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EUSTACE

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EU Surface Temperature for All Corners of Earth

Deliverable D3.*4*

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

Deliverable Title	*Intercomparison report for the final in-filled EUSTACE surface air temperature product*	
Brief Description	*A report will be written detailing the comparison to other surface air temperature datasets of the final infilled EUSTACE product (from T2.5) (Task 3.2).*	
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		DEC – Dissemination, Exploitation or Communication
		O - Other
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		CO - Confidential, only for members of the consortium, including the Commission services

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	19/03/2019	Nick Rayner	Added forward look
1.0	31/05/2019	Nick Rayner and John Kennedy	Added comparison of v1.0 product to other surface temperature data sets

Contents

1. Executive Summary

This report presents an intercomparison of the EUSTACE Global air temperature product with other air temperature datasets and reanalyses. Here, we report comparisons of both a prototype product (hereafter referred to in this report as the EUSTACE Prototype Analysis) with high resolution products across land in Europe and the v1.0 product with independently-constructed monthly instrumental surface temperature data sets and with air temperatures from reanalyses across all surfaces globally.

Data were collocated and monthly anomalies were calculated relative to a common baseline.

Over Europe, where station density is high, the Prototype Analysis shows close agreement with air temperatures from the Berkley Earth Monthly Land Europe dataset and the UERRA UKMO reanalysis.

EUSTACE Global daily air temperature estimates v1.0 is broadly consistent with the comparison data sets, but with some residual issues remaining after masking.

The EUSTACE Global air temperature estimates v1.0 are warmer than the comparison data between 1850 and 1895 over Europe. Nonetheless, it provides daily information for Europe which is consistent with the other instrumental data sets on monthly and annual timescales from 1895 onwards.

In the 1850s, EUSTACE Global air temperature estimates v1.0 are higher than the comparison data sets by around 0.8 deg C on the global average. At this time, daytime marine air temperature data are used (there being almost no night-time data available).

Between 1855 and 1880, EUSTACE Global air temperature estimates v1.0 are around 0.1-0.2 deg C higher than the comparison data sets because observations in the North Atlantic are thought to be warm biased then, particularly during windy conditions.

A cold bias affects Africa and parts of southern Asia starting in 2000. This is associated with residual biases from the EUSTACE satellite derived air temperatures over land.

For North America, EUSTACE Global air temperature estimates v1.0 are consistent with other long-term surface temperature data sets on the continental scale from 1870 onwards. In the 1860s when the EUSTACE data set is relatively cool for a time, but based on very few data.

Over parts of South America, a cold bias exists in EUSTACE Global air temperature estimates v1.0 between 1945 and 1957. The criteria used to filter out erroneous values in the analysis were not able to completely remove this feature, so users need to be aware of it and are advised not to use the data over this part of South America between 1945 and 1957. The EUSTACE data are also biased warm here in the 1870s.

Prior to 1957, the representation of temperature trends over Australia in EUSTACE Global air temperature estimates v1.0 appears inconsistent with that in the instrumental comparison data sets and likely erroneous.

EUSTACE Global air temperature estimates v1.0 are consistent with the comparison data sets where they all have data over the Arctic after 1892, with the exception of a period in the 1920s when EUSTACE data are erroneously warm. Prior to 1892, EUSTACE Global air temperature estimates v1.0 are biased warm in the Arctic by up to a few degrees C. Although the data have been masked in unconstrained regions, there are still areas early in the record where the analysis takes unrealistic high values.

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.		No
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 presents a comparison between EUSTACE Global air temperature estimates, v1.0 with other air temperature datasets and air temperatures from a selection of reanalyses. Four comparisons have been performed. The first is with high spatial resolution datasets over Europe and also uses EUSTACE Air temperature estimates from satellite, v1.0 over land, together with a prototype version of the EUSTACE Global air temperature estimates which is largely consistent with the v1.0 product. The other three are global: a comparison with air temperature datasets over land only, a comparison with air temperature analyses over land and ocean, and a comparison with reanalyses over all surfaces.

b) Approach and data

EUSTACE Global air temperature estimates, v1.0 provides daily temperatures on a 0.25° x 0.25° grid. The daily temperatures are estimates for the 24 hour period from midnight to midnight in local solar time. As many of the datasets used for comparison are monthly averages or have daily temperatures using Universal Time, in all experiments monthly means of daily mean temperature were compared.

As a first step, each dataset was regridded to monthly means on a 0.25° x 0.25° grid. In the case of EUSTACE Air temperature estimates from satellite over land which provides daily minimum and maximum temperatures, these were averaged to a daily mean temperature before averaging to monthly mean temperatures in a preliminary step and daily mean temperatures were calculated only where both minimum and maximum temperatures were available for the grid box.

The reanalyses were remapped using Climate Data Operators (Schulzweida, 2019).

In order to reduce sampling effects, comparisons were mostly made between collocated monthly data only (the figures indicate where this is and is not the case). Thus, for each comparison, sampling was consistent between the datasets but not between months. The only exception was for periods beyond the time coverage of a particular dataset, for example, in comparison 1, four datasets were compared but the Berkley Earth Land Monthly Europe time coverage ceases after August 2013 so after this date the collocation was between the other three datasets.

The base period chosen for the climatology also depended on the time coverage of the comparison datasets and varied accordingly.

Since the data were collocated, the only time when all datasets were not present is when the dataset time coverage did not cover the whole of the experiment period, in this case the median was calculated from the datasets that were available. For example in comparison 1, since the coverage of the EUSTACE Air temperature estimates from satellite starts in July 2002, for months prior to that date the median was calculated from the EUSTACE Prototype Analysis, the Berkley Earth Monthly Land Europe and the UERRA UKMO reanalysis datasets. The lowest number of datasets used to calculate the median in any experiment was three (in comparison 1).

Fields of difference from the dataset median were then calculated for each dataset.

Table 1: Details of datasets used in comparison

Product	Reference	Code used in plots
EUSTACE Products		
EUSTACE Analysis Prototype ensemble		eusf ens
EUSTACE Prototype Analysis		eustf
EUSTACE Air temperature estimates from satellite v1.0		eustl
EUSTACE Global air temperature estimates v1.0		
Air temperature Datasets		
Berkley Earth Monthly Land Europe		BEMLE
Berkley Earth Monthly Land and Ocean		BEMLO
CRUTEM4 median	Jones et al., 2012	CRT4M
HadNMAT2	Kent et al., 2013	
GISTEMPv3.0	Hansen and Lebedeff, 1987	GIS12
HadCRUT4 ensemble median	Morice et al., 2012	HC ens
Reanalyses		
CREATE NCEP CSFRv2	Saha, S., et al. (2010),	cCSFR
CREATE NOAA CIRES 20CRv2c	Compo, G. P., et al. (2011),	C20CR
CREATE ERA Interim	Dee et al., 2011	cERAI
CREATE JRA 25	Onogi et al., 2007	cJR25
CREATE JRA 55	Kobayashi et al., 2015	cJR55
CREATE MERRA	Rienecker, M. M., et al. (2011),	cMER1
CREATE MERRA 2	Gelaro, 2017	cMER2
CREATE Ensemble median	Potter,2018	c_ENS
ERACLIM CERA-20C ensemble		C20C ens
UERRA UKMO UM ensemble		uUM ens

Table 2: Spatial and temporal, coverage and resolution of datasets

Product	Spatial resolution (longitude x latitude)	Spatial coverage	Temporal resolution	Temporal coverage
EUSTACE Products				
EUSTACE Analysis Prototype	0.25° x 0.25°	Global	Daily	2000 – 2016
EUSTACE Air temperature estimates from satellite v1.0	0.25° x 0.25°	Global	Daily	07/2002 – 2016
EUSTACE Global air temperature estimates v1.0	0.25° x 0.25°	Global	Daily	1850 – 2015
Air temperature Datasets				
Berkley Earth Monthly Land Europe	0.25° x 0.25°	Europe	Monthly	1850 – 08/2013
Berkley Earth Monthly Land and Ocean	1.0° x 1.0°	Global	Monthly	1850 – present
CRUTEM4	5.0° x 5.0°	Global	Monthly	1850 – present
HadNMAT2	5.0° x 5.0°	Global	Monthly	1885 - 2010
GISTEMPv3.0	2.0° x 2.0°	Global	Monthly	1880 – present
HadCRUT4	5.0° x 5.0°	Global	Monthly	1850 – present
Reanalyses				
CREATE NCEP CSFRv2	0.3125° x ~0.34°	Global	Monthly	1979 – 2017
CREATE CIRES 20CRv2c	~1.875°	Global	Monthly	1851 - 2012
CREATE ERA Interim	0.75° x 0.75°	Global	Monthly	1979 – 2017
CREATE JRA 25	1.25° x 1.125°	Global	Monthly	1979 – 2013
CREATE JRA 55	1.25° x 1.25°	Global	Monthly	1958 – 2017
CREATE MERRA	0.667° x 0.5°	Global	Monthly	1979 – 02/2016
CREATE MERRA 2	0.625° x 0.5°	Global	Monthly	1980 – 2017
CREATE Ensemble median	1.25° x 1.25°	Global	Monthly	1980 – 2015
ERACLIM CERA-20C ensemble	~1.6° x 1.125°	Global	Monthly	1901 – 2010
UERRA UKMO UM ensemble	0.3125° x ~0.3125°	Europe	6 hourly	1979 – 2016

c) Comparisons

i Intercomparison of air temperature estimates from EUSTACE Prototype Analysis, EUSTACE Air temperature estimates from satellite, Berkley Earth Monthly Land Europe, and UERRA UKMO Unified Model over Europe

Here we compare datasets with spatial resolutions comparable to that of the EUSTACE Prototype Analysis over a limited region. The EUSTACE data analysis has a higher grid resolution than most air temperature analyses however Berkley Earth produced an experimental analysis over Europe at the same spatial resolution as the EUSTACE datasets, i.e. 0.25° x 0.25° and the UERRA (Uncertainties in Ensembles of Regional ReAnalyses) Project has produced several high resolution regional reanalyses for Europe. Here, we compare the EUSTACE Prototype Analysis, the EUSTACE Air temperature estimates from satellite product, the Berkley Earth Monthly Land Europe analysis and the UERRA UKMO Unified Model reanalysis ensemble (native resolution 0.3125°) over land in Europe.

A climatology base period of 2003 to 2012 was chosen because it covers all years where all the datasets are present for the whole year. Coverage of collocated data for the climatology period is shown for winter and summer in Figure 1. The region limits are dictated by the coverage of the Berkley Earth data however the coverage within the region in any particular month is limited by the coverage of the EUSTACE Air temperature estimates from satellite data v1.0. The Air temperature estimates from satellite product is limited by cloud cover as determined by the MODIS LST algorithm and also by the availability of fractional vegetation data (in turn limited by the availability of visible (daytime) data in the polar winter). Hence, coverage is near full for most of the region in summer but in winter there is zero coverage in the north and less than full coverage elsewhere in the region.

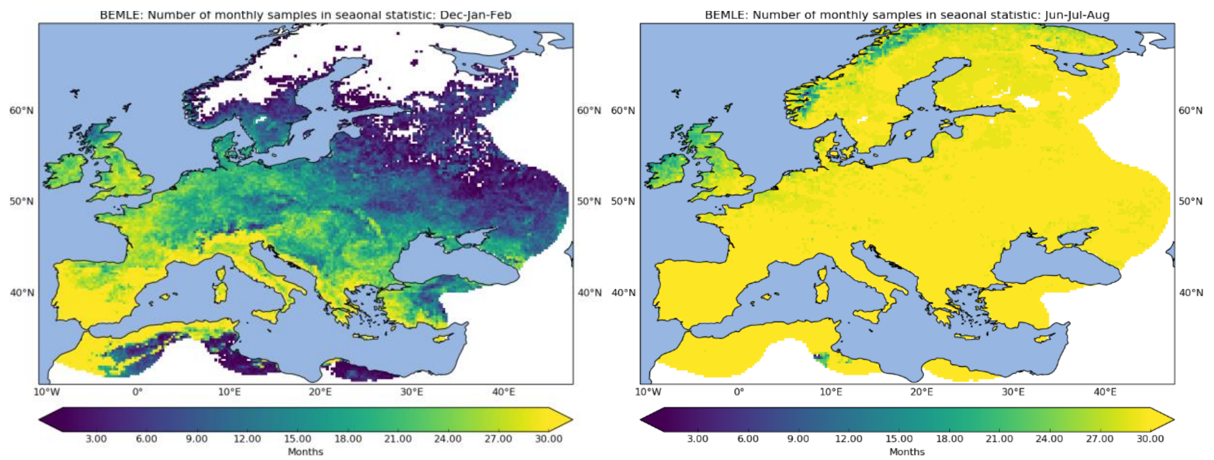

Figure 1: Coverage for collocated data in period 2003 to 2012 for winter and summer seasons

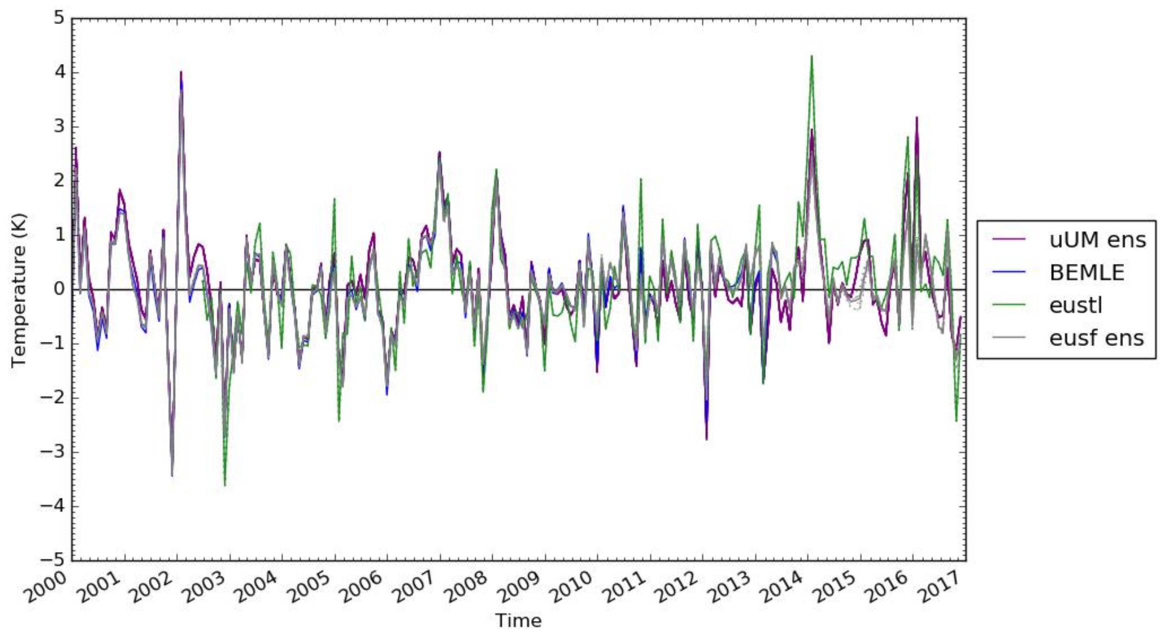

Figure 2: Time series of surface air temperature mean monthly anomaly (base period 2003 - 2012) for collocated data over Europe. Year labels are placed at 1st of January. Data points are plotted on the first of the month averaging period to which they refer. For ensembles, the ensemble members are plotted as dashed lines, the ensemble median as a solid line and the ensemble median +/- two times the ensemble RSD as dotted lines. For other datasets, the mean is plotted as a solid line and where uncertainties are available the mean +/- two times the one sigma uncertainty are plotted as dotted lines. Note: in most cases the uncertainties and RSDs are of order of millikelvin and not visible on the plot. Datasets: uUM ens is UERRA UKMO Unified Model reanalysis ensemble, BEMLE is Berkley Earth Monthly Land Europe, eustl is EUSTACE Air temperature estimates from satellite, eusf ens is EUSTACE Prototype Analysis ensemble.

Time series of mean regional, monthly air temperature anomaly for all four datasets are plotted in Figure 2. There is close agreement between the time series from EUSTACE Prototype Analysis, Berkley Earth and UERRA UKMO Unified Model reanalysis. The mean monthly regional anomalies from the three datasets are within

0.3 K in most months. However, in the case of the EUSTACE Air temperature estimates from satellite v1.0, the mean anomalies show greater variability with the regional anomaly magnitude sometimes over 1K greater than the other datasets.

Maps of season median difference from the dataset median for summer (Figure 3) and winter (Figure 4) show that whilst the EUSTACE Prototype Analysis, Berkley Earth Europe and UKMO Unified Model datasets exhibit differences from the median of less than 0.1 K for most of the region in both summer and winter, EUSTACE Air temperature estimates from satellite v1.0 has many small areas in winter where the difference from the median exceeds 1K especially in the eastern half of the region.

In summer, the EUSTACE Air temperature estimates from satellite show a small (0.1 - 0.2 K) negative bias across most of the region in summer. The bias is highest in the northern margins (as low as -0.8 K for a few grid boxes).

Possible reasons for biases in the EUSTACE Air temperature estimates from satellite Land monthly anomalies include poor temporal sampling, especially during the winter months, so that month means may be calculated from a few days of data in particularly cloudy months; regression model errors; the impact of errors in dynamic snow and fractional vegetation cover on the regression model or on the MODIS LST retrieval; or cloud contamination of the input LSTs.

The Berkley Earth product has a few grid boxes with positive differences up to 0.5 K towards the eastern edge of the region and over the Alps in winter.

The UERRA UKMO Unified Model reanalysis has a region of positive bias to the median of 2-3 K around the White Sea coast in summer. These biases persist into autumn although with smaller magnitude (not shown).

The EUSTACE Prototype Analysis shows small areas with large (up to and over 1 K) positive and negative differences over the Alps. These biases to the median are strongest in summer but persist throughout all seasons. Mountainous regions also demonstrate larger RSDs (> 2 K). In mountainous regions the temperature at a station may differ considerably from the mean grid box temperature if the station altitude differs from the mean altitude. Corrections for altitude were not implemented in the Prototype Analysis but are in EUSTACE Global air temperature estimates v1.0.

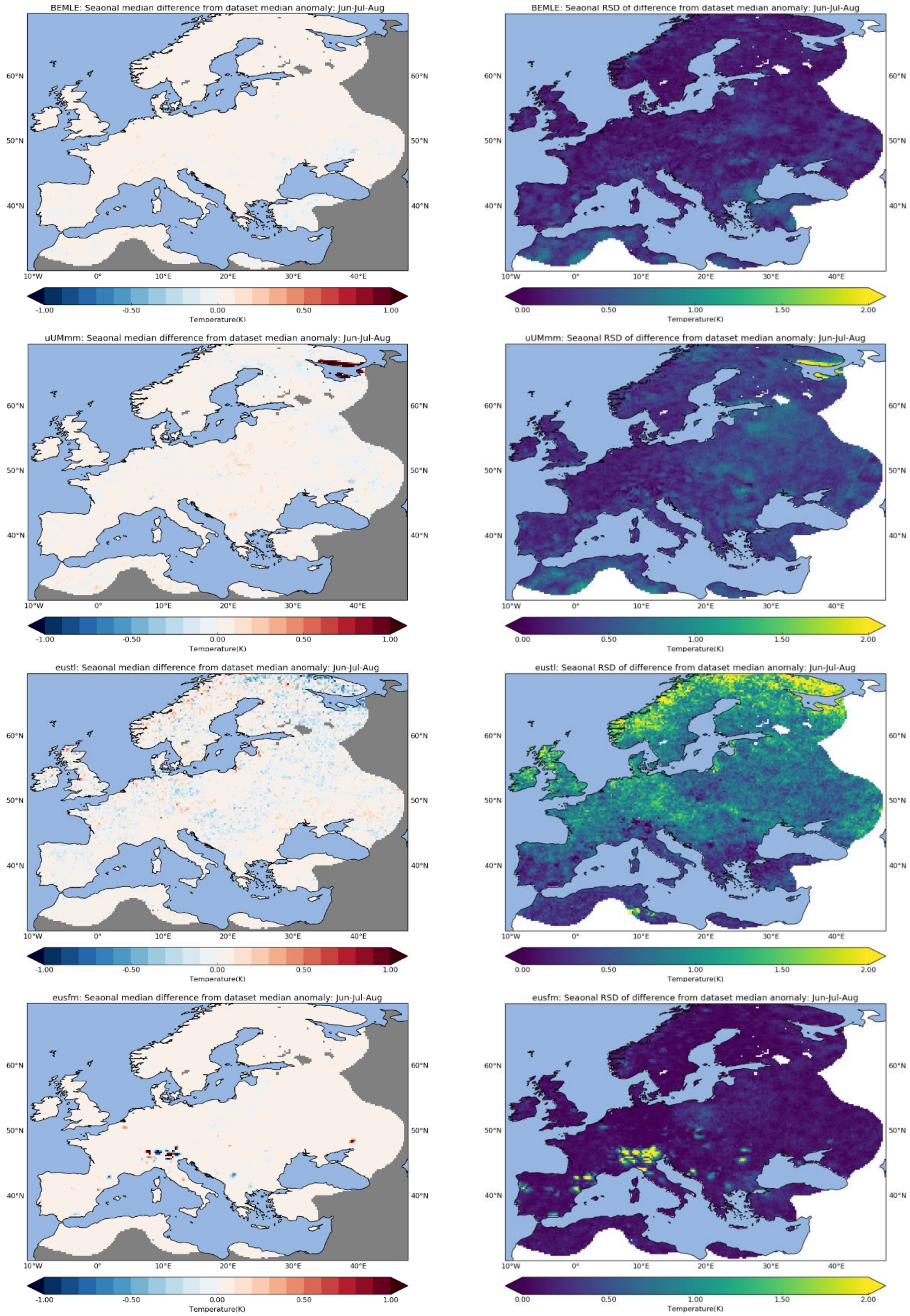

Figure 3: Summer (June, July, August) seasonal median (left) and RSD (right) of difference from median of dataset ensemble seasonal anomaly for Berkley Earth Month Land Europe (row 1), UERRA UKMO Unified Model (row 2), EUSTACE Air temperature estimates from satellite (row 3) and EUSTACE Prototype Analysis (row 4). Median anomaly colourbar ranges from - 1.0 to + 1.0 K, RSD colourbar ranges from 0.0 to 2.0 K.

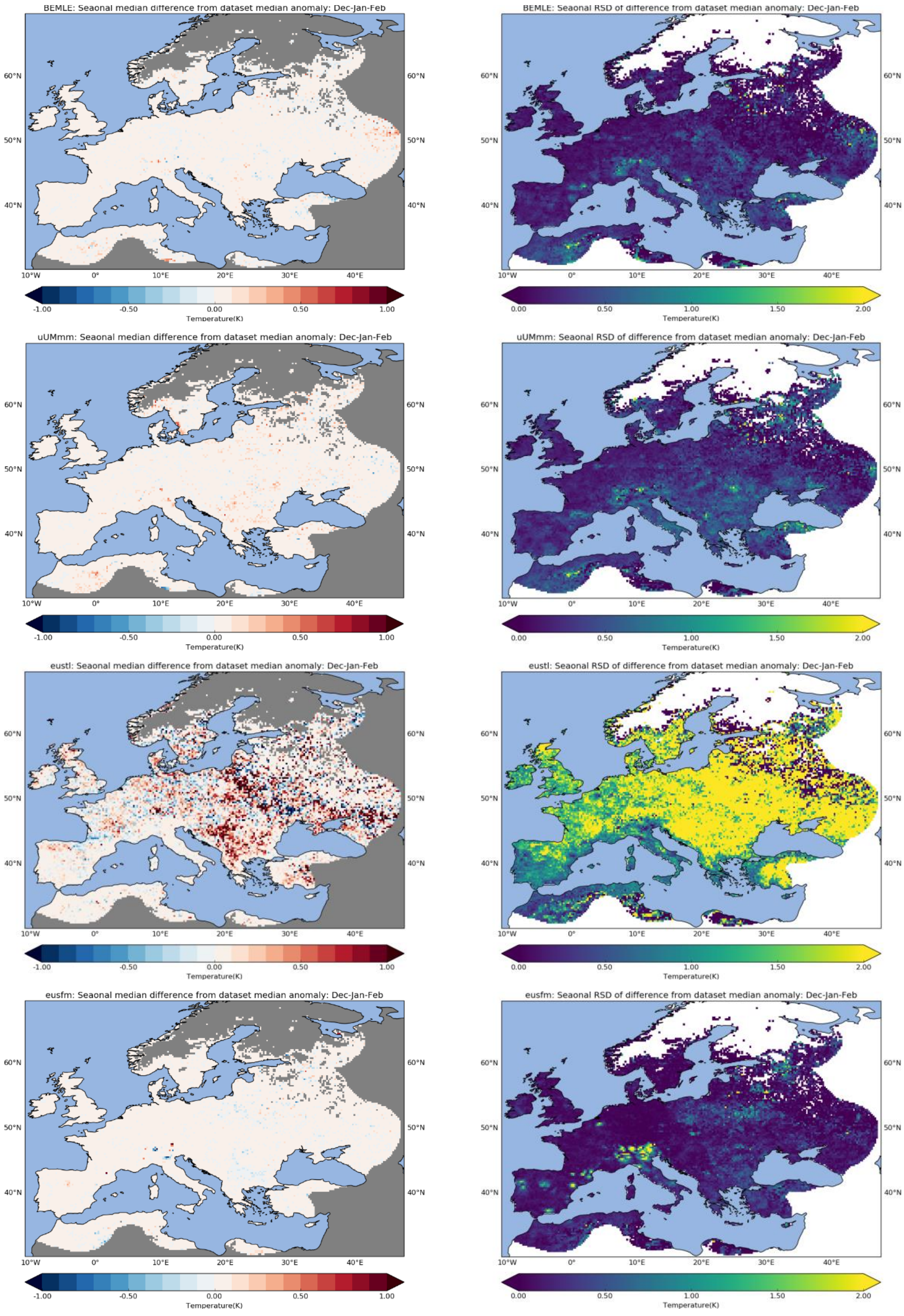

Figure 4: Winter (December, January, February) seasonal median (left) and RSD (right) of difference from median of dataset ensemble seasonal anomaly for Berkley Earth Monthly Land Europe (row 1), UERRA UKMO Unified Model (row 2), EUSTACE Air temperature estimates from satellite (row 3) and EUSTACE Prototype Analysis (row 4). Colourbar ranges are the same as in Figure 3.

To put these results into their longer term context, we now compare the EUSTACE Global air temperature estimates v1.0 with other long data sets over Europe (Figure 5).

The data sets agree closely on both a monthly and annual timescale back to 1900. Prior to 1895, the EUSTACE Global air temperature estimates v1.0 diverges from the other data sets. There are very few daily station data over Europe prior to 1895 in the EUSTACE Global Station Dataset and the homogenisation in the EUSTACE analysis system is not able to detect breaks and/or correct discontinuities in the few station series that are available before this time; other data sets include more numerous monthly station data for this period. Consequently, the EUSTACE Global air temperature estimates v1.0 are warmer than the comparison data between 1850 and 1895 over Europe. Nonetheless, it provides daily information for Europe which is consistent with the other data sets on monthly and annual timescales from 1895 onwards.

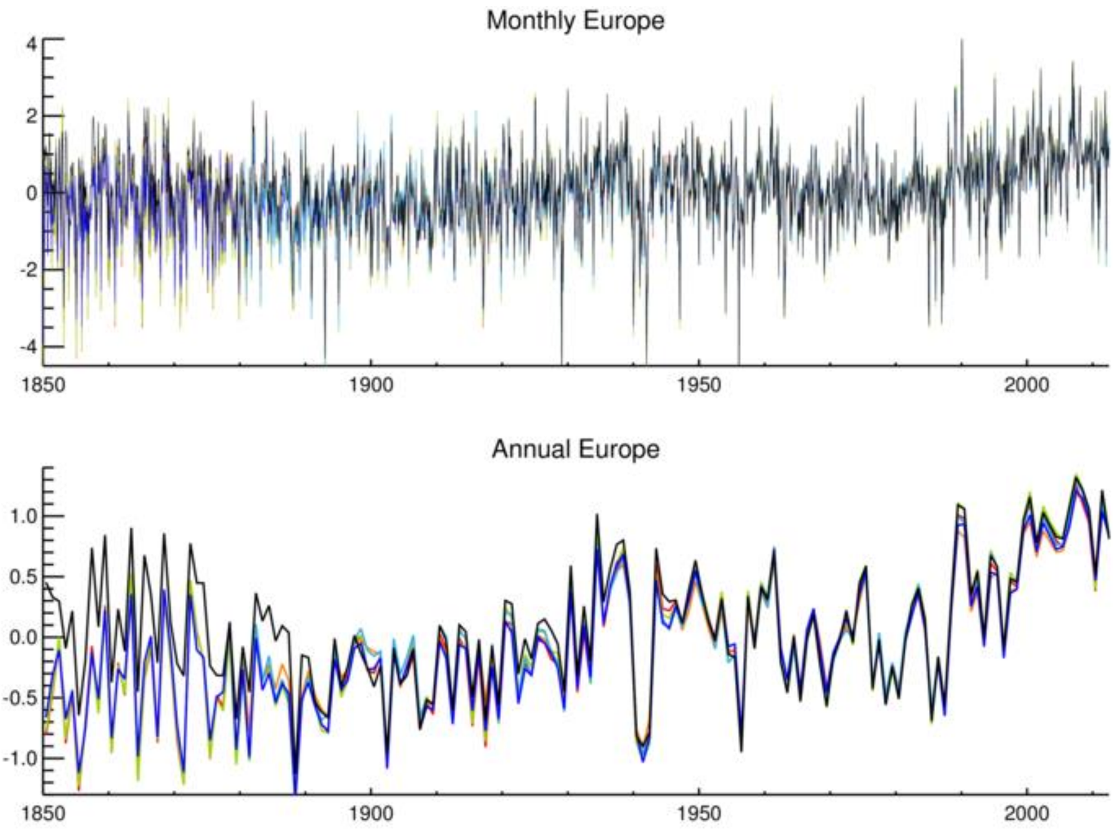

Figure 5. Air temperature anomalies for Europe (ºC, relative to 1961-1990) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Olive green: HadCRUT4; Red: HadNMAT2 + CRUTEM4; Dark Blue: Berkeley Earth; Orange: NOAAGlobalTemp; Pale blue: NASA GISTEMP. Data sets are collocated to match CRUTEM4 coverage.

ii Intercomparison with air temperature datasets over land

Here, we compare surface air temperature anomalies from the EUSTACE Global air temperature estimates v1.0, HadCRUT4, HadNMAT2+CRUTEM4, NOAAGlobalTemp, GISTEMP v3.0 and Berkley Earth Monthly Land and Ocean. Time series of mean monthly and annual anomaly for various land regions are shown in Figure 6 to Figure 12.

It is worth considering how the EUSTACE Global air temperature estimates v1.0 was created before we begin. EUSTACE Global air temperature estimates v1.0 is a daily data set, whereas the data set we compare to here are monthly data sets. This means that EUSTACE Global air temperature estimates v1.0 are based on records of daily station measurements over land, instantaneous measurements onboard ships and satellite-based estimates of daily mean air temperature over ocean and ice, and estimates of daily maximum and daily minimum air temperature over land. These are then combined using an analysis system which grids onto a 0.25 degree daily grid, estimates values where no measurements exist and corrects inhomogeneities in station timeseries where breaks have been identified beforehand. This is an entirely independent construction from that of any of the comparison data sets, which use monthly station timeseries (which are typically more plentiful), gridded monthly fields of sea-surface temperature measurements from ships and drifting buoys (except for the HadNMAT2 + CRUTEM4 blend which we use here, which comprises monthly gridded air temperature measurements over the ocean) and no satellite-based estimates of air temperature. The level of consistency that we see in all the time series shown here is very high, considering that they have been derived in such an independent manner.

A number of differences between the EUSTACE Global air temperature estimates v1.0 and the other global temperature data sets are worthy of note.

Figure 6 shows that there is a period at the beginning of the record which is inconsistent with the other data sets. In the 1850s, air temperature anomalies in EUSTACE Global air temperature estimates v1.0 are very high. This arises because of the impact on the 5 degree averages used as the basis of these comparisons of ocean grid boxes containing daytime marine air temperature data in this earliest part of the record (there being almost no night-time data available, see also Figure 19). Between 1855 and 1900, EUSTACE Global air temperature estimates v1.0 are also relatively high. Between 1855 and 1880, observations in the North Atlantic are thought to be warm biased, particularly during windy conditions (see also Figure 19).

From 2000 onwards, the data sets again diverge with EUSTACE Global air temperature estimates v1.0 being relatively cool and HadCRUT4 being relatively warm over global land. In EUSTACE Global air temperature estimates v1.0, this arises because of uncorrected biases in the EUSTACE Air temperature estimates from satellite v1.0 over Africa and southern Asia, in particular (see also Figure 19, Figure 20 and Veal 2019); there is insufficient information to make a good estimate of the bias in the analysis system, which therefore remains close to its prior of zero. Elsewhere, where there are more daily station observations, the analysis system is able to very effectively correct such biases.

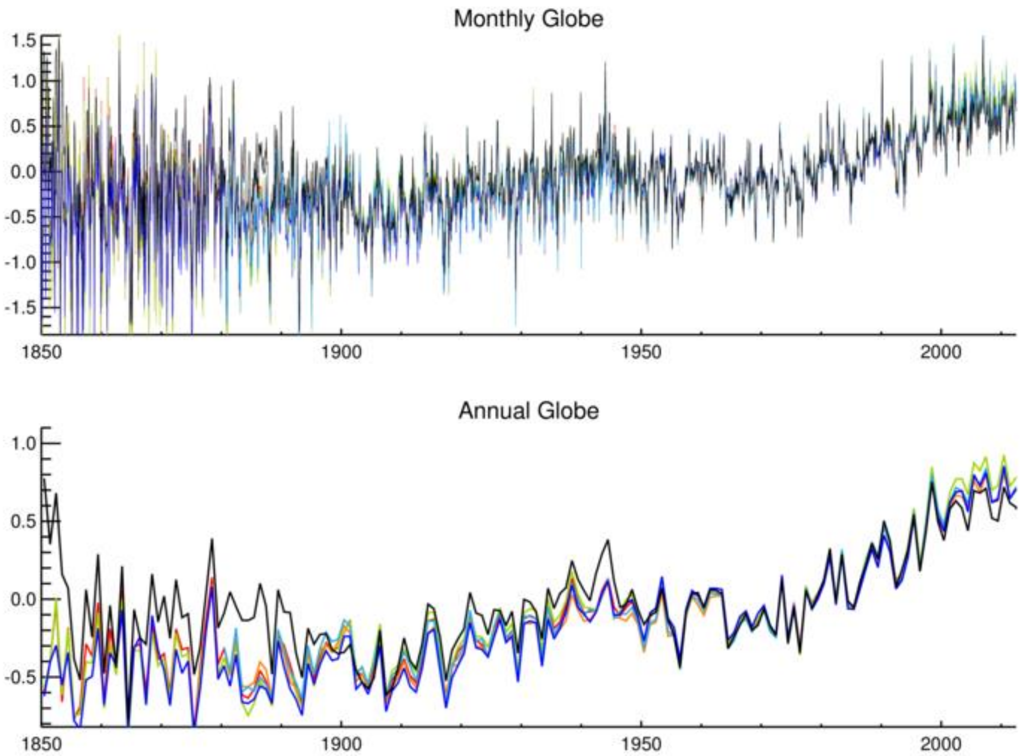

Figure 6. Air temperature anomalies for Global land (ºC, relative to 1961-1990) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Olive green: HadCRUT4; Red: HadNMAT2 + CRUTEM4; Dark Blue: Berkeley Earth; Orange: NOAAGlobalTemp; Pale blue: NASA GISTEMP. Data sets are collocated to match CRUTEM4 coverage.

The differences just discussed between EUSTACE Global air temperature estimates v1.0 and the comparison data are echoed in the Northern Hemisphere average series (Figure 7) because the Northern Hemisphere contributes approximately two thirds of the global average over land.

In the Southern Hemisphere average (Figure 8) all the data sets are very consistent after 1950, but EUSTACE Global air temperature estimates v1.0 is consistently warmer by between 0.2 and 0.3 deg C between 1880 and 1945. Figure 20 suggests this may arise from the apparent bias over Australia in this period (see also Figure 11 and associated discussion below).

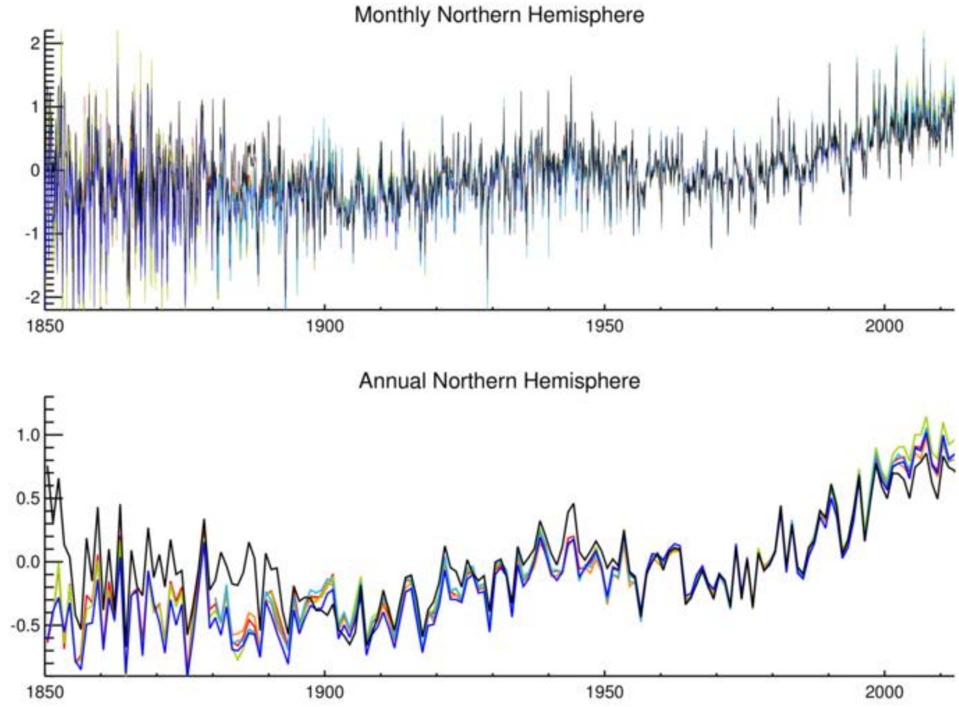

Figure 7. Air temperature anomalies for Northern Hemisphere land (ºC, relative to 1961-1990) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Olive green: HadCRUT4; Red: HadNMAT2 + CRUTEM4; Dark Blue: Berkeley Earth; Orange: NOAAGlobalTemp; Pale blue: NASA GISTEMP. Data sets are collocated to match CRUTEM4 coverage.

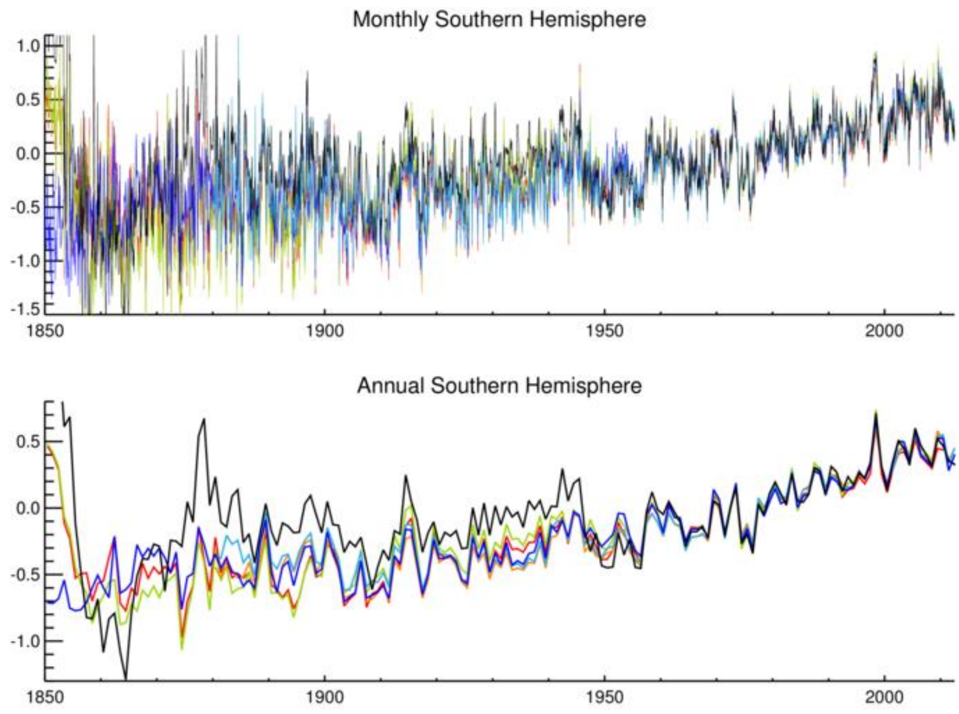

Figure 8. Air temperature anomalies for Southern Hemisphere land (ºC, relative to 1961-1990) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Olive green: HadCRUT4; Red: HadNMAT2 + CRUTEM4; Dark Blue: Berkeley Earth; Orange: NOAAGlobalTemp; Pale blue: NASA GISTEMP. Data sets are collocated to match CRUTEM4 coverage.

Close agreement between the data sets is seen over North America (Figure 9) from 1900 onwards. There is no inconsistency between EUSTACE Global air temperature estimates v1.0 and the comparison data, except in the 1860s when the EUSTACE data set is relatively cool for a time, but note from Figure 20 that the timeseries is based on very few data over North America in the 1860s.

Over South America (Figure 10), two periods are particularly noticeable: the 1870s and 1945-1956. Interestingly, the discrepancy in the later period, which manifests as a cold bias in EUSTACE Global air temperature estimates v1.0 (see also Figure 19 and Figure 20), arises because of a sudden appearance of data in Bolivia in the EUSTACE Global station data set in 1957. A feature of the EUSTACE analysis system is that it can suffer “shocks” from a sudden influx of data where there had been none before. The “shocks” appear just before the start of the data and are a feature of the slowly-varying component of the statistical model. The criteria used to filter out erroneous values in the analysis were not able to completely remove this feature, so users need to be aware of it and are advised not to use the data over this part of South America between 1945 and 1957.

There appears to be a clear change point in the EUSTACE Global air temperature estimates v1.0 in about 1957 over Australia relative to other data sets (Figure 11). Prior to this date, the representation of temperature trends over Australia in EUSTACE Global air temperature estimates v1.0 appears inconsistent with that in the comparison data sets and likely erroneous. Further investigation is needed to understand this, but Figure 20 suggests that it originates mostly over the western part of Australia.

The clearest discrepancy of EUSTACE Global air temperature estimates v1.0 with the comparison data over Antarctic land (Figure 12) occurs after 2000, when air temperature estimates from satellite are incorporated. The analysis system isn’t able to correct the cold bias in these estimates due to sparse in situ data across the continent and so the bias remains.

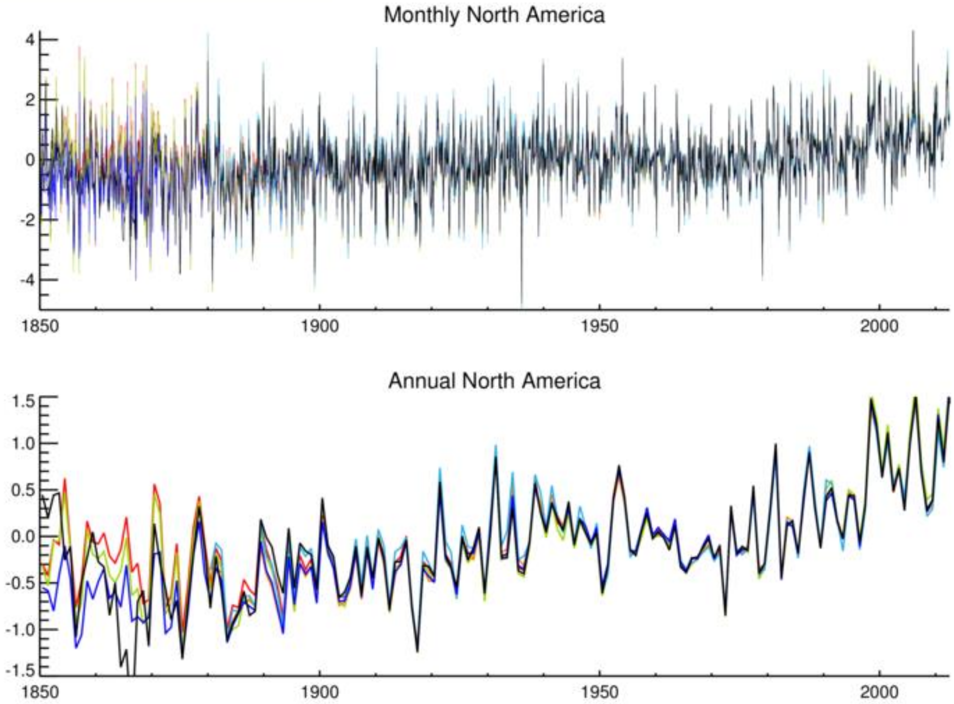

Figure 9. Air temperature anomalies for North America (ºC, relative to 1961-1990) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Olive green: HadCRUT4; Red: HadNMAT2 + CRUTEM4; Dark Blue: Berkeley Earth; Orange: NOAAGlobalTemp; Pale blue: NASA GISTEMP. Data sets are collocated to match CRUTEM4 coverage.

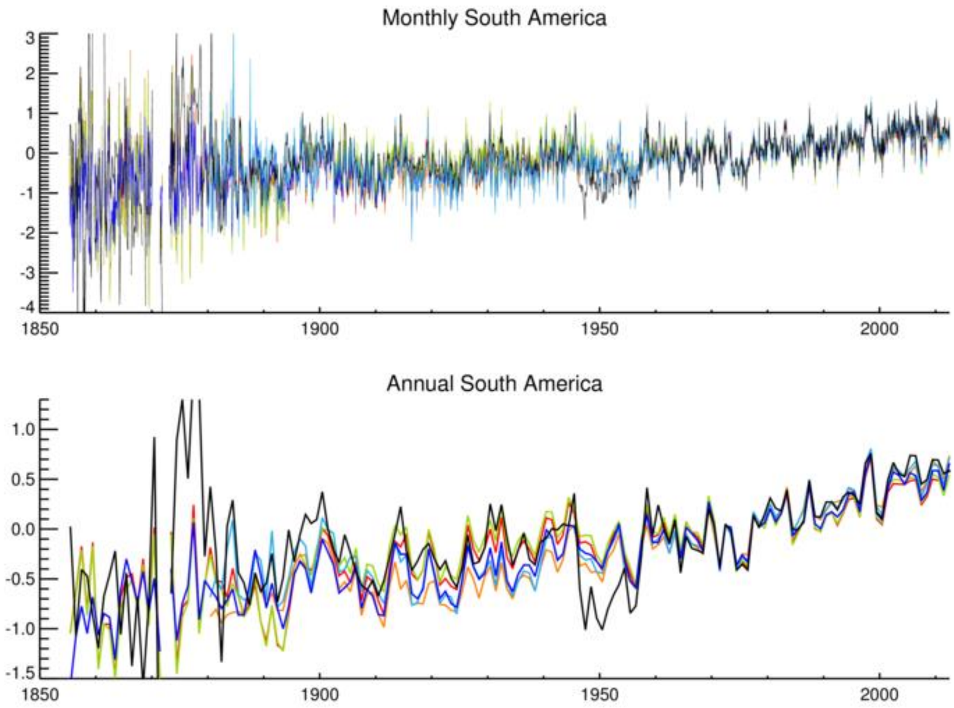

Figure 10. Air temperature anomalies for South America (ºC, relative to 1961-1990) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Olive green: HadCRUT4; Red: HadNMAT2 + CRUTEM4; Dark Blue: Berkeley Earth; Orange: NOAAGlobalTemp; Pale blue: NASA GISTEMP. Data sets are collocated to match CRUTEM4 coverage.

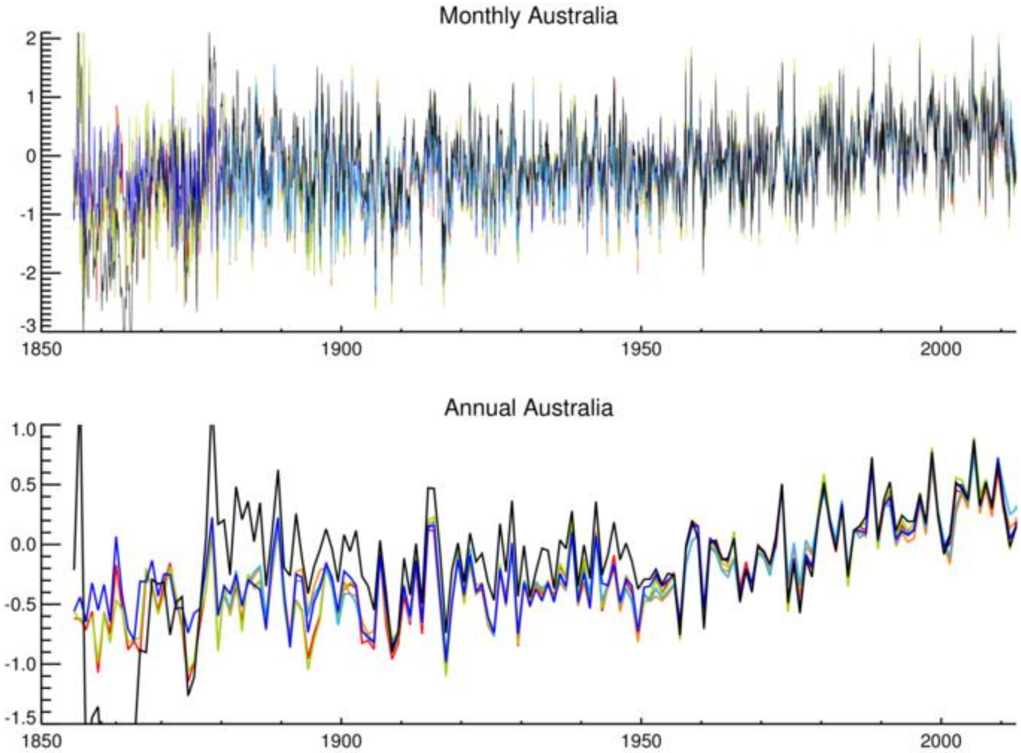

Figure 11. Air temperature anomalies for Australia (ºC, relative to 1961-1990) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Olive green: HadCRUT4; Red: HadNMAT2 + CRUTEM4; Dark Blue: Berkeley Earth; Orange: NOAAGlobalTemp; Pale blue: NASA GISTEMP. Data sets are collocated to match CRUTEM4 coverage.

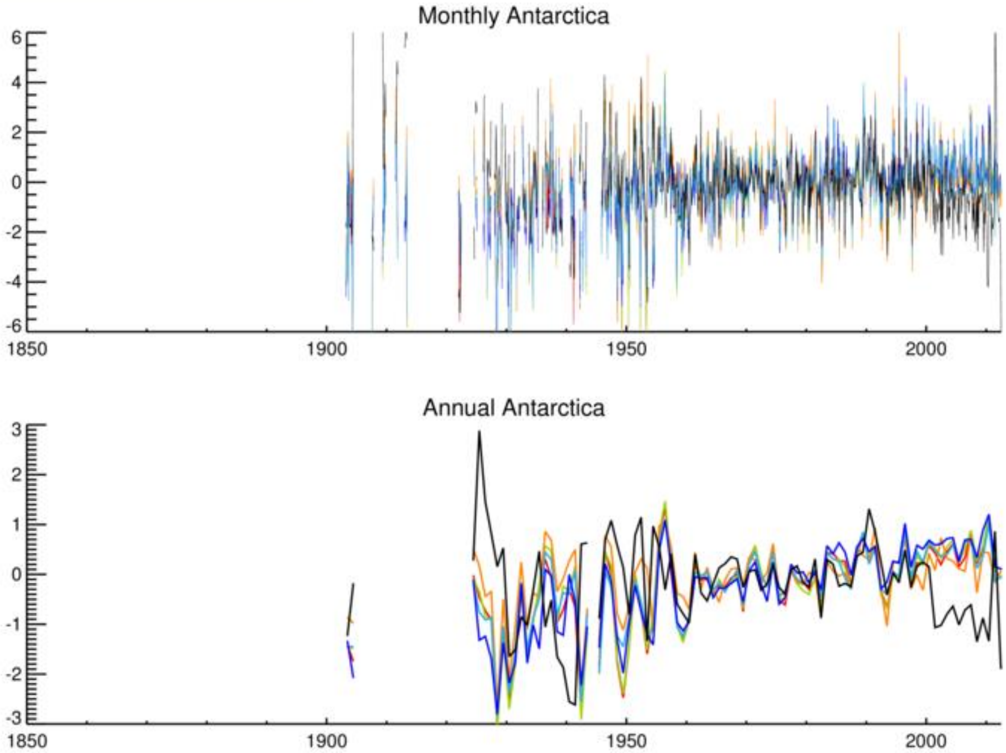

Figure 12. Air temperature anomalies for Antarctic land (ºC, relative to 1961-1990) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Olive green: HadCRUT4; Red: HadNMAT2 + CRUTEM4; Dark Blue: Berkeley Earth; Orange: NOAAGlobalTemp; Pale blue: NASA GISTEMP. Data sets are collocated to match CRUTEM4 coverage.

iii Intercomparison with air temperature datasets over land and ocean

Here, the EUSTACE Global air temperature estimates v1.0 are compared to other instrumental surface temperature datasets over global land and ocean: HadCRUT4, NOAAGlobalTemp, GISTEMP v3.0, the HadNMAT2 + CRUTEM4 blend and the Berkley Earth Month Land and Ocean dataset. Note, the coverage of permanent ice regions (Greenland and Antarctica) is limited in these comparison datasets. Note also that the EUSTACE Global air temperature estimates v1.0 provides air temperature over ocean, whereas the comparison data sets all use sea-surface temperature anomalies, so we would expect to see differences, but perhaps fewer on the timescales compared here since sea-surface temperature anomalies are usually assumed to be representative of air temperature anomalies on these scales.

The inclusion of the ocean in the global and hemispheric averages here mitigates some of the larger differences seen in the previous section (Figure 13, Figure 14 and Figure 15). Only the large biases in marine air temperature in the late 19th century and during the Second World War remain.

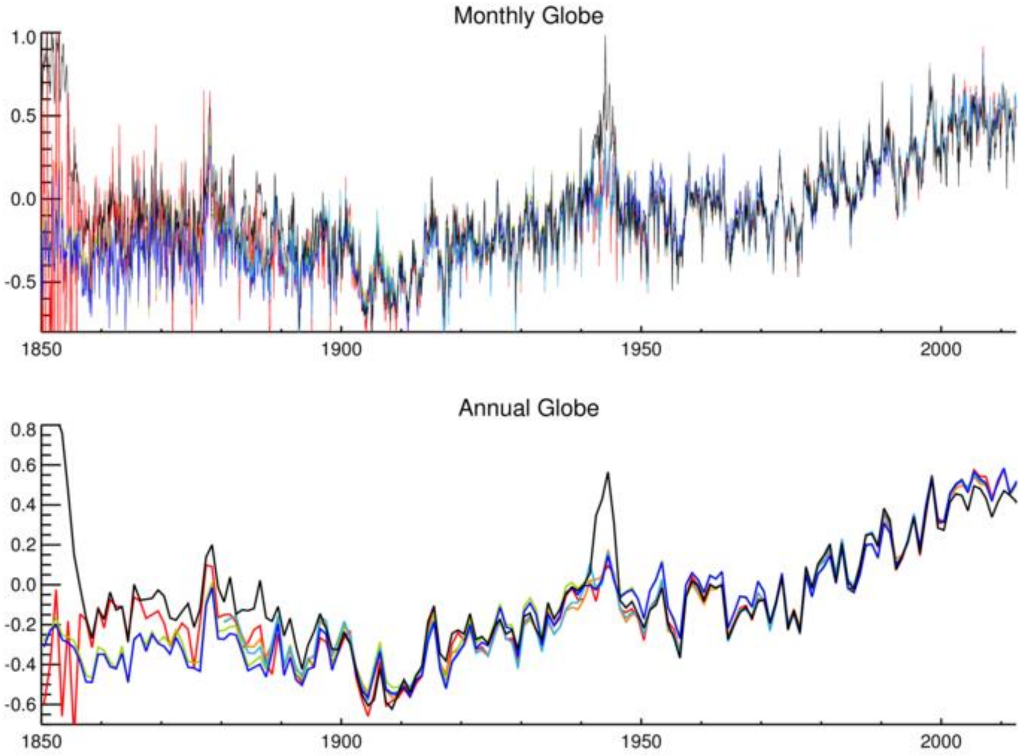

Figure 13. Surface temperature anomalies for Global land and ocean (ºC, relative to 1961-1990) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Olive green: HadCRUT4; Red: HadNMAT2 + CRUTEM4; Dark Blue: Berkeley Earth; Orange: NOAAGlobalTemp; Pale blue: NASA GISTEMP. Data sets are collocated in this Figure.

EUSTACE Global air temperature estimates v1.0 is consistent with the comparison data sets where they all have data over the Arctic (Figure 16) after 1890, with the exception of a relatively warm period in the 1920s. Differences arise in the 2000s, with EUSTACE Global air temperature estimates v1.0 being most consistent with Berkley Earth and least consistent with NOAAGlobalTemp over this period. When we plot the Arctic time series without colocation (Figure 17), the differences in the 2000s increase as the Arctic warms (as is commonly seen when comparing global surface temperature data sets over this period in this region). The warmth in EUSTACE Global air temperature estimates v1.0 in the 1920s and 1930s also becomes clearer and remnants of the drift in the complete analysis in the Arctic are seen prior to about 1892. Now we also see a further analysis “shock” in 2000, just prior to the introduction of the air temperature estimates from satellite in this region.

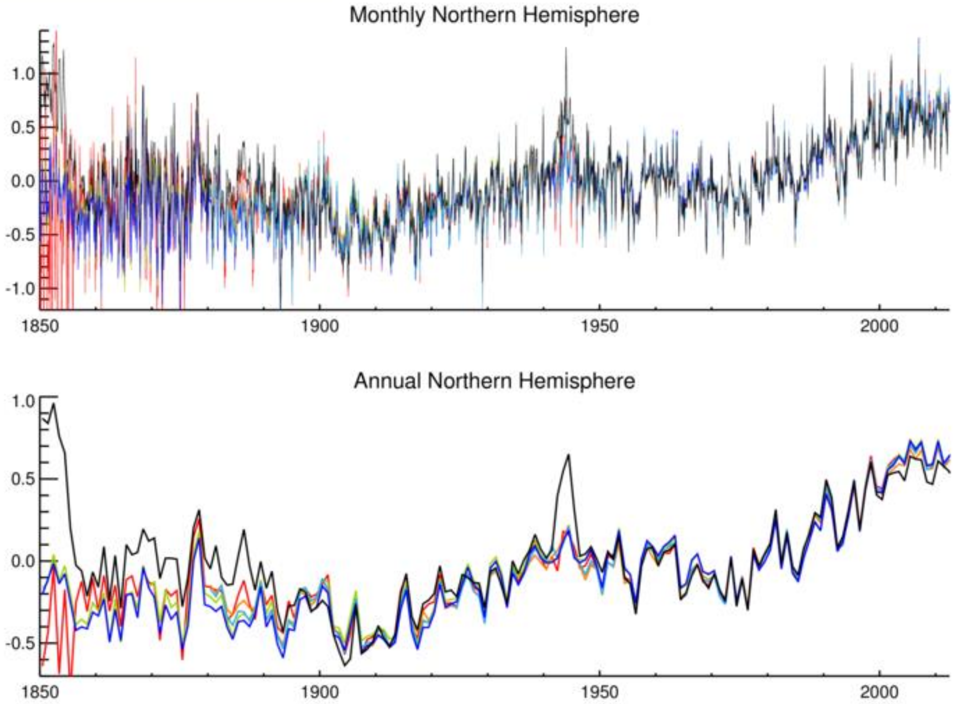

Figure 14. Surface temperature anomalies for Northern Hemisphere land and ocean (ºC, relative to 1961-1990) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Olive green: HadCRUT4; Red: HadNMAT2 + CRUTEM4; Dark Blue: Berkeley Earth; Orange: NOAAGlobalTemp; Pale blue: NASA GISTEMP. Data sets are collocated in this Figure.

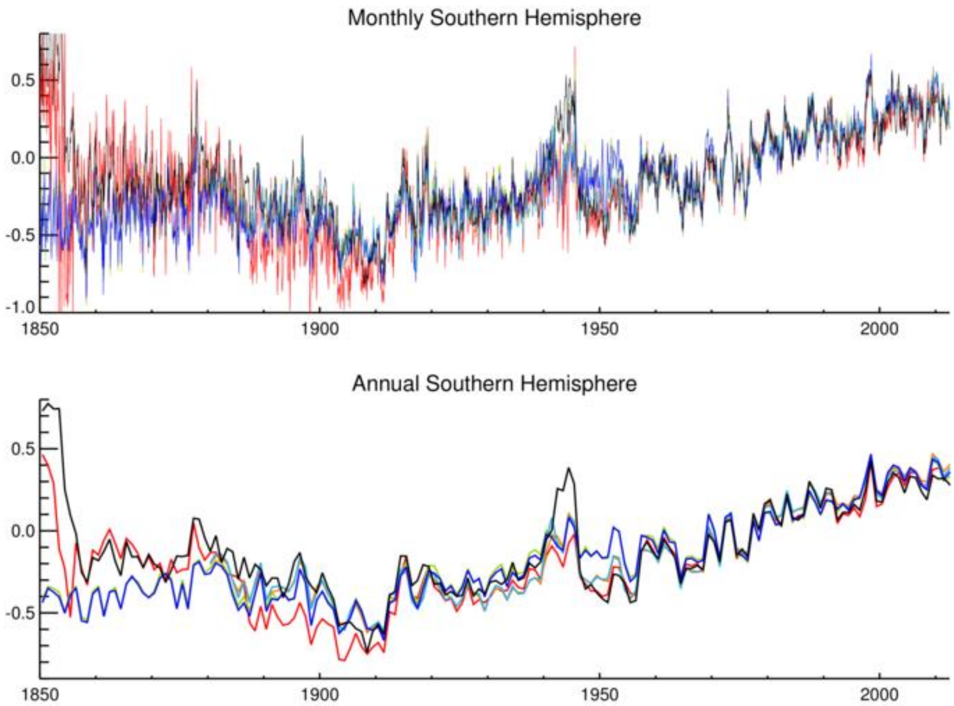

Figure 15. Surface temperature anomalies for Southern Hemisphere land and ocean (ºC, relative to 1961-1990) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Olive green: HadCRUT4; Red: HadNMAT2 + CRUTEM4; Dark Blue: Berkeley Earth; Orange: NOAAGlobalTemp; Pale blue: NASA GISTEMP. Data sets are collocated in this Figure.

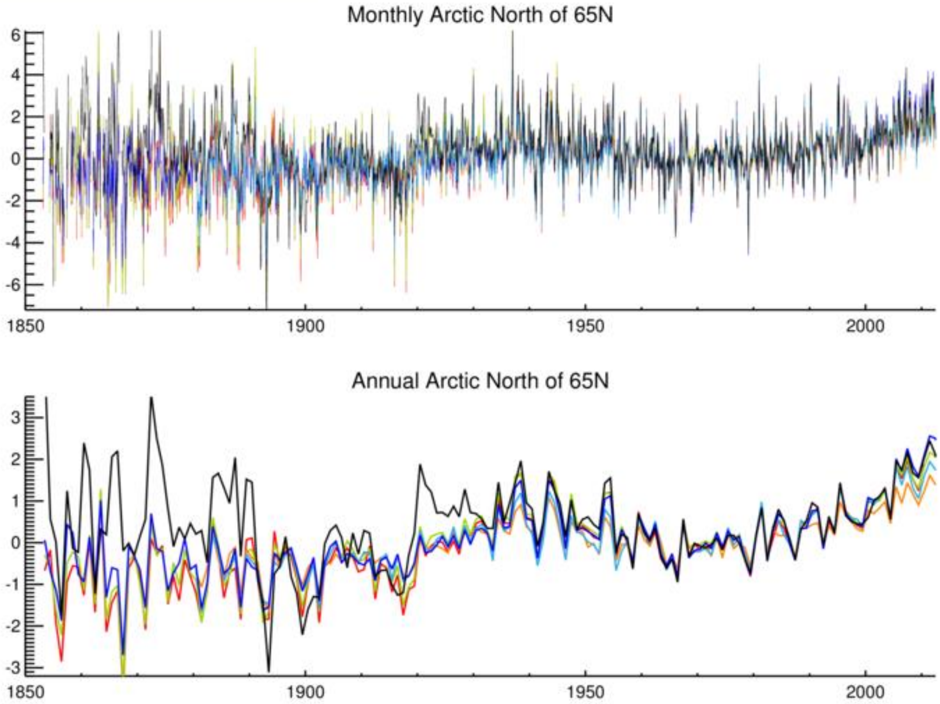

Figure 16. Surface temperature anomalies for Arctic land and ocean (ºC, relative to 1961-1990) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Olive green: HadCRUT4; Red: HadNMAT2 + CRUTEM4; Dark Blue: Berkeley Earth; Orange: NOAAGlobalTemp; Pale blue: NASA GISTEMP. Data sets are collocated in this Figure.

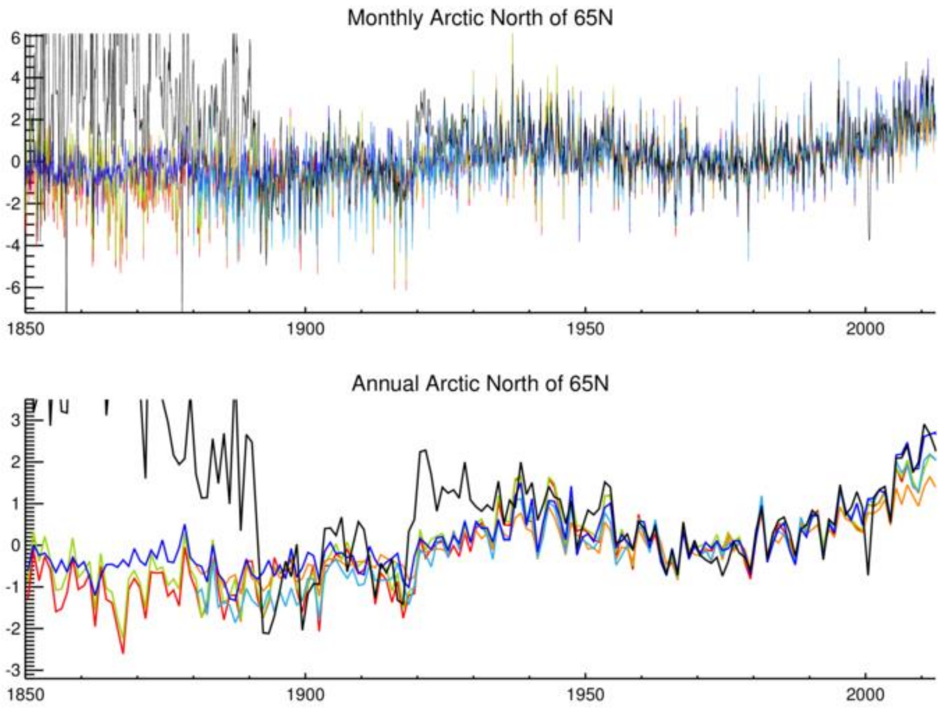

Figure 17. Surface temperature anomalies for Arctic land and ocean (ºC, relative to 1961-1990) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Olive green: HadCRUT4; Red: HadNMAT2 + CRUTEM4; Dark Blue: Berkeley Earth; Orange: NOAAGlobalTemp; Pale blue: NASA GISTEMP. Data sets are not collocated in this Figure.

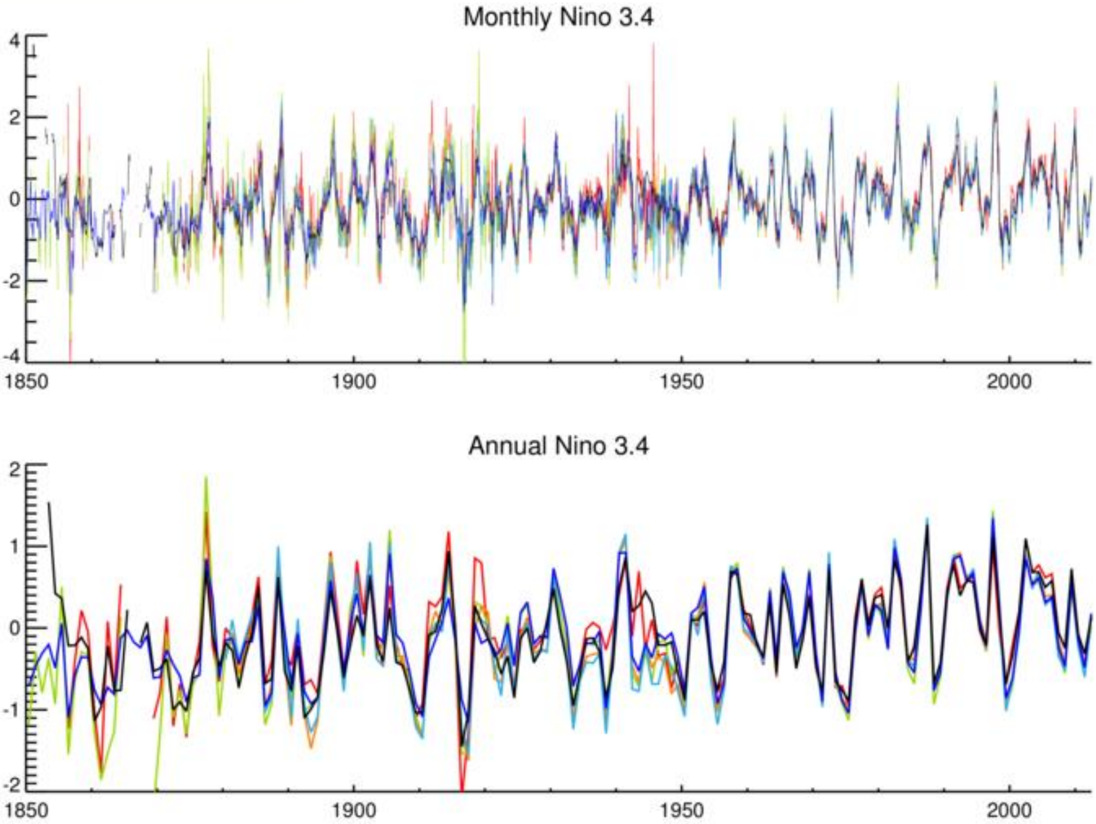

Figure 18. Surface temperature anomalies for Nino 3.4 region (ºC, relative to 1961-1990) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Olive green: HadCRUT4; Red: HadNMAT2 + CRUTEM4; Dark Blue: Berkeley Earth; Orange: NOAAGlobalTemp; Pale blue: NASA GISTEMP. Data sets are not collocated in this Figure.

Variations in the Nino 3.4 region (Figure 18, not colocated) are well represented back to 1855.

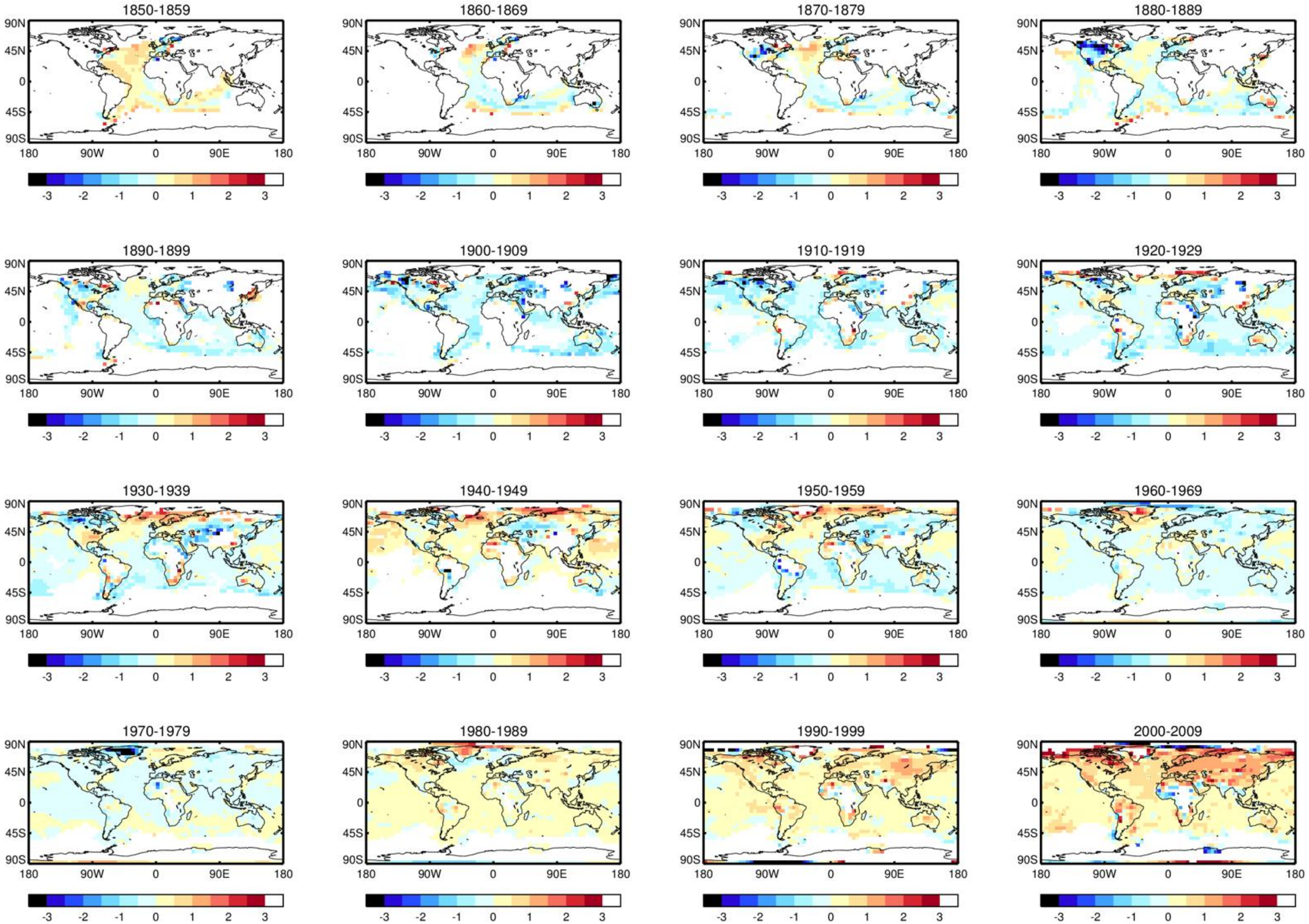

Figure 19. Decadal average surface temperature anomalies (deg C, relative to 1961-1990) EUSTACE Global air temperature estimates v1.0, 1850-1859 through 2000-2009.

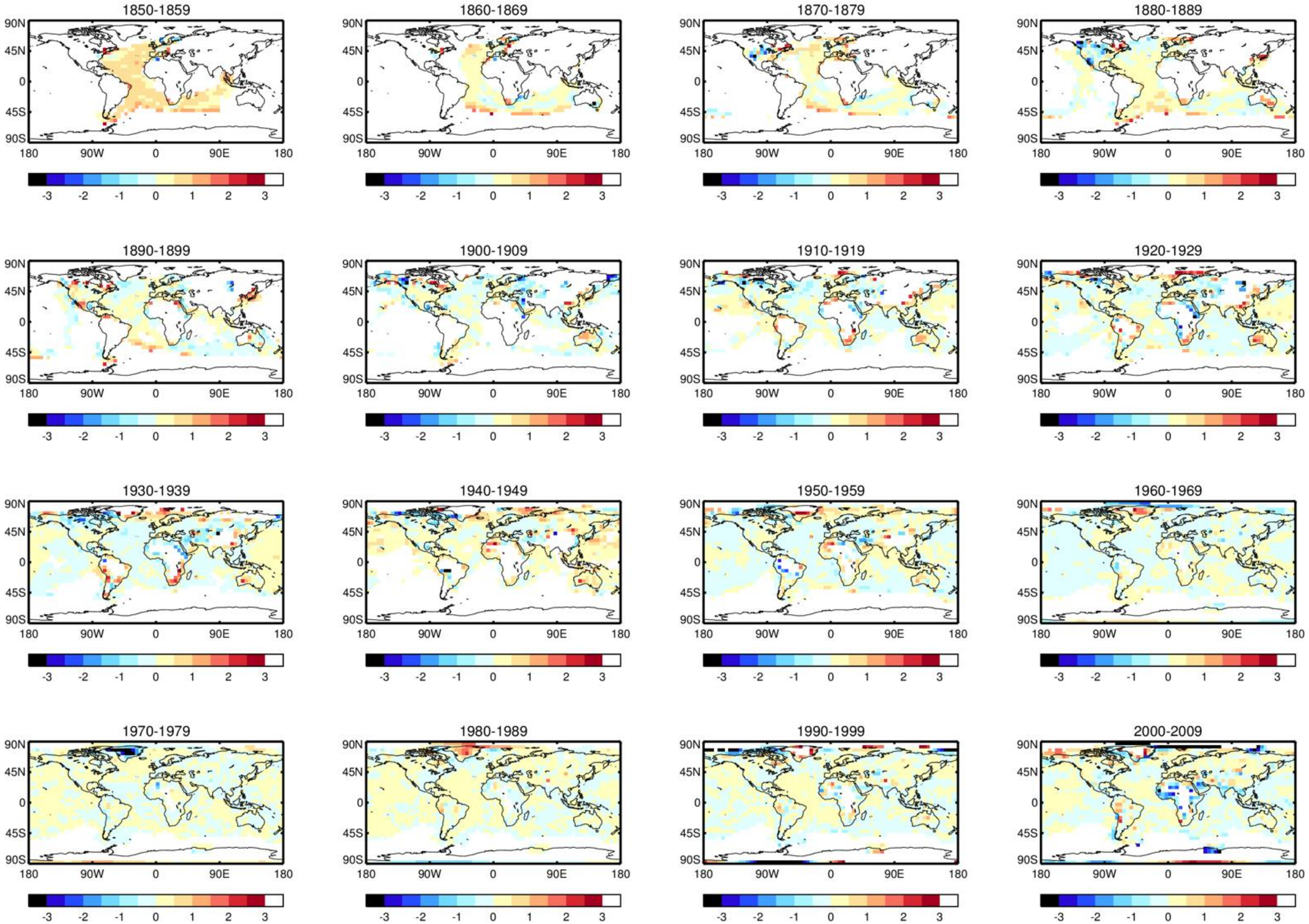

Figure 20. Decadal average surface temperature differences (deg C) EUSTACE Global air temperature estimates v1.0 minus the ensemble mean of the comparison data sets (GISTEMP, NOAAGlobalTemp, HadNMAT2+CRUTEM4, HadCRUT4), 1850-1859 through 2000-2009.

iv Intercomparison with global reanalyses

Here, EUSTACE Global air temperature estimates v1.0 are compared to surface air temperatures from global reanalyses. We take advantage of the CREATE (Collaborative Reanalysis Technical Environment, Potter 2018) reanalysis products which provide data from several reanalyses in the same file format. ECMWF ERA Interim, JRA-25, JRA-55, MERRA, MERRA2, NCEP CFSRv2 and NOAA CIRES 20CRv2c are provided by CREATE along with an ensemble median. Air temperatures from ECMWF CERA-20C were obtained in its native format. Further details of these datasets can be found in Table 1 and Table 2. A climatology period of 1981 to 2010 was used from which to calculate anomalies.

The comparisons to instrumental data sets have highlighted some differences in the EUSTACE Global air temperature estimates v1.0, since the existing instrumental data sets agree very closely with each other on the whole. We see more difference between reanalyses in the diagnostics in this section and EUSTACE Global air temperature estimates v1.0 are largely consistent with the reanalysis ensemble, except in a few cases, which we will discuss further below.

Over global land and ocean (Figure 13) we see again the relative warmth of EUSTACE Global air temperature estimates v1.0 in the late 19th century and World War 2, arising from the marine air temperature biases discussed above. Outside of these periods, EUSTACE Global air temperature estimates v1.0 are very consistent with the reanalyses on the global and Northern Hemisphere (Figure 22) scales.

There is more divergence between the reanalyses in the Southern Hemisphere (Figure 23), as there are fewer data to constrain their air temperature fields here. CERA-20C appears cooler than the other analyses and EUSTACE Global air temperature estimates v1.0 in this region between 1910 and 1980.

There is more divergence between EUSTACE Global air temperature estimates v1.0 and the reanalyses over Europe between 1895 and 1920, than between the EUSTACE data and the instrumental data sets over that period (compare Figure 24 and Figure 5). Neither 20CRv2c nor CERA-20C assimilate surface air temperature measurements, so EUSTACE Global air temperature estimates v1.0 may be more accurate here between 1895 and 1920.

Over the same period, EUSTACE Global air temperature estimates v1.0 are consistent with CERA-20C over North America (Figure 25), but 20CRv2c appears the outlier. Between 1956 and 1962, EUSTACE Global air temperature estimates v1.0 are more consistent with 20CRv2c and the other reanalyses than with CERA-20C.

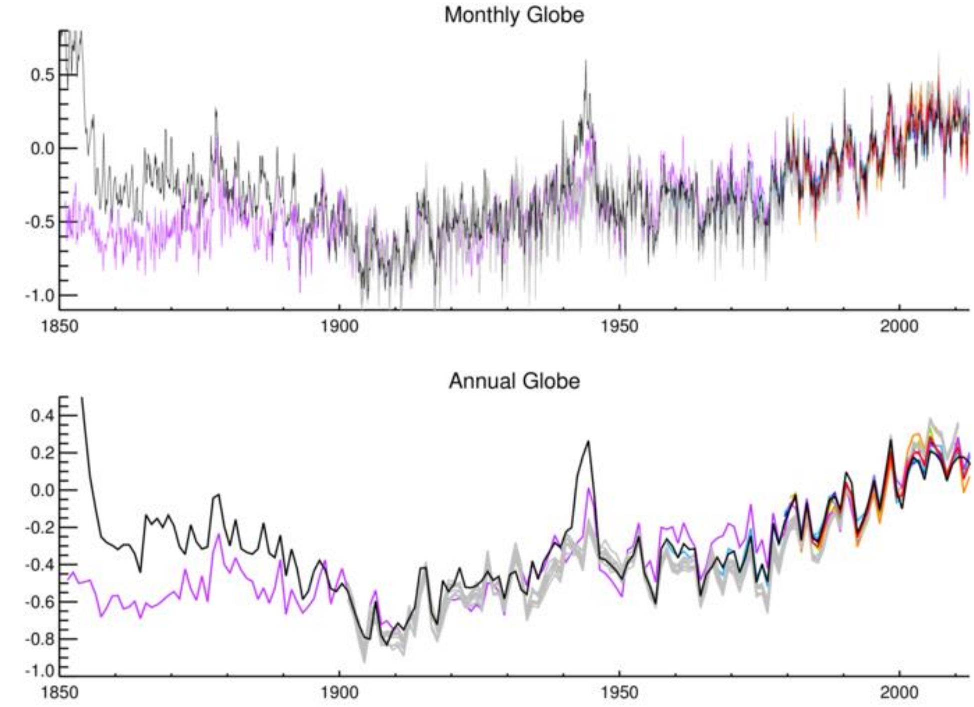

Figure 21. Air temperature anomalies for Global land and ocean (ºC, relative to 1981-2010) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Red: CREATE Reanalysis ensemble mean; Dark blue: ERA reanalyses; Light blue: JRA reanalyses; Olive green: MERRA 2; Purple: 20CRv2c; Grey: CERA20C ensemble members (grey); Orange: CSFR. Data sets are collocated in this Figure.

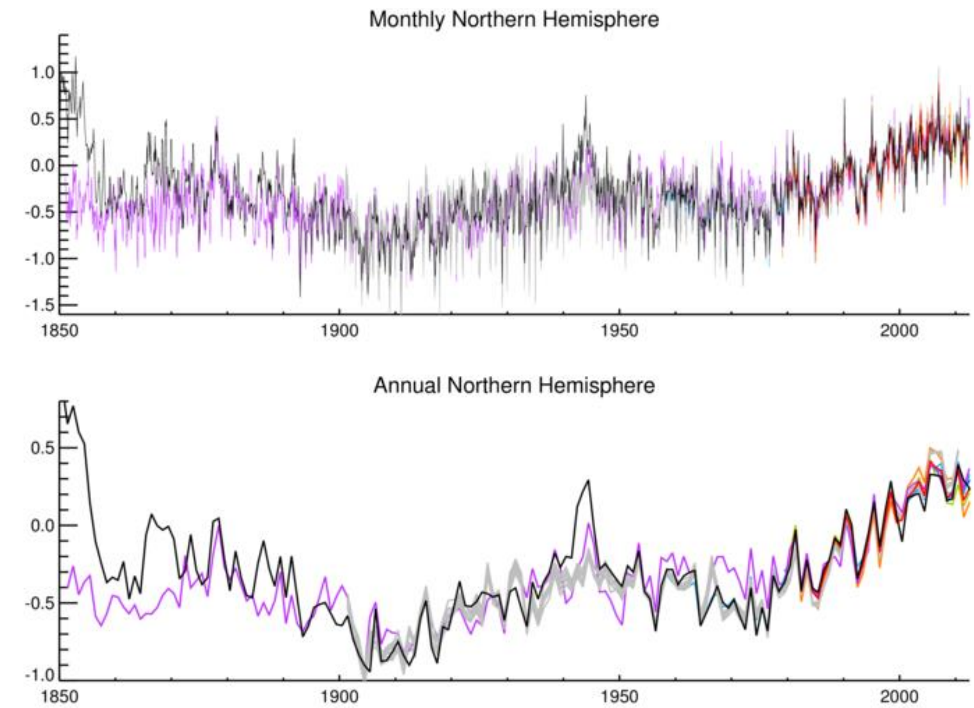

Figure 22. Air temperature anomalies for Northern Hemisphere land and ocean (ºC, relative to 1981-2010) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Red: CREATE Reanalysis ensemble mean; Dark blue: ERA reanalyses; Light blue: JRA reanalyses; Olive green: MERRA 2; Purple: 20CRv2c; Grey: CERA20C ensemble members (grey); Orange: CSFR. Data sets are collocated in this Figure.

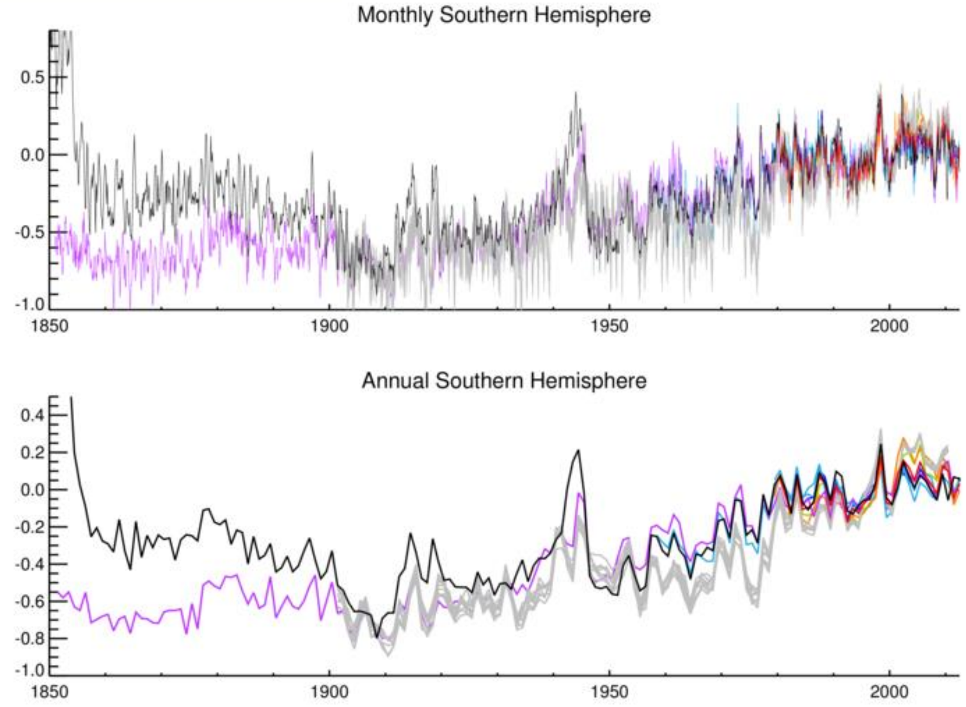

Figure 23. Air temperature anomalies for Southern Hemisphere land and ocean (ºC, relative to 1981-2010) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Red: CREATE Reanalysis ensemble mean; Dark blue: ERA reanalyses; Light blue: JRA reanalyses; Olive green: MERRA 2; Purple: 20CRv2c; Grey: CERA20C ensemble members (grey); Orange: CSFR. Data sets are collocated in this Figure.

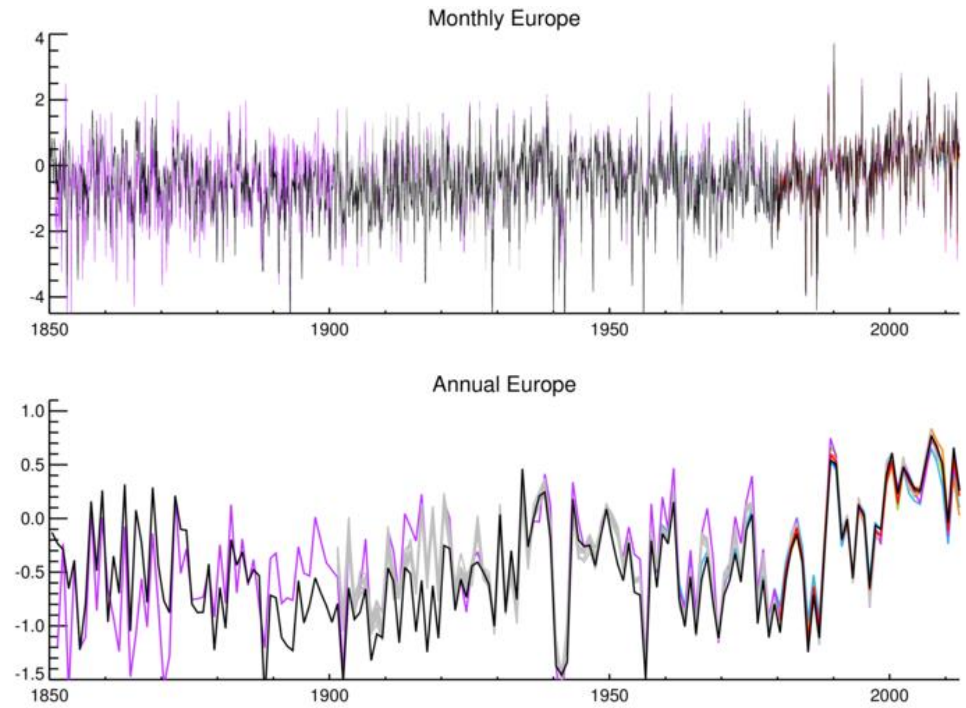

Figure 24. Air temperature anomalies for European land (ºC, relative to 1981-2010) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Red: CREATE Reanalysis ensemble mean; Dark blue: ERA reanalyses; Light blue: JRA reanalyses; Olive green: MERRA 2; Purple: 20CRv2c; Grey: CERA20C ensemble members (grey); Orange: CSFR. Data sets are collocated to match CRUTEM4 coverage in this Figure.

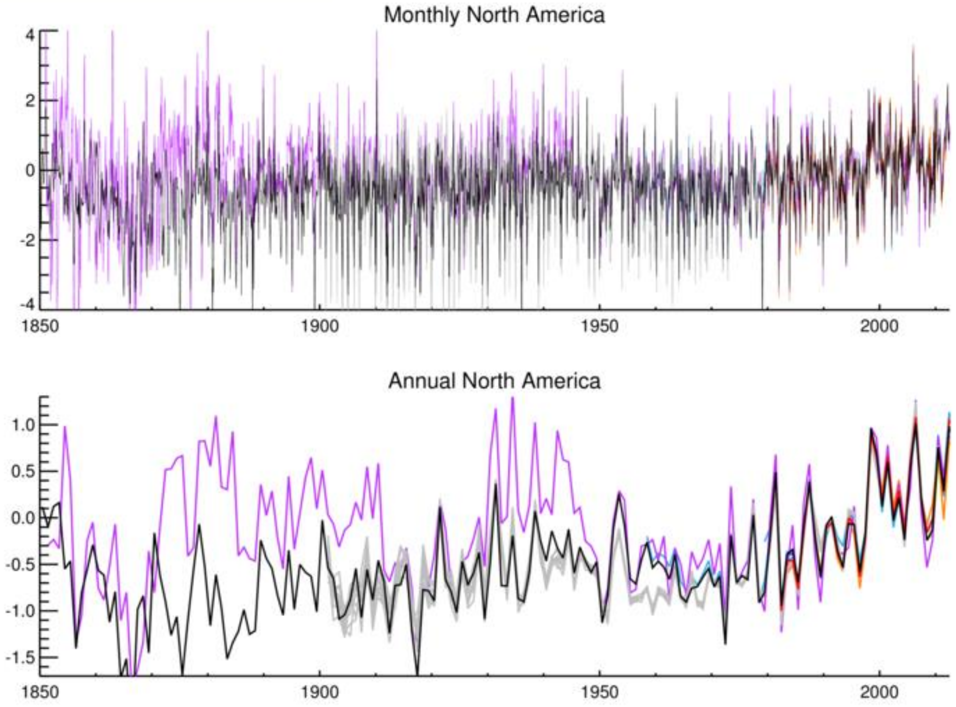

Figure 25. Air temperature anomalies for North America land (ºC, relative to 1981-2010) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Red: CREATE Reanalysis ensemble mean; Dark blue: ERA reanalyses; Light blue: JRA reanalyses; Olive green: MERRA 2; Purple: 20CRv2c; Grey: CERA20C ensemble members (grey); Orange: CSFR. Data sets are collocated to match CRUTEM4 coverage in this Figure.

The ensemble spread in CERA-20C is large over Australia (Figure 26) and EUSTACE Global air temperature estimates v1.0 are not inconsistent with this back to 1900. Recall that here when compared to the other instrumental data sets (Figure 11) EUSTACE Global air temperature estimates v1.0 appeared to exhibit a different trend prior to 1957, but clearly there is significant uncertainty in the reanalyses over Australia prior to 1970.

Over Antarctica (Figure 27), EUSTACE Global air temperature estimates v1.0 are broadly consistent with 20CRv2c. CERA-20C is cooler than the other reanalyses here prior to 1980, sometimes by 3 degrees C.

EUSTACE Global air temperature estimates v1.0 and the reanalyses are consistent over the Arctic after 1980 (Figure 28), apart from the “shock” in 2000 in EUSTACE Global air temperature estimates v1.0 discussed above. The comparison with the reanalyses confirms the bias in EUSTACE Global air temperature estimates v1.0 in the Arctic in the 1920s and 30s and prior to 1892, discussed above.

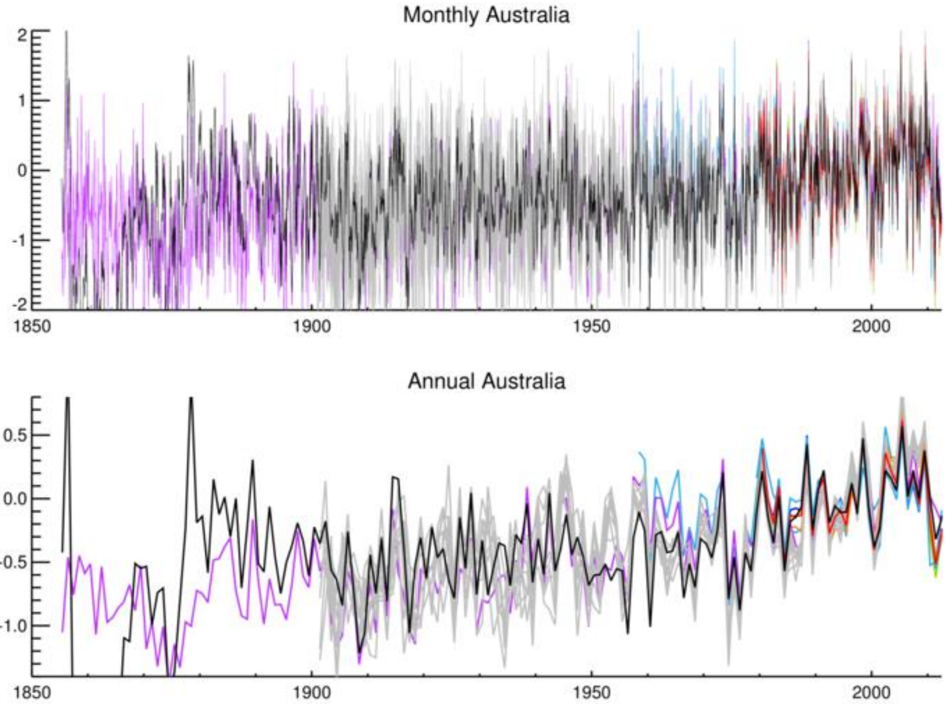

Figure 26. Air temperature anomalies for Australia land (ºC, relative to 1981-2010) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Red: CREATE Reanalysis ensemble mean; Dark blue: ERA reanalyses; Light blue: JRA reanalyses; Olive green: MERRA 2; Purple: 20CRv2c; Grey: CERA20C ensemble members (grey); Orange: CSFR. Data sets are collocated to match CRUTEM4 coverage in this Figure.

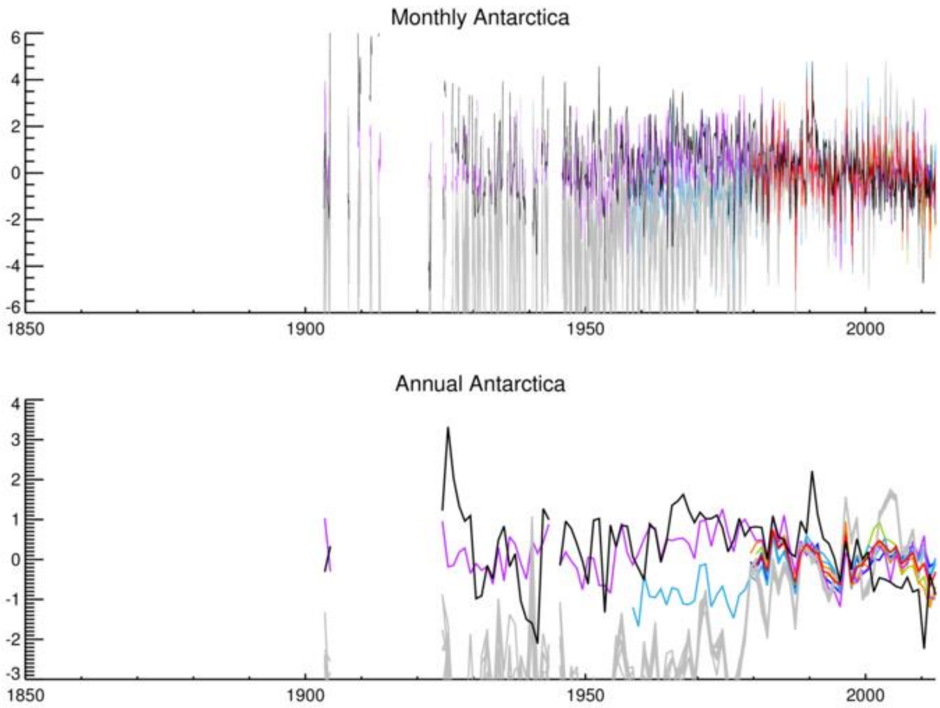

Figure 27. Air temperature anomalies for Antarctic land (ºC, relative to 1981-2010) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Red: CREATE Reanalysis ensemble mean; Dark blue: ERA reanalyses; Light blue: JRA reanalyses; Olive green: MERRA 2; Purple: 20CRv2c; Grey: CERA20C ensemble members (grey); Orange: CSFR. Data sets are collocated to match CRUTEM4 coverage in this Figure.

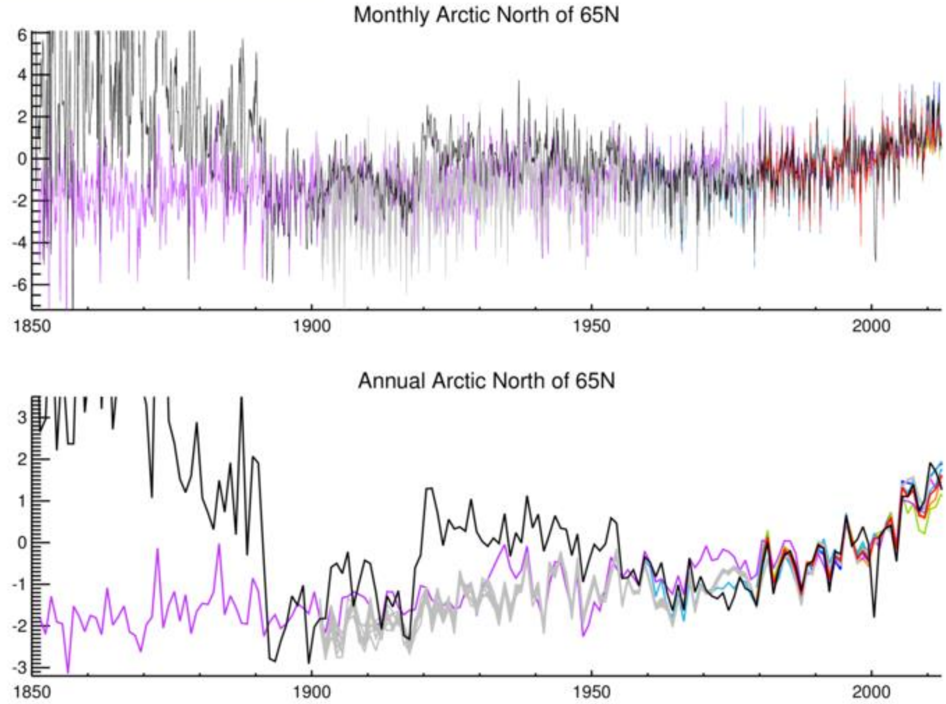

Figure 28. Air temperature anomalies for Arctic land and ocean (ºC, relative to 1981-2010) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Red: CREATE Reanalysis ensemble mean; Dark blue: ERA reanalyses; Light blue: JRA reanalyses; Olive green: MERRA 2; Purple: 20CRv2c; Grey: CERA20C ensemble members (grey); Orange: CSFR. Data sets are collocated in this Figure.

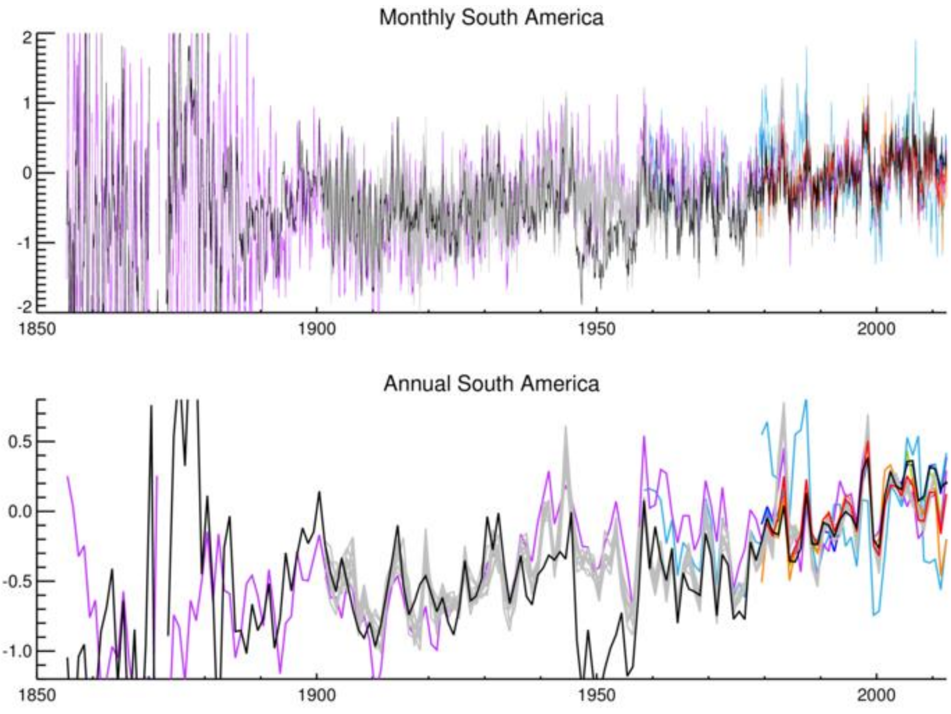

Figure 29. Air temperature anomalies for South America land (ºC, relative to 1981-2010) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Red: CREATE Reanalysis ensemble mean; Dark blue: ERA reanalyses; Light blue: JRA reanalyses; Olive green: MERRA 2; Purple: 20CRv2c; Grey: CERA20C ensemble members (grey); Orange: CSFR. Data sets are collocated to match CRUTEM4 coverage in this Figure.

Also confirmed by the reanalysis comparison is the large cold “shock” over South America between 1945 and 1957 (Figure 29) and the warm bias in the 1870s. Clearly, South America is a region where the reanalyses are divergent, with JRA presenting a very different trend since 1980 here.

Again, over the Nino 3.4 region, there is consistency, but with 20CRv2c being warmer than EUSTACE Global air temperature estimates v1.0 by a few tenths of a degree prior to 1910.

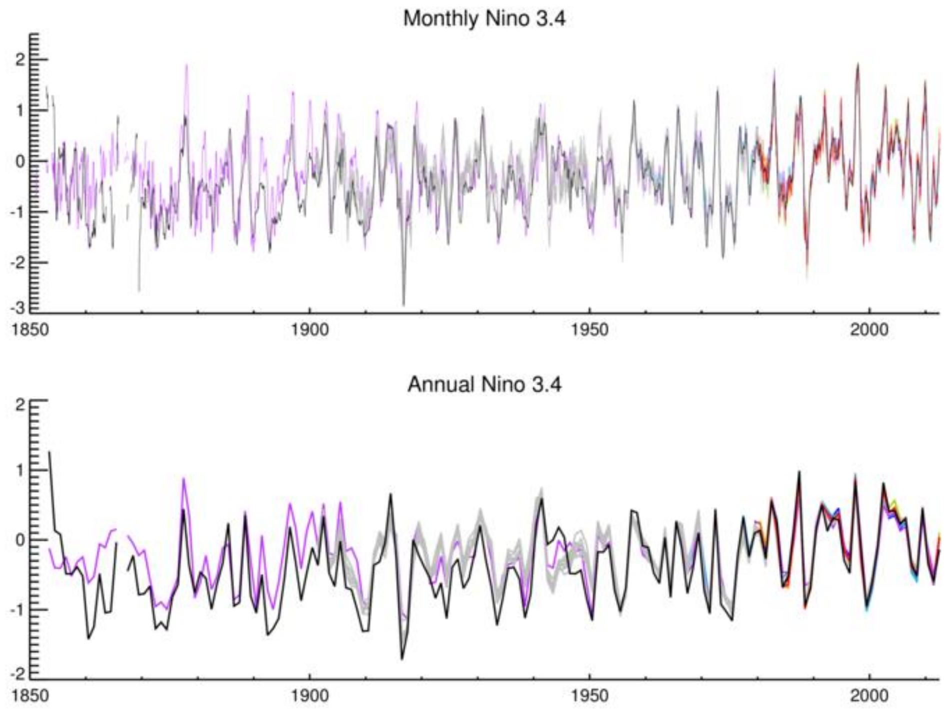

Figure 30. Air temperature anomalies for Nino 3.4 region (ºC, relative to 1981-2010) in various data sets, 1850-2012. Upper panel: monthly anomalies. Lower panel: annual anomalies. Black: EUSTACE Global air temperature estimates v1.0; Red: CREATE Reanalysis ensemble mean; Dark blue: ERA reanalyses; Light blue: JRA reanalyses; Olive green: MERRA 2; Purple: 20CRv2c; Grey: CERA20C ensemble members (grey); Orange: CSFR. Data sets are collocated in this Figure.

d) <u>Summary of results</u>

This report presents an intercomparison of the EUSTACE Global air temperature product with other air temperature datasets and reanalyses. Here, we report comparisons of both a prototype product (hereafter referred to in this report as the EUSTACE Prototype Analysis) with high resolution products across land in Europe and the v1.0 product with independently-constructed monthly instrumental surface temperature data sets and with air temperatures from reanalyses across all surfaces globally.

Data were collocated and monthly anomalies were calculated relative to a common baseline.

Over Europe, where station density is high, the Prototype Analysis shows close agreement with air temperatures from the Berkley Earth Monthly Land Europe dataset and the UERRA UKMO reanalysis.

EUSTACE Global daily air temperature estimates v1.0 is broadly consistent with the comparison data sets, but with some residual issues remaining after masking.

The EUSTACE Global air temperature estimates v1.0 are warmer than the comparison data between 1850 and 1895 over Europe. Nonetheless, it provides daily information for Europe which is consistent with the other instrumental data sets on monthly and annual timescales from 1895 onwards.

In the 1850s, EUSTACE Global air temperature estimates v1.0 are higher than the comparison data sets by around 0.8 deg C on the global average. At this time, daytime marine air temperature data are used (there being almost no night-time data available).

Between 1855 and 1880, EUSTACE Global air temperature estimates v1.0 are around 0.1-0.2 deg C higher than the comparison data sets because observations in the North Atlantic are thought to be warm biased then, particularly during windy conditions.

A cold bias affects Africa and parts of southern Asia starting in 2000. This is associated with residual biases from the EUSTACE satellite derived air temperatures over land.

For North America, EUSTACE Global air temperature estimates v1.0 are consistent with other long-term surface temperature data sets on the continental scale from 1870 onwards. In the 1860s when the EUSTACE data set is relatively cool for a time, but based on very few data.

Over parts of South America, a cold bias exists in EUSTACE Global air temperature estimates v1.0 between 1945 and 1957. The criteria used to filter out erroneous values in the analysis were not able to completely remove this feature, so users need to be aware of it and are advised not to use the data over this part of South America between 1945 and 1957. The EUSTACE data are also biased warm here in the 1870s.

Prior to 1957, the representation of temperature trends over Australia in EUSTACE Global air temperature estimates v1.0 appears inconsistent with that in the instrumental comparison data sets and likely erroneous.

EUSTACE Global air temperature estimates v1.0 are consistent with the comparison data sets where they all have data over the Arctic after 1892, with the exception of a period in the 1920s when EUSTACE data are erroneously warm. Prior to 1892, EUSTACE Global air temperature estimates v1.0 are biased warm in the Arctic by up to a few degrees C. Although the data have been masked in unconstrained regions, there are still areas early in the record where the analysis takes unrealistic high values.

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