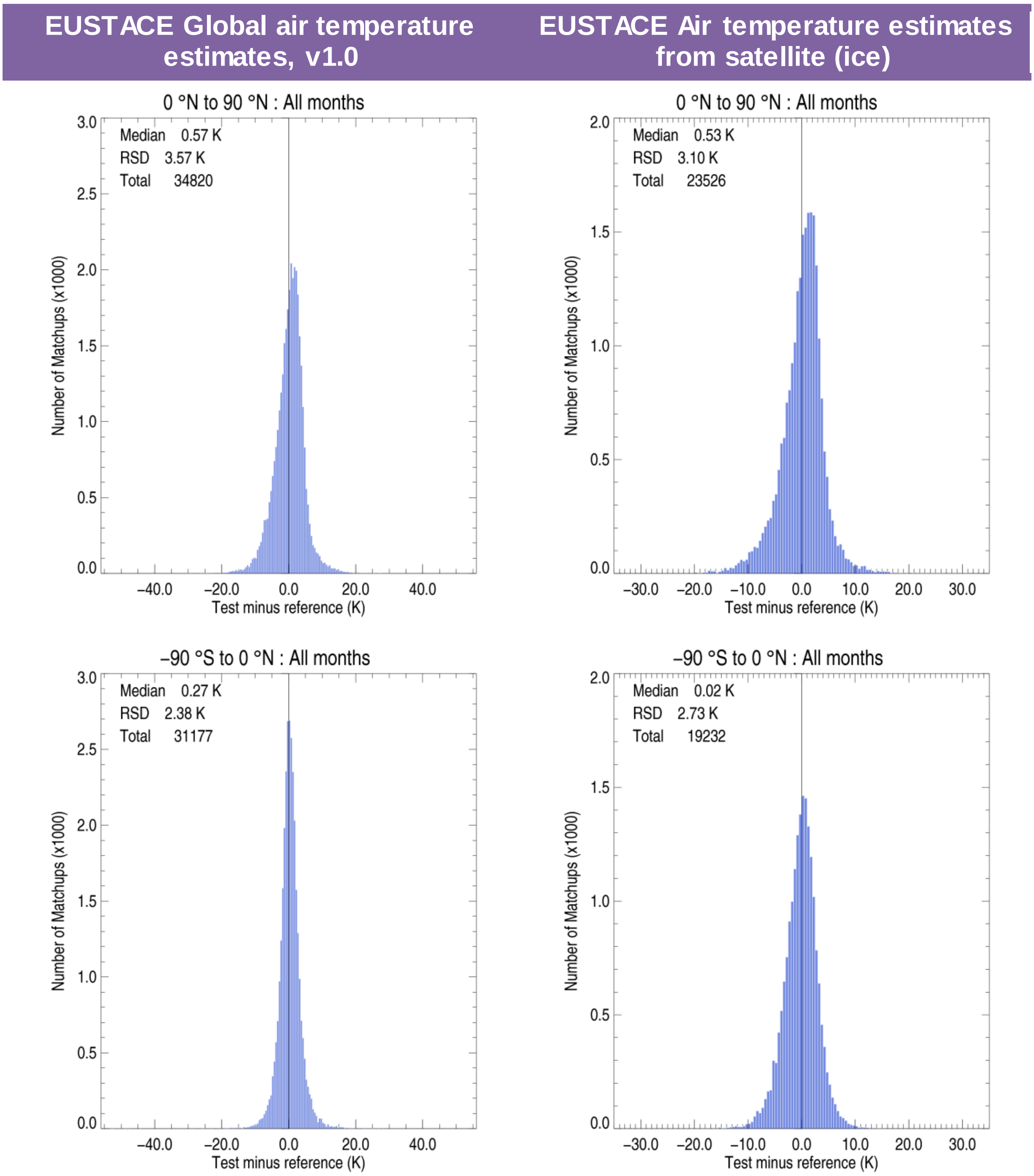


Figure 11: Histograms of matchup discrepancy (K) for matchups of EUSTACE Global air temperature estimates, v1.0 Tmean (left) and EUSTACE Air temperature estimates from satellite v1.0 Ice Tmean (right) to DMI Quality Controlled Ice Station data for the Arctic (top row) and Antarctic (bottom row), 2001-2009.

EUSTACE Global air temperature estimates, v1.0	EUSTACE Air temperature estimates from satellite (ice)

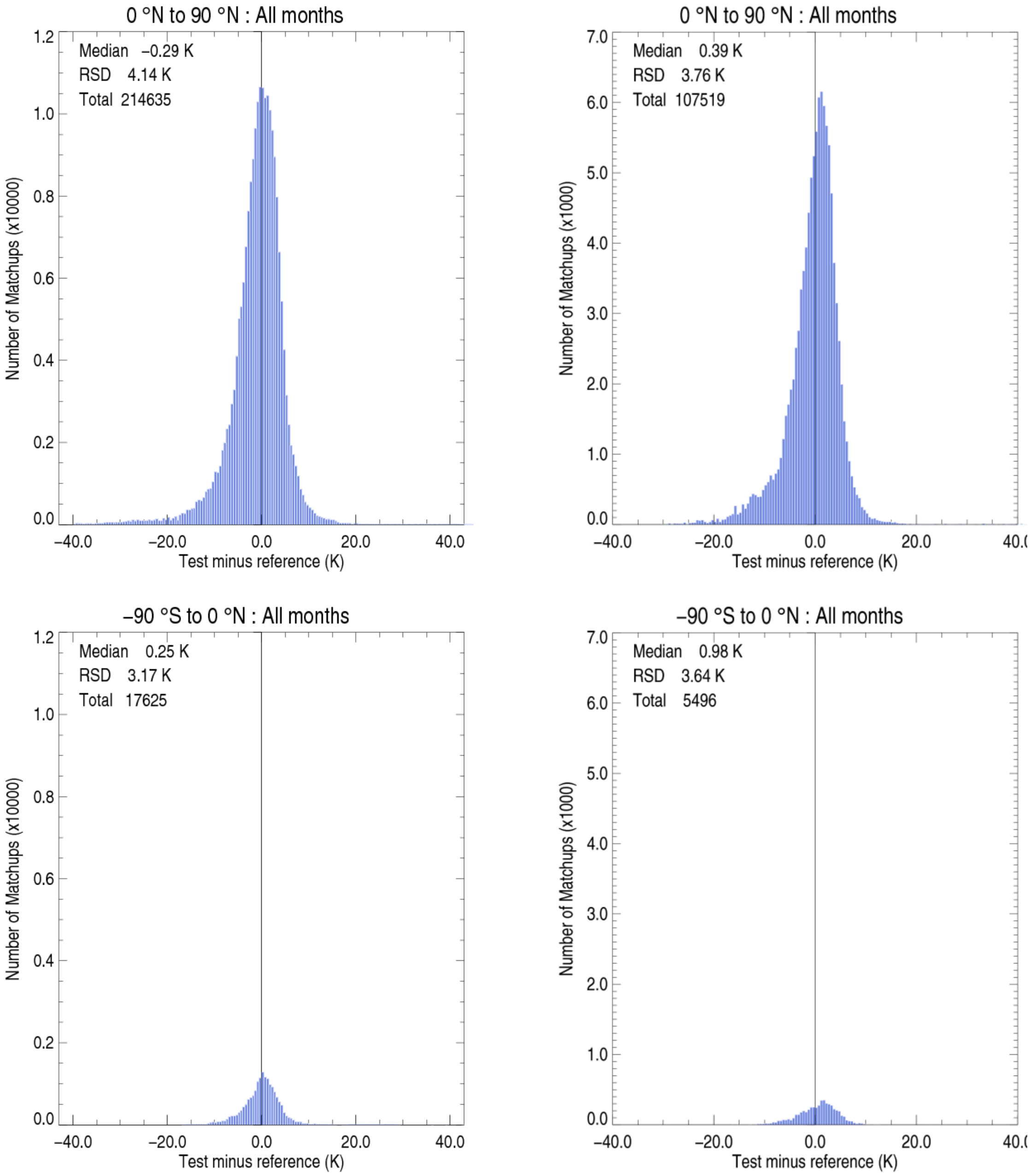


Figure 12: Histograms of matchup discrepancy (K) for matchups of EUSTACE Global air temperature estimates, v1.0 Tmean (left) and EUSTACE Air temperature estimates from satellite Ice Tmean (right) to DMI Quality Controlled Ice Buoy data for the Arctic (top row) and Antarctic (bottom row), 2001-2009.

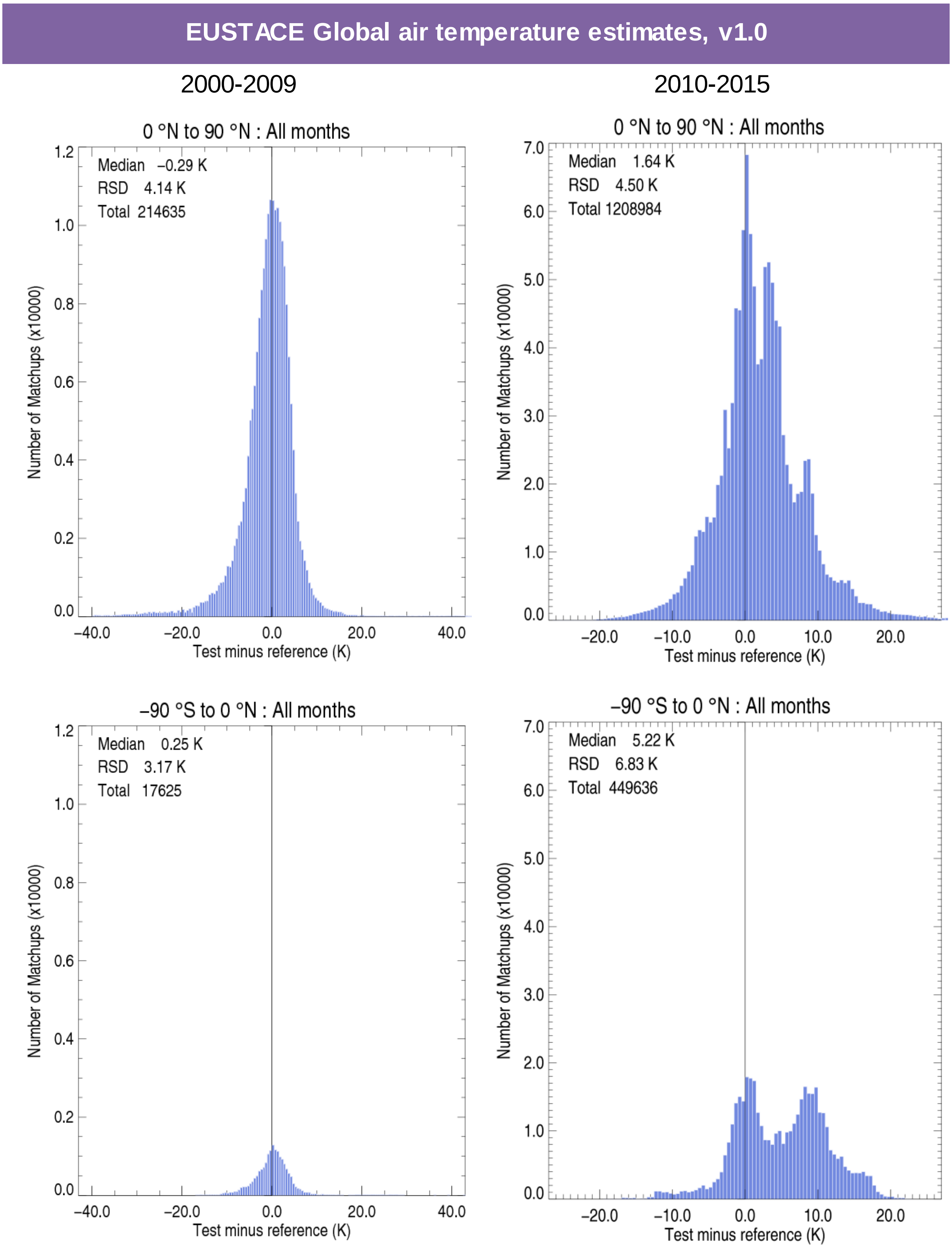


Figure 13: Histograms of matchup discrepancy (K) for matchups of EUSTACE Global air temperature estimates, v1.0 Tmean to DMI Quality Controlled Ice Buoy data 2001-2009 (left) and 2010-2015 (right) for Arctic (top row) and Antarctic (bottom row)

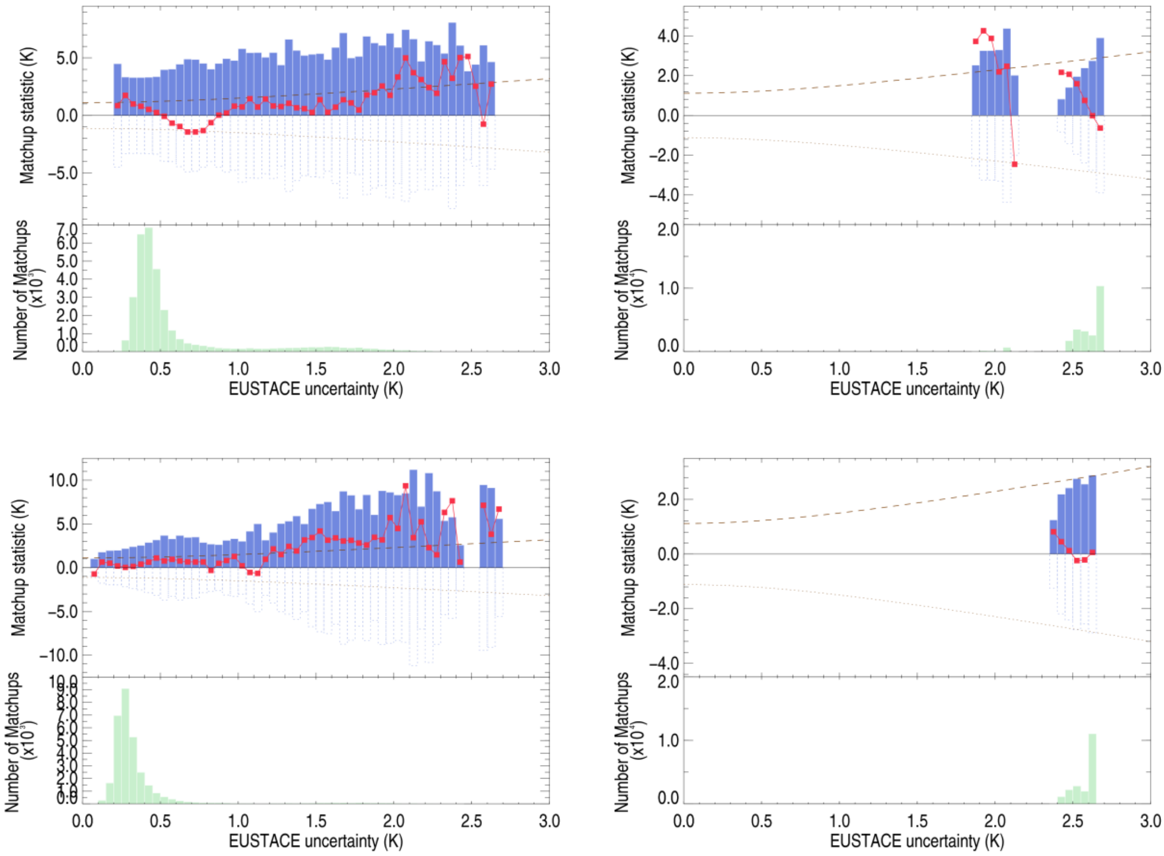


Figure 14: Matchup discrepancy against EUSTACE uncertainty estimate (K) for the EUSTACE Global air temperature estimates, v1.0 Tmean (left) and EUSTACE Air temperature estimates from satellite Ice (right) for matchups to DMI Quality Controlled Station Data in the Arctic (top row) and Antarctic (bottom row), 2001-2009. See caption to Figure 5 for legend details.

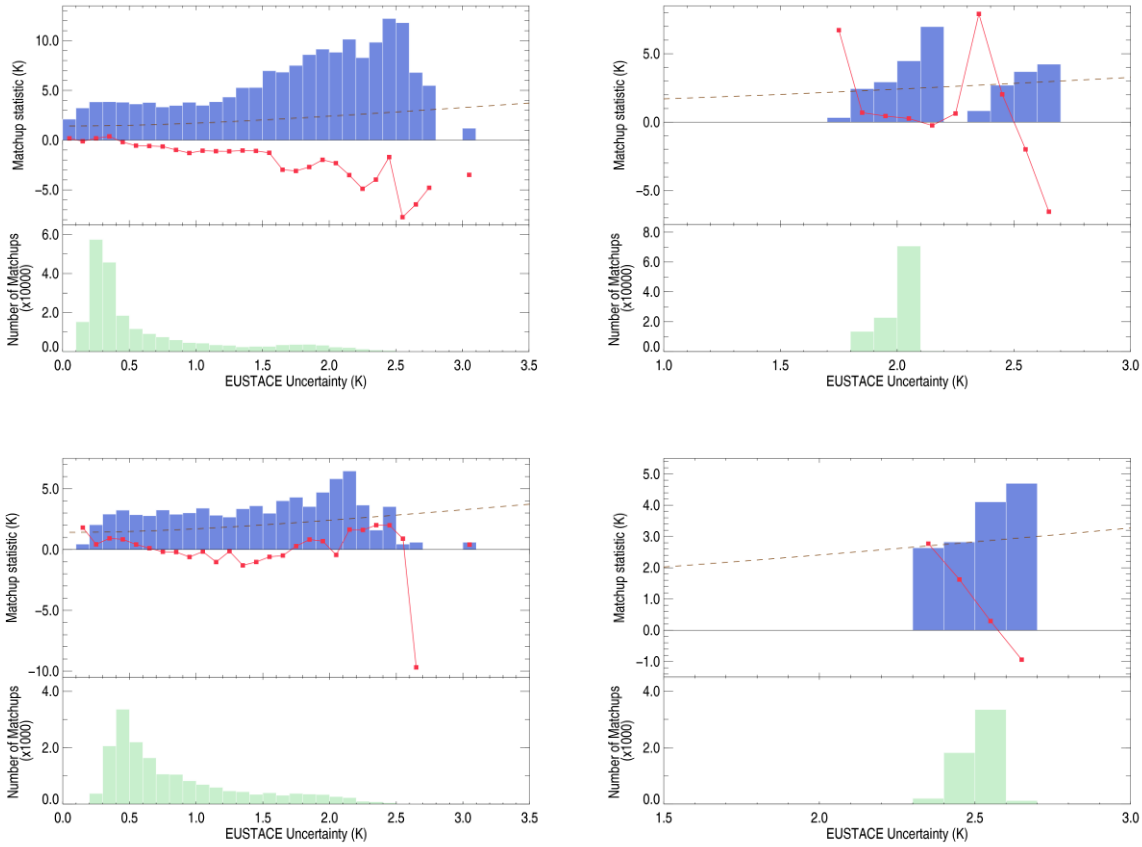


Figure 15: Matchup discrepancy against EUSTACE uncertainty estimate (K) for the EUSTACE Global air temperature estimates, v1.0 Tmean (left) and EUSTACE Air temperature estimates from satellite Ice (right) for matchups to DMI Quality Controlled Ice Buoy Data in northern hemisphere (top row) and southern hemisphere (bottom row), 2001-2009. See caption to Figure 5 for legend details.

d) Summary of results

The evaluation of the EUSTACE Global air temperature estimates, v1.0, alongside the EUSTACE Air temperature estimates from satellite, v1.0 has been reported.

The EUSTACE daily air temperature estimates were matched with reference daily air temperatures from land stations, ice stations and moored buoys and instantaneous observations of air temperature from ships and ice buoys. The reference data used for validation were excluded from both the relationship building in Work Package 1 and the inputs to the analyses produced by Work Package 2.

Over ocean the EUSTACE Global air temperature estimates, v1.0 performs well with a global median discrepancy (RSD) of +0.005 K (1.76 K) against HadNMAT2 inputs over 1995-2012 and 0.00 K (1.15 K) over 1850-2012. The highest discrepancies are found in the Southern Ocean, although matchups are sparse in this region.

The EUSTACE Global air temperature estimates, v1.0 also performs well in most land regions with a global median discrepancy (RSD) against withheld data from the EUSTACE Global Station Dataset of -0.13K (1.76K) over 2002-2015 and -0.23K (1.76 K) over 1850-2015; the negative discrepancy arises largely over some regions of Africa and the west of North America. However seasonal median discrepancies over central Asia can be high, 6-10 K in DJF at some stations. Nonetheless, comparison to the validation results of the EUSTACE Air temperature estimates from satellite v1.0 demonstrates that significant seasonal biases have successfully been removed by the analysis method over land in most locations.

Over ice domains, the EUSTACE Global air temperature estimates, v1.0 performs less well over 2001-2009, especially over Arctic land. Regional median discrepancies (RSDs) against DMI Quality Controlled ice buoy data are +0.25 K (3.17 K) in the Arctic and -0.29 K (4.14 K) in the Antarctic sea ice regions. However, these results also represent a reduction in bias compared to those seen in the EUSTACE Air temperature estimates from satellite v1.0 here (see below). The median discrepancies and RSDs for sea-ice are much larger in the years after 2009 when the satellite air temperature estimates end in these regions. The regional median discrepancies over land-ice (including the Antarctic ice-shelf) against station data are: +0.57 K (3.57 K) in the Arctic and +0.27 K (2.38 K) in the Antarctic; here a warm bias relative to withheld validation data is introduced in the analysis in the Antarctic.

Over the longer period, 1890-2015, the EUSTACE Global air temperature estimates, v1.0 shows discrepancies of +0.37 K (4.04 K) over Northern Hemisphere land ice, +0.47 K (2.68 K) over Southern Hemisphere land ice, +1.19 K (4.60 K) over Northern Hemisphere sea ice and +4.76 K (6.81 K) over Southern Hemisphere sea ice. The increase in positive bias when the whole period is considered arises from a drift in the EUSTACE Global air temperature estimates, v1.0 over the Poles prior to about 1960;

these erroneous data have not been released in these regions, as they do not provide useful information.

The EUSTACE Air temperature estimates from satellite v1.0 demonstrate a positive median discrepancy (RSD) against HadNMAT2 of +0.25 K (1.19 K) with the highest discrepancies occurring in the mid to high northern latitudes. Note there were few matchups south of 20° N and none south of 50° S.

Over land EUSTACE Air temperature estimates from satellite v1.0 provides estimates of Tmin and Tmax. Although the global median discrepancies (RSDs) against EUSTACE GSD are not large, –0.23 K (2.95 K) for Tmin and +0.21 K (3.37) for Tmax, there is considerable regional and seasonal variation in median discrepancy.

Over ice, the EUSTACE Air temperature estimates from satellite v1.0 have regional median discrepancies of +0.02 to +0.98 K and RSDs of 2.73 to 3.64 K depending on region and surface type (land or sea-ice).

The uncertainty estimates accompanying the EUSTACE Air temperature estimates from satellite v1.0 vary in quality depending on domain. Over ocean the uncertainty estimates are accurate, over land for both Tmin and Tmax the uncertainties are accurate for the smaller uncertainties but underestimated on data with higher uncertainties, and over ice the uncertainties are underestimated.

The uncertainty estimates provided with the EUSTACE Global air temperature estimates, v1.0 show little agreement with the modelled value over ocean (overestimated and show little variation with actual discrepancy), but good agreement over land, which will allow users to filter out poor quality data there. Since the EUSTACE Global air temperature estimates, v1.0 validates extremely well in comparison to withheld data over the ocean, this hopefully mitigates the impact of the less-effective uncertainty estimates here. Analysis uncertainties are underestimated over ice regions, particularly in the Northern Hemisphere and over Southern Hemisphere land ice; here, this arises from the treatment by the analysis method of the over-sampled air temperature estimates from satellite.

Results from the validation, alongside the development of other objective criteria, have been used to determine where and when EUSTACE Global air temperature estimates, v1.0 is suitable for release. The results shown here are derived from matchups with the globally-complete, pre-release fields produced by the statistical analysis. Users will find that the data which are shown here to validate particularly poorly are likely not to have been released in the final product.

e) References

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Appendix – validation of the EUSTACE Global air temperature estimates, v1.0, 1850-2015

Here, the preceding results for a sub-period of the EUSTACE Global air temperature estimates, v1.0 (coincident with the period of the EUSTACE Air temperature estimates from satellite, v1.0) are extended to cover the whole period of record, 1850-2015, where possible. Figures are reproduced for the full period in the order shown in the main report.

Table 5. Global match up statistics for the EUSTACE Global air temperature estimates, v1.0 Tmean, 1850-2015

Ocean			
	Median (K)	**RSD (K)**	**Number**
HadNMAT2	0.00	1.15	3048230
Land			
	Median (K)	**RSD (K)**	**Number**
EUSTACE GSD	-0.23	1.76	38205881
Ice			
	Median (K)	**RSD (K)**	**Number**
DMIQC NH	+0.37	4.04	67856
DMIQC SH	+0.47	2.68	66719
DMIQC_SEA NH	+1.19	4.60	1508922
DMIQC_SEA SH	+4.76	6.81	471143

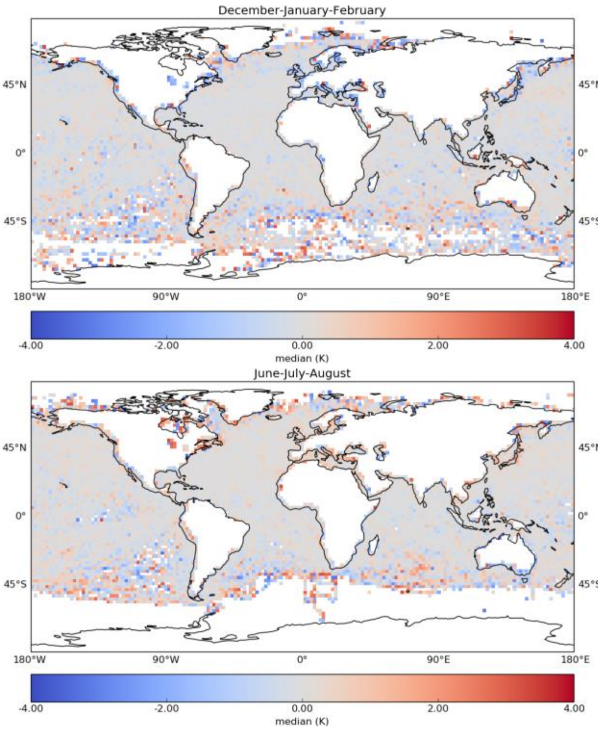

Figure 16: Maps of gridded seasonal mean discrepancy (K) for EUSTACE Global air temperature estimates, v1.0, 1850-2012, minus HadNMAT2 subset

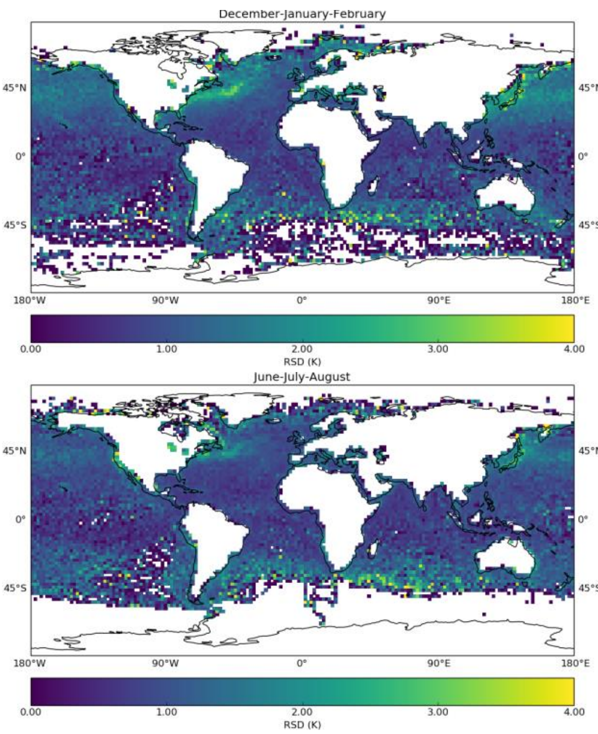

Figure 17: Maps of RSD of gridded seasonal mean discrepancy (K) for EUSTACE Global air temperature estimates, v1.0, 1850-2012, minus HadNMAT2 subset

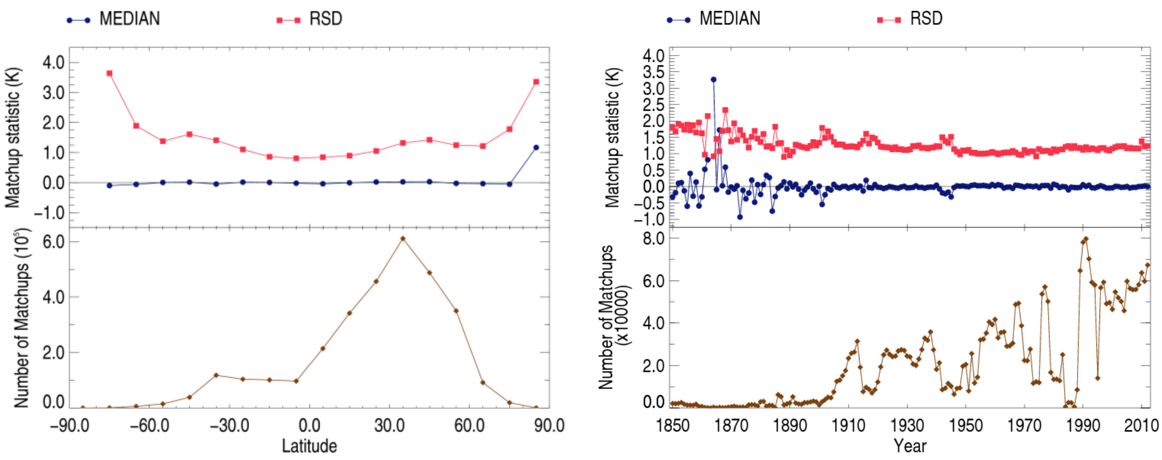

Figure 18: Matchup discrepancy and RSD (K) v. latitude (left) and time (right) for matchups of EUSTACE Global air temperature estimates, v1.0 to HadNMAT2 subset, 1850-2012

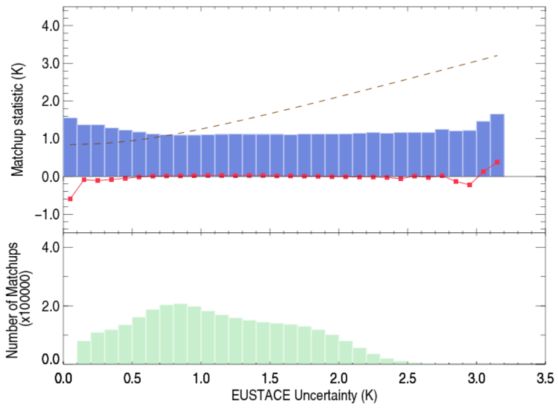

Figure 19: Matchup discrepancy RSD against EUSTACE uncertainty estimate (K) for matchups to HadNMAT2 subset 1850-2012 for the EUSTACE Global air temperature estimates, v1.0. Blue bars indicate the matchup discrepancy RSD and red squares show the matchup discrepancy median. The brown dashed line shows the modelled expected relationship between the matchup discrepancy RSD and the EUSTACE uncertainty. The number of matchups in each uncertainty bin is shown by the green bars in the lower histogram.

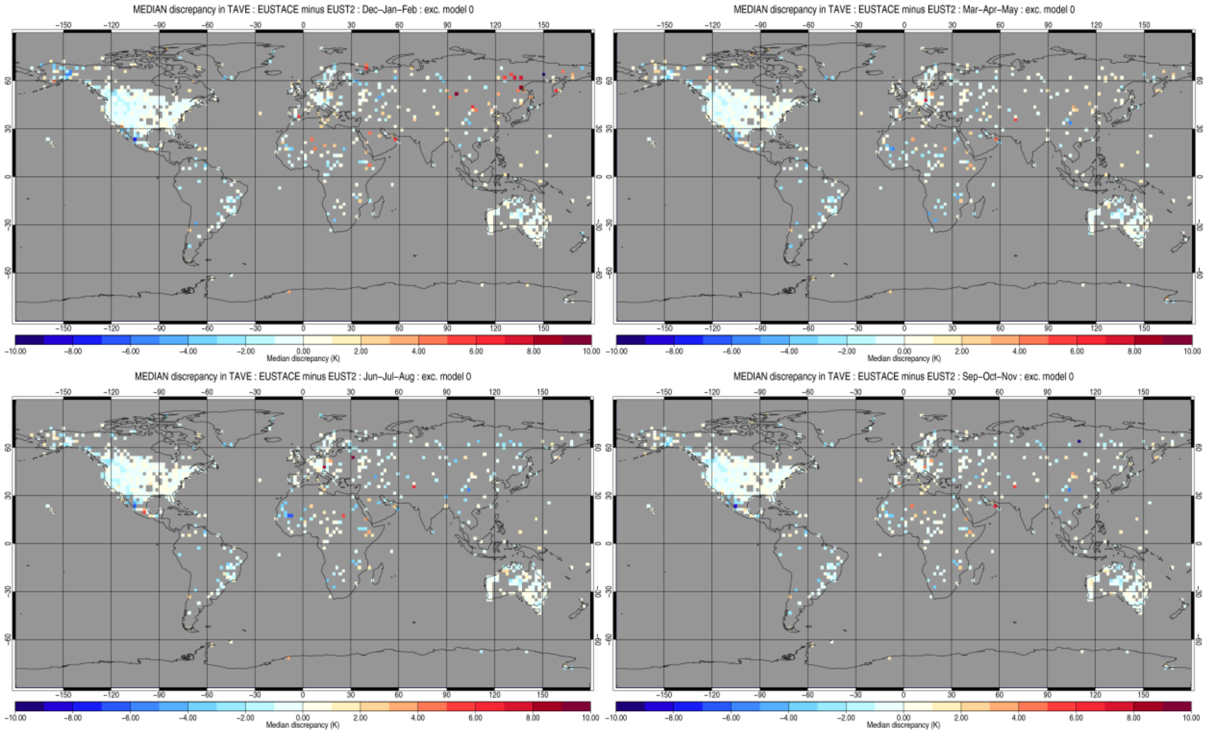

Figure 20: Maps of mean gridded seasonal median discrepancy (K) for EUSTACE Global air temperature estimates, v1.0 minus EUSTACE Global Station Dataset in situ surface air temperatures for December-January-February (top left), March-April-May (top right), June-July-August (bottom left) and September-October-November (bottom right) 1850-2015.

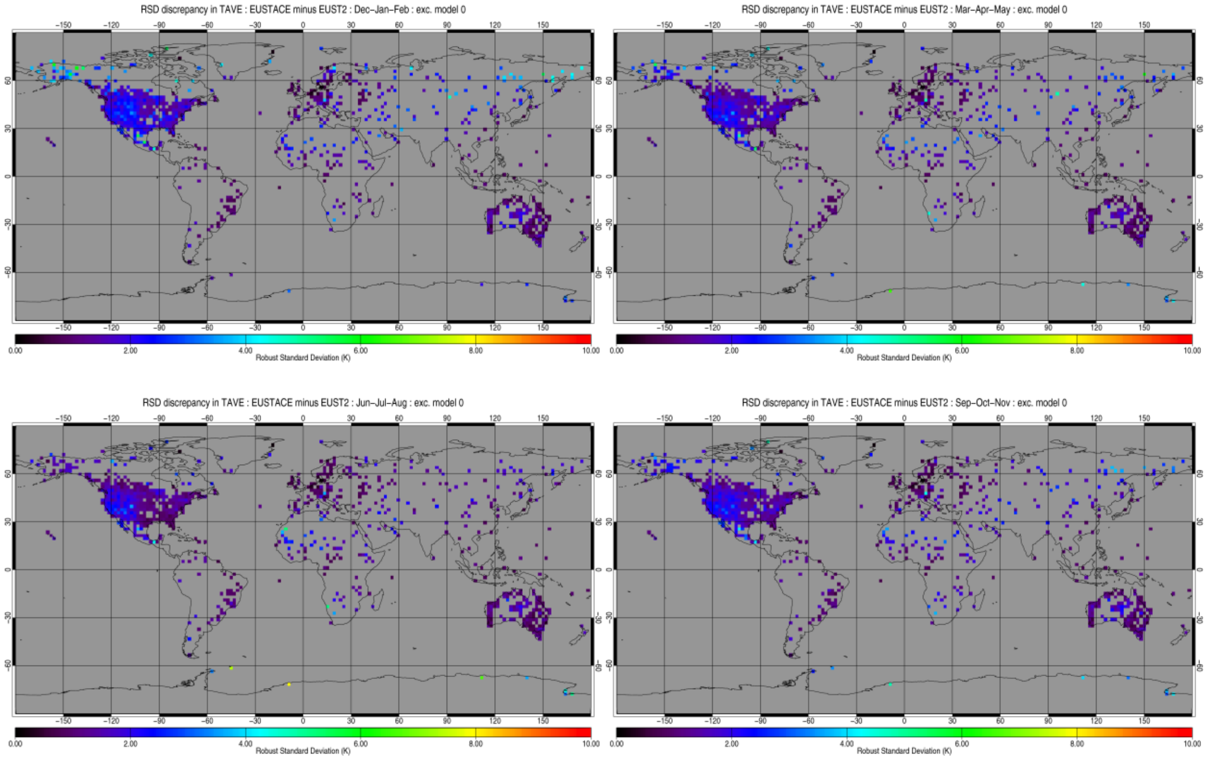

Figure 21: Maps of RSD of gridded seasonal mean discrepancy (K) for EUSTACE Global air temperature estimates, v1.0 minus EUSTACE Station Dataset in situ surface air temperatures for December-January-February (top left), March-April-May (top right), June-July-August (bottom left) and September-October-November (bottom right), 1850-2015.

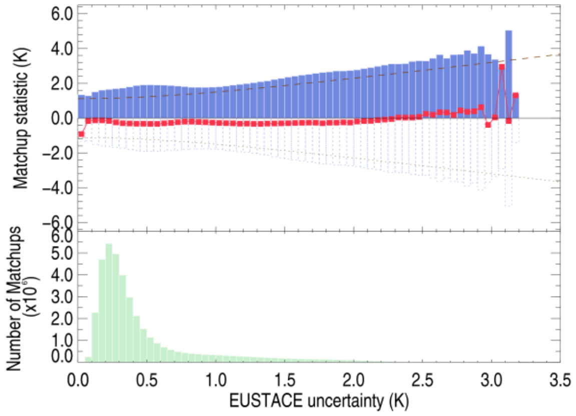

Figure 22: Matchup discrepancy against EUSTACE uncertainty estimate (K) for the EUSTACE Global air temperature estimates, v1.0 Tmean minus EUSTACE Station Dataset in situ surface air temperatures, 1850-2015. Blue bars indicate the matchup discrepancy RSD and red squares show the matchup discrepancy median. The brown dashed line shows the modelled expected relationship between the matchup discrepancy RSD and the EUSTACE uncertainty. The number of matchups in each uncertainty bin is shown by the green bars in the lower histogram.

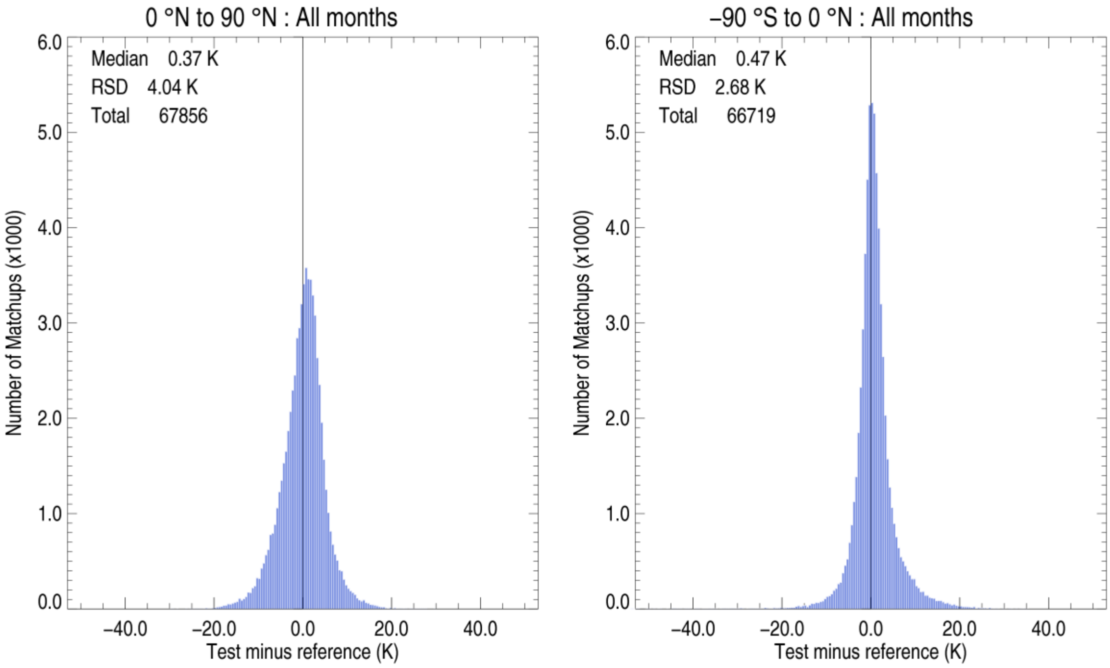

Figure 23: Histograms of matchup discrepancy (K) for matchups of EUSTACE Global air temperature estimates, v1.0 Tmean to DMI Quality Controlled Ice Station data for the Arctic (left) and Antarctic (right), 1890-2015.

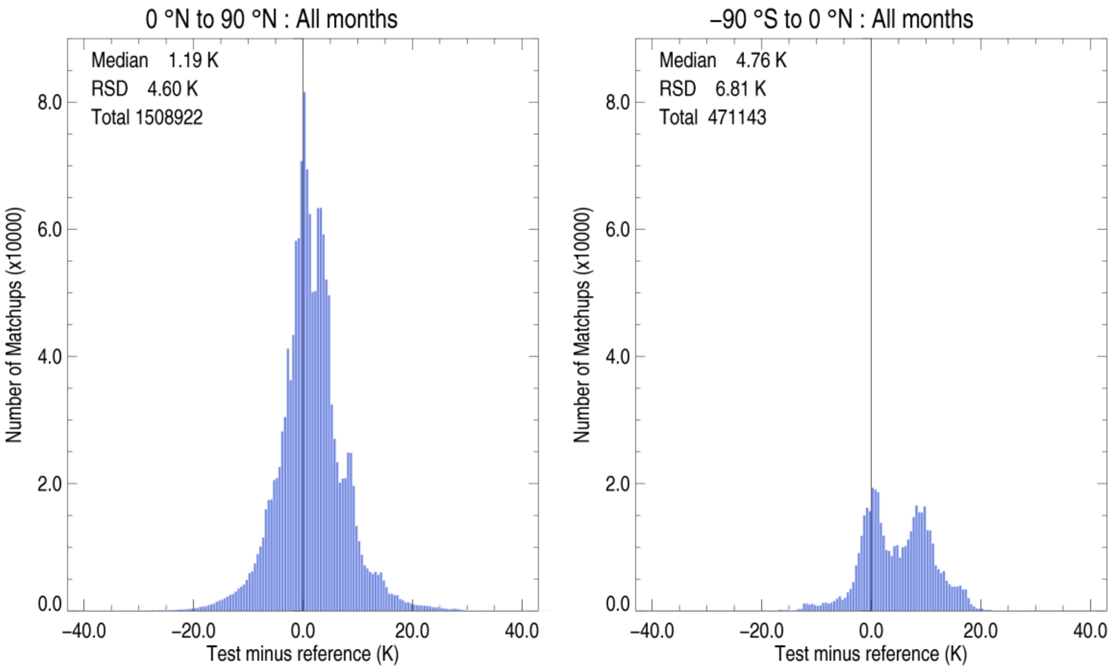

Figure 24: Histograms of matchup discrepancy (K) for matchups of EUSTACE Global air temperature estimates, v1.0 Tmean to DMI Quality Controlled Ice Buoy data for the Arctic (left) and Antarctic (right), 1890-2015.

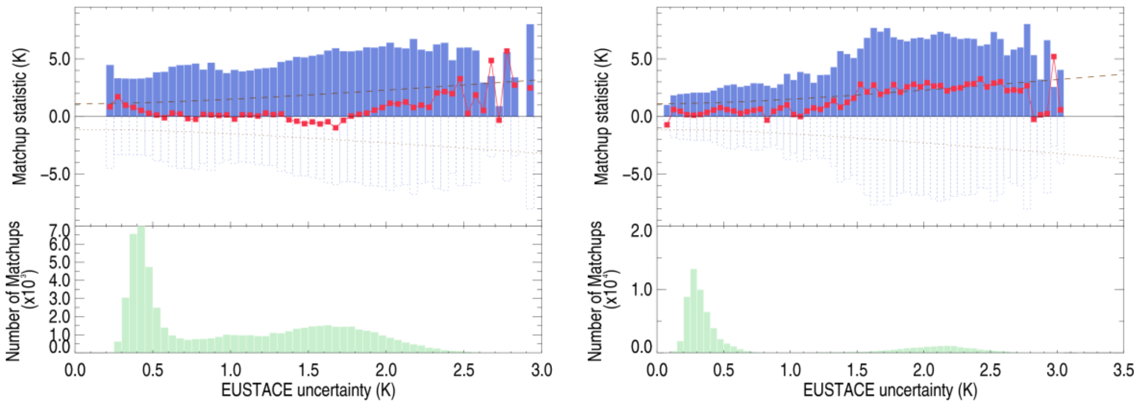

Figure 25: Matchup discrepancy against EUSTACE uncertainty estimate (K) for EUSTACE Global air temperature estimates, v1.0 Tmean for matchups to DMI Quality Controlled Station Data in the Arctic (left) and Antarctic (right), 1890-2015. Blue bars indicate the matchup discrepancy RSD and red squares show the matchup discrepancy median. The brown dashed line shows the modelled expected relationship between the matchup discrepancy RSD and the EUSTACE uncertainty. The number of matchups in each uncertainty bin is shown by the green bars in the lower histogram.

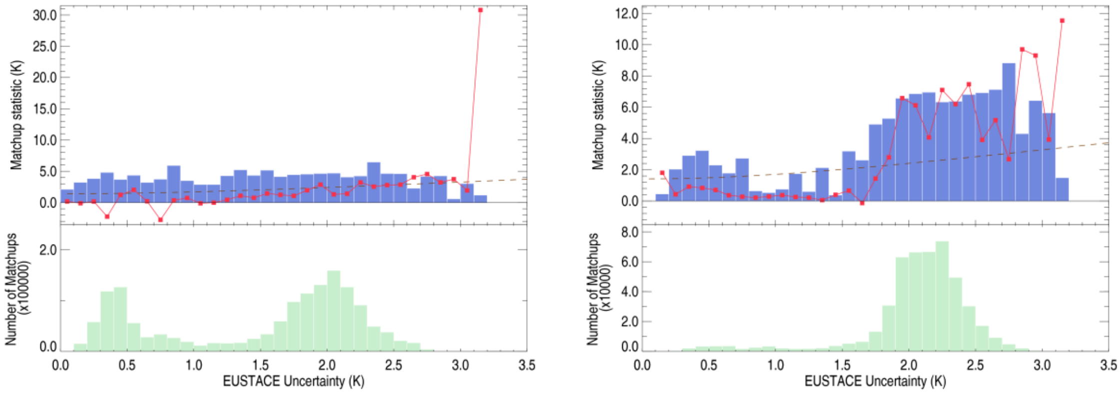

Figure 26: Matchup discrepancy against EUSTACE uncertainty estimate (K) for EUSTACE Global air temperature estimates, v1.0 Tmean for matchups to DMI Quality Controlled Ice Buoy Data in northern hemisphere (left) and southern hemisphere (right), 1850-2015. Blue bars indicate the matchup discrepancy RSD and red squares show the matchup discrepancy median. The brown dashed line shows the modelled expected relationship between the matchup discrepancy RSD and the EUSTACE uncertainty. The number of matchups in each uncertainty bin is shown by the green bars in the lower histogram.