The Danish Meteorological Institute

DMI Report 21-24
Arctic sea and ice surface temperatures since 1982

Final scientific report of the 2020 National Centre for Climate Research Work Package WP-1.3.2 GlobalIST

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Colophon

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Content

1 Abstract

It is important to determine the arctic surface temperature, since climate change in the arctic area is amplified relative to global changes. Moreover, the rise of surface temperatures is related to the decline of sea ice extent.

Until now temperature changes have been determined using the few in situ observations available in the Arctic. New research in the Danish National Centre for Climate Research (NCKF) has on the contrary utilized satellite observations to create a new consistent Climate Data Record (CDR) of surface temperatures for sea and sea ice in the Arctic.

This CDR, which is the first of its kind, covers all sea and sea ice areas in the Arctic and is therefore a new and important dataset for monitoring climate change in the area on earth, where it is most pronounced.

The dataset shows how much the temperatures have changed north of 58 ^{o}N during the last decades and contains a consistent climate indicator, which can be used to evaluate the current situation. The product has been developed for the Arctic but the same procedures can be applied for the Antarctic.

2 Resumé

Overfladetemperaturen i Arktis er meget vigtig at bestemme, da klimaforandringerne i de arktiske egne er forstærket i forhold til de globale ændringer. Desuden er opvarmningen i overfladetemperaturen relateret til formindskelsen i udbredelsen af havis.

Hidtil har ændringerne været bestemt ved at bruge de få in situ observationer der er tilgængelige. Ny forskning i det Nationale Center for Klimaforskning (NCKF) har derimod anvendt satellitobservationer til at skabe en ny konsistent klimatidsserie af overfladetemperaturen for hav og havis i Arktis. Datasættet, der er sin første af sin art, dækker alle ocean og havis områder i Arktis og er dermed et nyt vigtig datasæt til at overvåge klimaforandringer i det område på jorden hvor de er mest udtalte.

Datasættet kortlægger, hvor meget temperaturerne har forandret sig nord for 58 ^{o}N gennem de seneste årtier og kommer med bud på en konsistent klimaindikator, der kan bruges til at overvåge forholdene lige nu. Produkterne er udviklet for Arktis men metodikken kan også anvendes for Antarktis.

3 Introduction

The Danish National Centre for Climate Research (Nationalt Center for Klimaforskning, NCKF) has completed its first year in 2020. It has been a source of funding for the Danish Meteorological Institute and collaborators for climate change related research during this year. The 18 work packages fall under 4 general themes:

1. Arctic and Antarctic Research
2. Climate change in the near future
3. Use of climate data

4. Support for the IPCC

This work package (WP-1.3.2 GlobalIST) focused on the change of sea and sea ice surface temperatures in the Arctic since 1982 and the derivation of climate indicators to monitor the current conditions. Infrared satellite products for surface temperatures from ESA Climate Change Initiative (CCI), Copernicus Climate Change Service (C3S) and DMIs own products have been validated against each other and in situ observations to create a gap-free (Level 4 = L4) reanalysis dataset. The reanalysis consists of a daily, L4 field with a 0.05 degrees resolution. The spatial dimensions of the whole domain are shown in the table below.

Westernmost longitude	-179.975
Easternmost longitude	179.975
Southernmost latitude	58.
Northernmost latitude	89.95

The dataset contains Arctic surface temperatures of the ocean, the sea ice and the marginal ice zone without gaps and the analysis errors, currently for the time period January 1st, 1982- August 31st, 2019. An example of the coverage of the SST and IST product is shown in the figure below. This dataset makes it possible to investigate both the general temperature tendency for the whole domain, as well as regional differences in temperature changes.

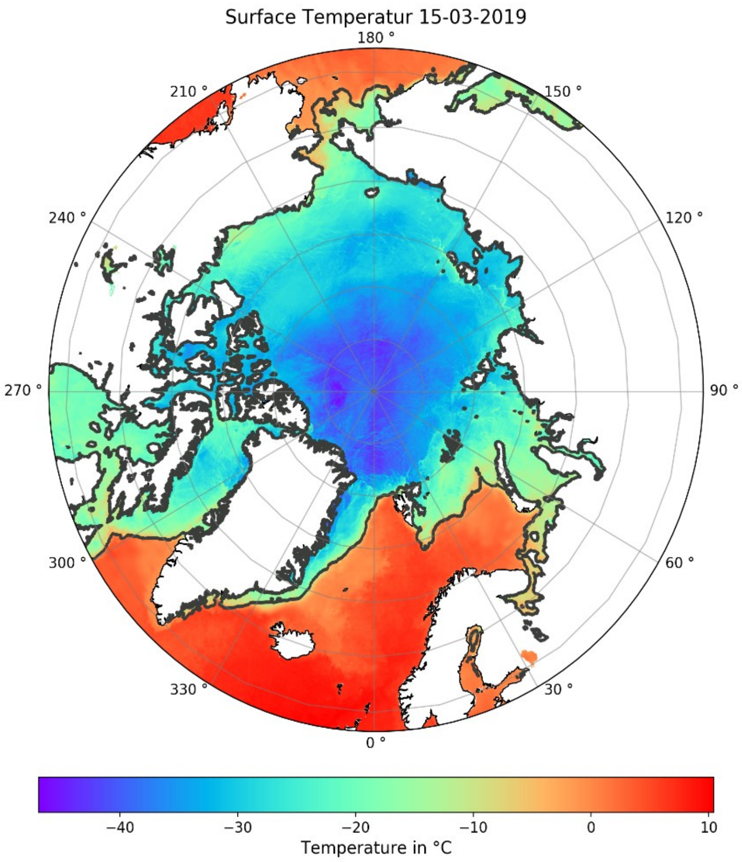

Figure 3.1: Example of the level 4 surface temperature over ocean and sea ice for March 15th, 2019. The gray line represents the ice edge (sea ice fraction >= 15%).

4 Production Description

4.1 Satellite Data Processing

4.1.1 Input data

The following inputs are collected for input to the DMI processing algorithm (DMIOI) that combines multi-satellite observations and perform statistical Optimal Interpolation to obtain a daily gap free field

SST CCI L2P data. The SST CCI version 2.1 are used, for the period January 1982 to December 31st,2019. Data are obtained through the ESA CCI project (http://cci.esa.int/, Merchant et al., 2019). The selected fields are the sea surface temperature retrievals at 20 cm depth. The ESA CCI data series include observations from the ATSR 1 instrument on board the ERS-1 satellite, ATSR 2 on board the ERS-2, satellite and the AATSR on board ENVISAT and AVHRR on board the NOAA satellites.

Copernicus C3S SST:

The recent SST observations from 2016-2019 are used from the Copernicus Climate Change Service (C3S). Level 2 data are obtained through personal communication (Owen Embury, 2018) and corresponds to the L3U data products available from https://cds.climate.copernicus.eu/ except for the higher spatial resolution. The selected fields are sea surface temperature depth retrievals representative of the SST at 20 cm depth. The C3S data series include observations from the SLSTR A/B instruments on board the Sentinel 3 satellites and the AVHRRs on board the NOAA and Metop satellites

AASTI v2 + OSI-SAF Metop AVHRR SST/IST

The SST/IST observations are mainly obtained from the Arctic and Antarctic ice Surface Temperatures from thermal Infrared (AASTI) satellite data set (Dybkjær et al., 2014). This CDR covers the period Jan 1982 to Dec, 2014. From 2015 and onwards, the operational OSI-SAF Metop AVHRR SST/IST product has been used (Dybkjær, et al., 2012). These data sets are consistent as the type of algorithms used to retrieve the SST and IST are similar.

Sea-ice concentration data:

The daily sea ice concentration fields are obtained from a combination of different SIC products. The Baltic Sea SIC fields consist of a SIC product from SMHI (1982-2011) and the CMEMS 1 km SIC fields (2012-present). In addition, the open ocean SIC fields are obtained using a combination of the OSI-SAF SIC and the ESA CCI SIC fields.

The figure below shows the temporal coverage of the input data used for the production and validation of the data set.

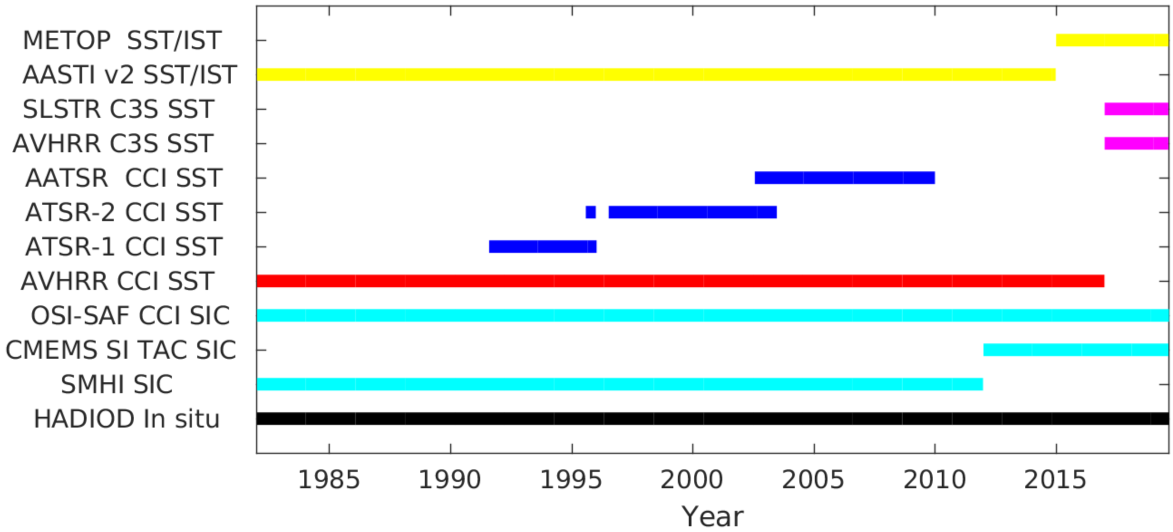

Figure: 4.1.1: Temporal coverage of the satellite and in situ products use as input and validation of the Arctic SST/IST CDR.

4.1.2 Quality control and pre-processing of input data

All satellite data valid for a particular day, within 12 hours from the analysis are considered. The input L2P SST data undergo various QC and processing steps to generate separate level 3 products:

- Only satellite data classified as cloud free are included
- Satellite observations using an ice algorithm in regions where the sea ice concentration is 0 are discarded.
- Satellite observations processed using an SST algorithm in regions where the sea ice concentration is larger than 70% are discarded
- Sensor specific and quality dependent biases are subtracted as a result of the validation procedure.

4.1.2.1 Uncertainties and errors sources

The current version of the Level 2 SST and IST products do not have included dynamic uncertainties associated with the observations. The main errors in the L2 input satellite observations come from undetected clouds that enter the data and appear as cold bias in the retrievals.

4.2 DMIOI L4 Processing Scheme

The processing scheme for the full level 4 processing system is shown below, with the input from level 2 observations and the OI level 4 SST/IST and uncertainty outputs

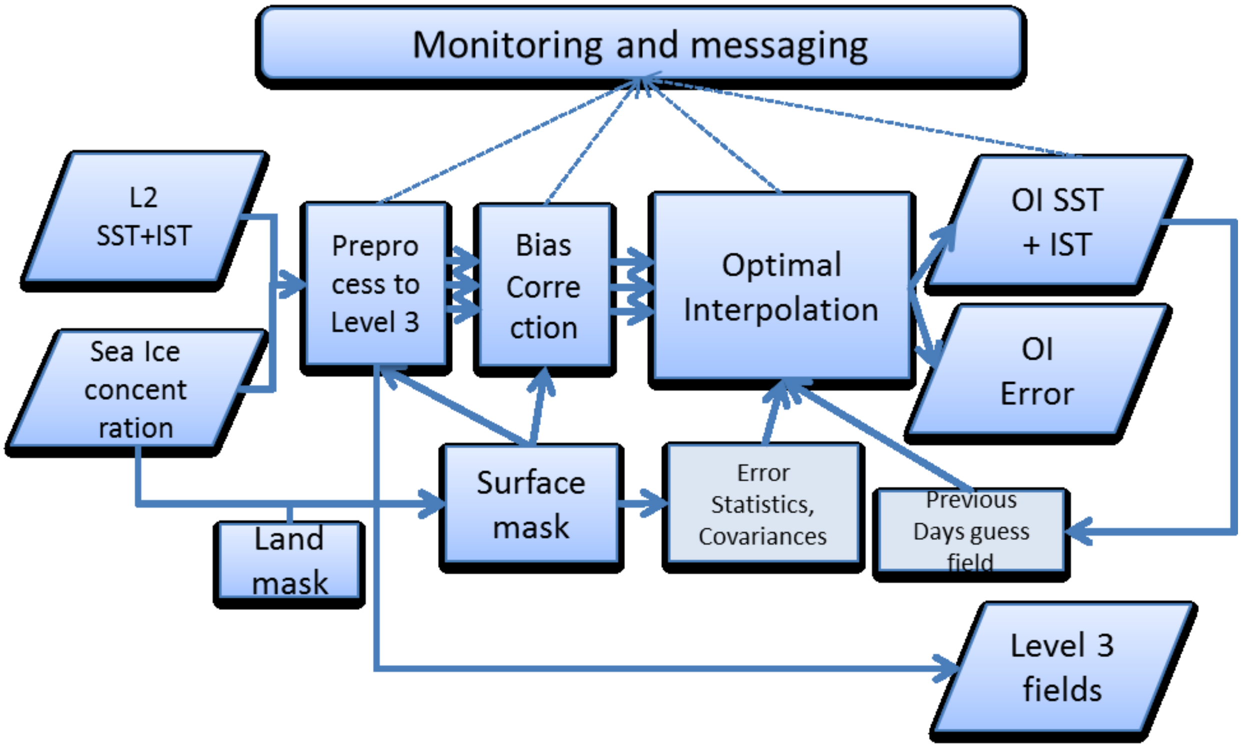

Figure 4.2.1 Schematic diagram of the operational DMIOI processing chain at DMI

The final level 4 analysis products is a merged and interpolated daily field with a 0.05° resolution in latitude and longitude, and covers surface temperatures in the ocean, the sea ice and the marginal ice zone. The optimal interpolation method used to construct the merged and gap free SST/IST analysis is taken from the high latitude SST DMI processing scheme described in Høyer and She (2007); Høyer et al. (2014). The OI method works with anomalies from a first guess field. In the current approach, a persistence based method is applied, which uses the previous analysis field as the first guess field. The SST and IST observations from the last +-12 hours are therefore interpreted as anomalies with respect to the first guess field. The OI method will for each grid point find the solution that has the lowest errors, given statistical input, such as a first guess error variance, error covariance functions and uncertainties on the individual observations. Due to the different physical conditions for ocean and sea ice surface temperature variability, separate statistics have been derived for the open ocean and the sea ice covered regions. The SST first guess variance and error covariance were very similar to the ones that were presented in Høyer and She (2007); Høyer et al. (2014). Figure 4.2.2 shows the SST guess variance derived from SST observations and from SST and IST observations.

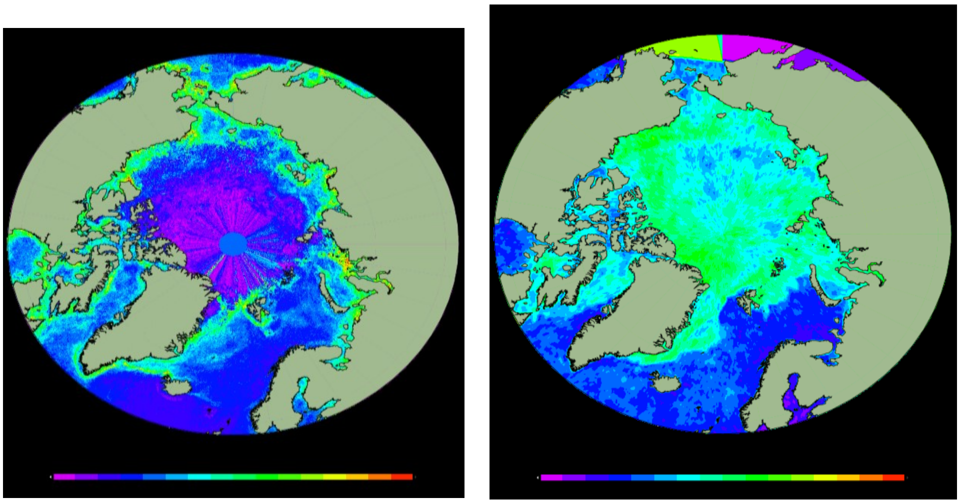

Figure 4.2.2 Guess error variance used for the OI estimation. Left figure is derived from the SST analysis. Right figure is derived from the SST and IST dataset.

Over sea ice, the first guess IST variability was derived using one year of Metop AVHRR L3 aggregated observations. The previous day L4 field was subtracted from the L3 IST observations and a spatial 2-dimensional field of standard deviations were calculated for one year of anomalies. The first guess field and the error covariance used in the MIZ is a weighted linear combination of the open waters and the ice values, where the ice concentration was used as the weighting factor. In this context, the Marginal Ice Zone is defined as areas where the ice concentration from the EUMETSAT OSI-SAF project is between 30% and 70%. The search radius for the OI method is set to 100 km and the maximum number of satellite observations included in the optimal estimation is 20. The average number of satellite observations included in the analysis is about 19.9, indicating a good satellite data coverage within the search limits.

The background error covariance matrix: The correlation scales of the satellite anomalies have been derived empirically from observations. Spatially dependent error covariance functions have been fitted, based upon a year of analysis of level 3 SST and IST observations. The functions take the form of:

$$C_{ij} = \exp(-\lambda * dist_{i,j}{}^{\gamma})$$

Where $dist_{i,j}$ is the distance between two observations and λ and γ are the two parameters that have been empirically determined. The observation error covariance matrix is assumed to be a diagonal matrix (observation errors are uncorrelated with each other). The diagonal elements are specified using the error obtained from validation against in situ observations and the reduced error estimate from the noise weighting procedure.

The error covariance functions, the first guess fields and the satellite observations are combined in an Optimal interpolation algorithms that invert the covariance matrix and determines the optimal weights for the observations for each DMIOI grid point. Each analysis value is accompanied by an uncertainty estimate which is a result of the Optimal Interpolation algorithm.

The statistical parameters, such as first guess variance and error correlation functions are different for SST and IST. In the construction of the combined OI field, the sea ice concentration field is used to construct the full SST/IST field in this way:

- SST: Sea ice concentration < 15 : SST statistical parameters are used
- IST: Sea ice concentration > 70 : IST Statistical parameters are used
- MIZ: Sea ice concentration > 15 and < 70. linear weighting of the SST and IST statistical parameters are used, based upon the sea ice concentration.

Grid points with undefined sea ice concentration values use the SST statistics. The figure below shows an example of the surface mask for a day in October, identifying the SST, IST and the MIZ region.

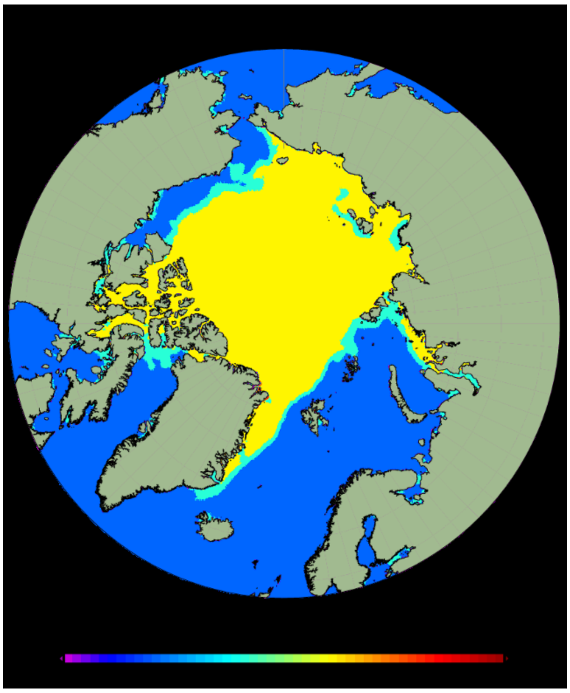

Figure 4.2.3. Example of a surface mask for October 3rd, 2012, identifying the regions with open ocean (=1), sea Ice covered (=3) and Marginal Ice zone (=2).

The SST bias correction method indicated in Figure 4.2.1 corrects the AASTI SST and METOP AVHRR SST data against the available SST CCI and C3S SST observations. The temporal window for the comparison is 7 days and the bias fields are smoothed over 500 km. See Høyer et al., 2014. An additional bias static correction is performed based on the SST validation against independent in situ observations using drifting buoy observations.

4.3 In situ data for validation

4.3.1 In situ SST data

Observations from drifting buoys, moored buoys and ship observation are obtained from the HADIOD database (Atkinson, et al., 2014). The spatial and temporal coverage of the three types of data are shown in Figure 4.3.1.

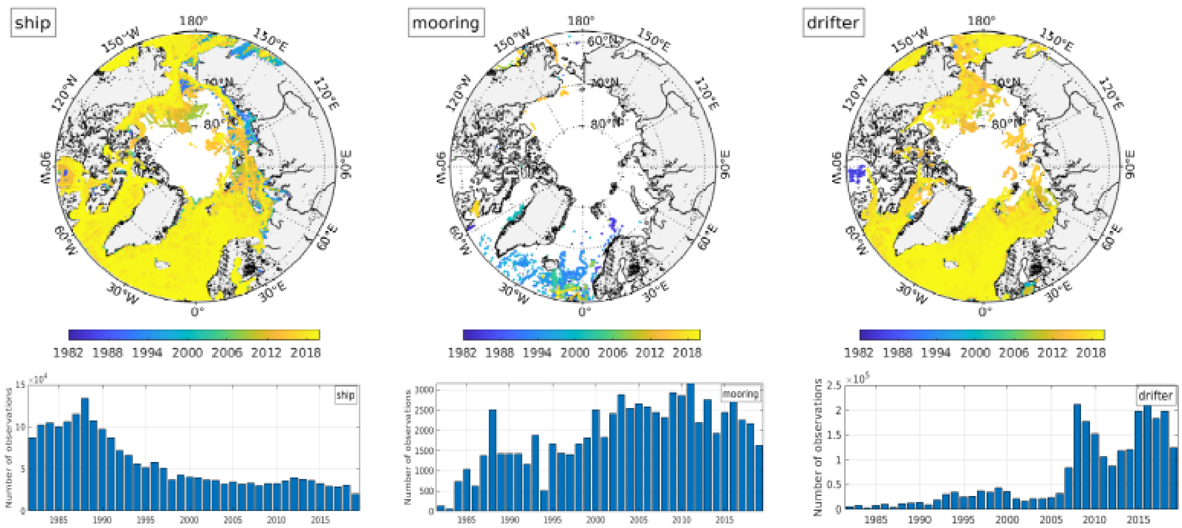

Figure 4.3.1 An overview of Ship (left), Moored bouy (middle) and drifting buoys (right) observations used for SST validation.

4.3.2 In situ IST data

Independent sea ice in situ observations from ECMWF(Sep 15th, 1993- Jan 1st, 2015) and CRREL(Apr 14th, 2001- Sep 4th, 2017) drifting buoys are used for the IST validation. The spatial and temporal coverage of the two types of data are shown in Figure 4.3.2.

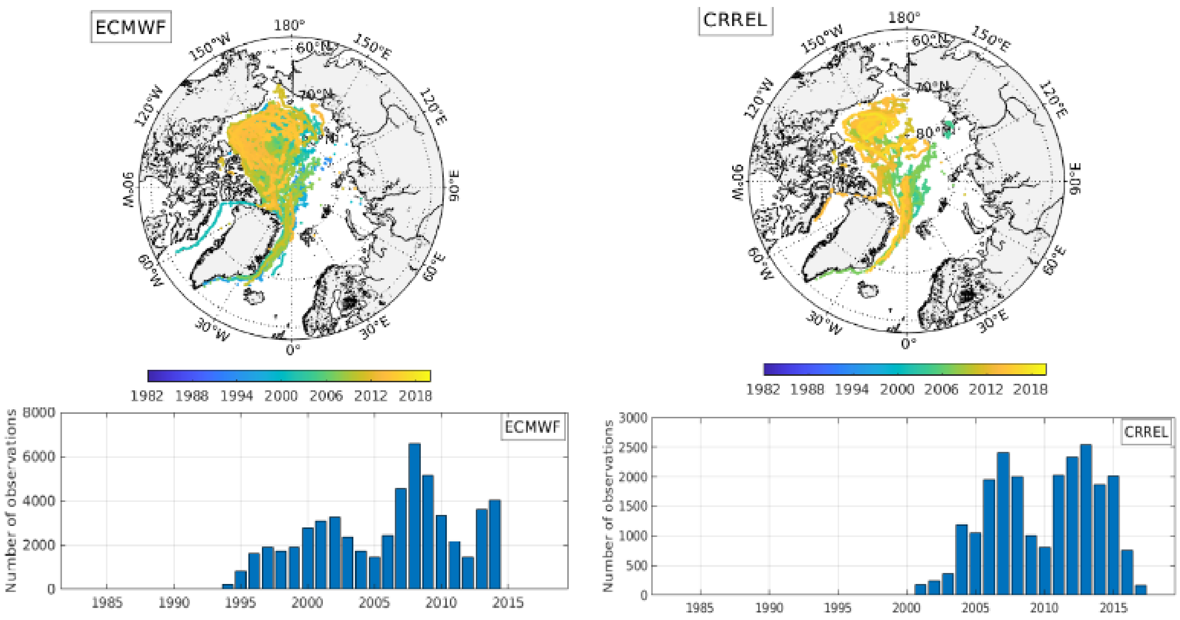

Figure 4.3.2 An overview of ECMWF (left) and CRREL (right) drifting buoys observations used for IST validation.

5 Validation SST/IST

5.1 Principles

5.1.1 SST

The baseline for the validation of the SST product is to use drifting buoy measurements only, as recommended currently by the GHRSST group on satellite SST validation (STVAL). Mean and standard deviations of the departures from drifting buoy SST measurements are computed over the full domain (North of 58°N). Various quality check procedures are applied on drifting buoy measurements to discard suspect data, using gross error checks and/or blacklists made available by various centres. Additional validation statistics were also calculated with in situ observations from moored buoys as well as ship observations. As the different types of observations also have different error characteristics, all the validation statistics shown here will be separated into, drifting buoys, moored buoys and ship statistics. The individual in situ observations have been matched to the closest satellite observations in space and time and all differences are computed as satellite – in situ. The sea ice concentration data have been used here only as a mask and will not be validated.
The SST drifting buoys observations were used for a static mean bias correction of the L4 surface temperature analysis. The moored buoys and ship In situ observations are not included in the

reanalysis and the validation statistics therefore represent an independent estimate of the performance of the L4 SST analysis.

Area	Type In situ	Parameter	Overall validation stats
Full Area (Arctc Ocean)	Drifting buoys	SST (°C)	Mean/stddev/RMS/Nobs
	Moored buoys	SST (°C)	Mean/stddev/RMS/Nobs
	Ship observations	SST (°C)	Mean/stddev/RMS/Nobs

Table 6.1.1: Summary of the SST validation numbers presented in the next section

In addition to the overall validation statistics, yearly results (mean, stddev, Nmatch/ups) will also be presented graphically for all three types of in situ observations.

5.1.2 IST

The availability of IST observations for the Arctic Sea ice is much lower than for SST and is very limited in the early years of the period. We have chosen to validate the IST part of the L4 reanalysis against drifting buoy measurements of buoys deployed in the Arctic by ECMWF (European Centre for Medium-Range Weather Forecasts)(Sep 15th, 1993- Jan 1st, 2015) and CRREL (Cold Regions Research and Engineering Laboratory)(Apr 14th, 2001- Sep 4th, 2017).
Note that those buoys measured the 2m air temperature, while the L4 analysis consists of the surface temperature, but no reference skin observations are available for several years. The physical difference between Tskin and T2m introduces a difference in the comparisons, which can be several degrees and not related to the performance of the product.

Area	Type In situ	Parameter	Overall validation stats
Full Area (Arctic Ocean)	Drifting buoys ECMWF - Tair	IST (°C)	Mean/stddev/RMS/Nobs
	Drifting buoys CRREL - Tair	IST (°C)	Mean/stddev/RMS/Nobs

Table 6.1.2: Summary of the IST validation numbers presented in the next section

In addition to the overall validation statistics, yearly results (mean, stddev, Nmatch/ups) will also be presented graphically for the two different types of buoys.

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5.2 Results

The validation of the L4 SST and IST reanalysis product is shown below. Note that the SST validation results cover the whole reanalysis period from January 1982 to August 2019, while the IST validation results cover multi year periods for buoy data from ECMWF (Sep 15th, 1993- Jan 1st, 2015) and CRREL (Apr 14th, 2001- Sep 4th, 2017).

SST observations from ships typically have larger uncertainties than traditional drifting buoy observations. This can also be seen in the validation statistics.

The overall SST validation of the reanalysis shows biases less than 0.1°C and a standard deviation of differences less than 0.7°C when compared against drifting and moored buoys, whereas the ship observations have larger bias and standard deviations.

Yearly validation statistics throughout the record from 1982 to 2019 show a stable mean performance when the product is compared against moored and drifting buoy observations. The comparisons against all three types of in situ observations show a slight tendency towards smaller standard deviations in the second half of the record compared to the first half, especially when the product is compared against ship observations. This is probably due to higher quality input satellite products in the recent times. Note that the annual validation statistics for 2019 are not based on a full year, but only cover January through August 2019.

Note that the number of drifting and moored buoy in situ observations available for validation is very low in the beginning of the record and much larger by the end of the record. This thus makes the yearly validation statistics less reliable in the beginning of the period.

Air temperature measurements of ECMWF and CRREL buoys have been used to validate the L4 IST. Note that the ice surface temperatures cover a limited region of the domain as the sea ice extent varies through the years.

The physical difference between Tskin and T2m introduces a difference in the comparisons, which can be several degrees and not related to the performance of the satellite product.
Overall, both types of buoys show similar validation statistics, with a bias of -3.7°C & -3.4°C and a standard deviation of differences of 3.4°C.

Area	Type	Parameter	Mean	Stddev	RMS	Number of matches
Full Area (Arctic Ocean)	Drifting buoys	SST (°C)	0.03	0.66	0.66	2497478
	Moored buoys	SST (°C)	0.08	0.62	0.63	71792
	Ship	SST (°C)	0.11	1.13	1.14	2154399
	Drifting buoys ECMWF – Tair	IST (°C)	-3.73	3.44	5.08	56136
	Drifting buoys CRREL – Tair	IST (°C)	-3.40	3.40	4.80	22952

Table 6.2.1: Overall validation statistics for comparisons between the full level 4 reprocessed data set and in situ observations not included in the analysis. The table shows statistics for the full area (North of 58°N).

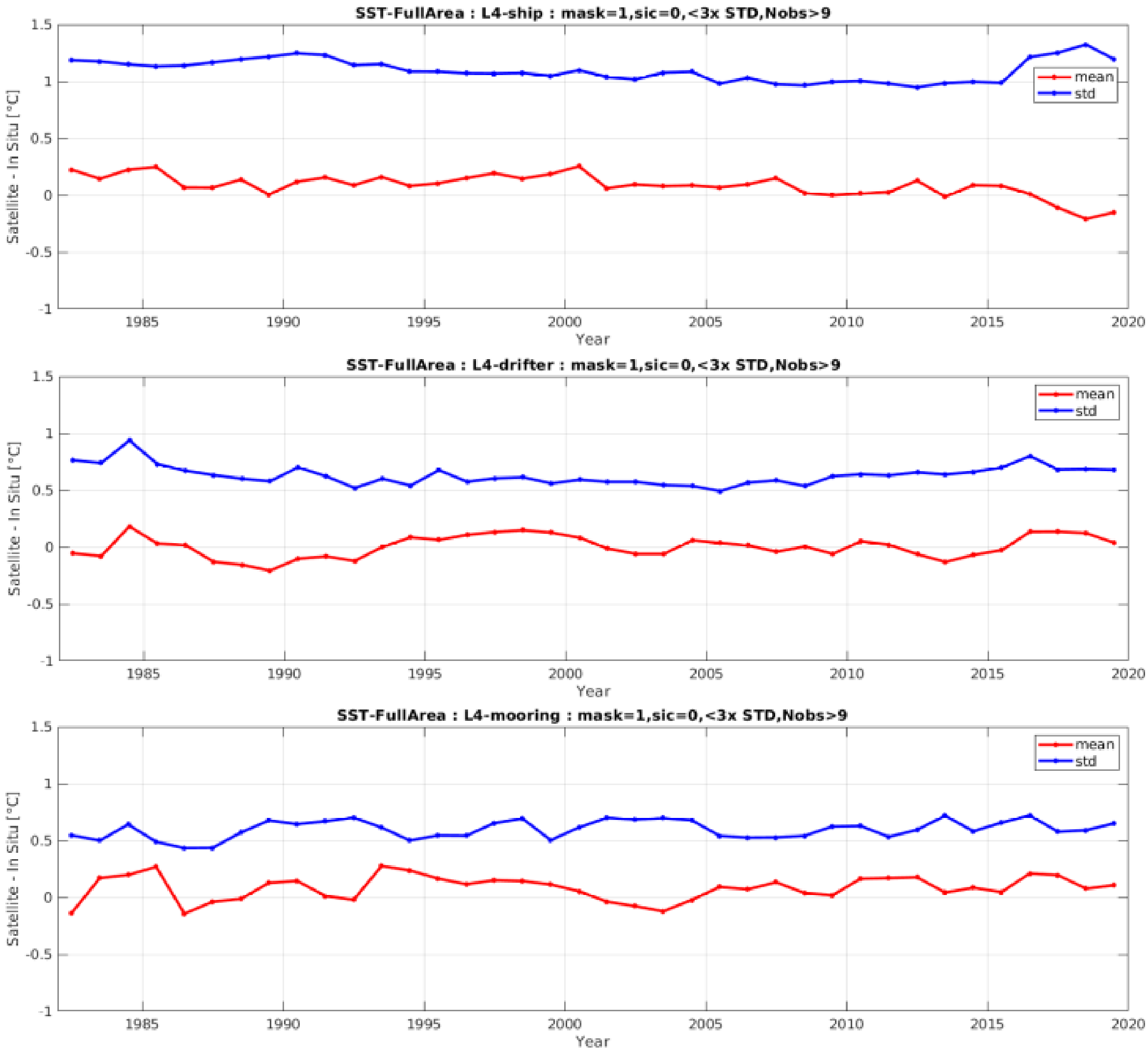

Figure 6.2.1 Yearly SST validation statistics of the level 4 reanalysis from ships (upper), drifting buoys (middle), and moored buoys (lower). Mean biases are red and standard deviations are blue. The spatial and temporal coverage of the satellite analysis vs in situ matchups throughout the record are shown in **Figure 4.3.1.**

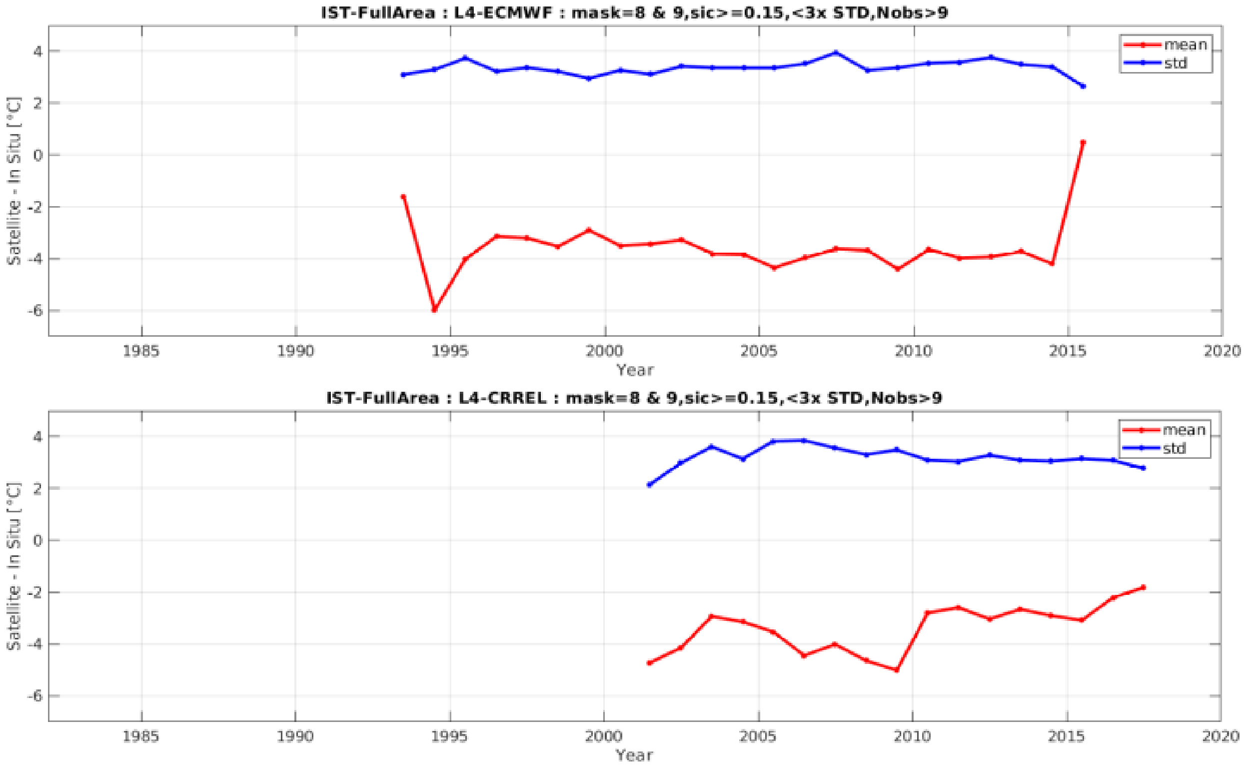

Figure 6.2.2 Yearly IST validation statistics of the level 4 reanalysis from ECMWF buoys (upper) and CRREL buoys (lower). Mean biases are red and standard deviations are blue. The spatial and temporal coverage of the satellite analysis vs in situ matchups throughout the record are shown in **Figure 4.3.2.**

Note that the numbers given here are differences between satellite and in situ observations and not errors on the satellite products. As mentioned above, the use of air measurements to validate IST will introduce a difference due to the vertical stratification in the near surface temperature where the ice surface temperature is typically colder than the temperature at 2 meter, in agreement with the results.

6 Results – Climate Indicators

The climate data record can be used to investigate the changes of surface temperatures of the Arctic Ocean and Sea ice. Figure 5.1 shows the trend for the Arctic area north of the 60th northern parallel, i.e. the mean temperature of all sea and sea ice temperatures. The black curve shows the average values for the reference period 1993-2014, while the coloured lines show individual years. It can be seen, that the recent years have been consistently warmer than the reference period. Also, it can be noted that the variation and fluctuations of the coloured lines are larger during winter, while there are only small differences during summer. This is most likely associated with the larger variability in the surface skin temperature for sea ice, which has largest extent in the winter.

The figure represents a candidate for a temperature indicator, since one can easily identify how much the temperature in the Arctic is different from the climatology at a given time and assess if the deviations from the mean is significant, compare to the variability observed in the reference years (1993-2014).

Figure 5.2 shows the monthly mean surface anomaly north 60ºN for the time period 1982-2019. The anomaly is the difference between the monthly mean temperatures and the monthly mean value of the reference period (1993-2014). The dark blue curve shows the running yearly mean. Both blue curves show a tendency, for which the temperatures have risen significantly during the recent decades, especially since the end of the 1990’s until now.

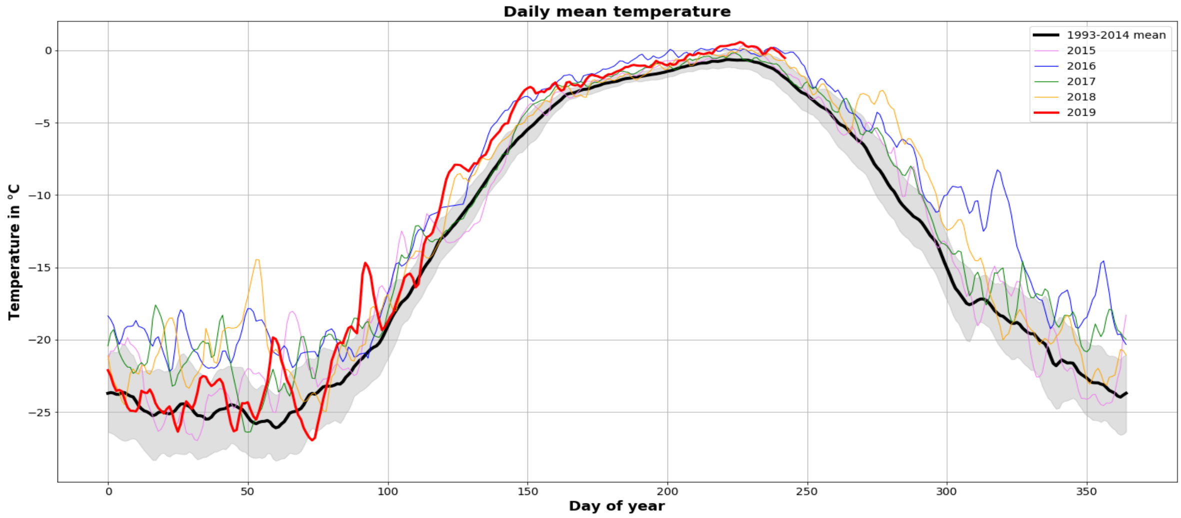

Figure 5.1*:The daily mean temperature of ocean and sea ice north of 60°N. The black curve shows the average value of the reference period 1993-2014, while the gray band around it represents the climatological variability (+- 1 standard deviation). The coloured lines depict the mean temperature for individual years since 2015.*

The large fluctuations of the monthly anomalies illustrate a large variation in sea and sea ice temperatures. From the figure, the linear trend for the area north of 60ºN can be calculated to be +0.12 degrees per year in the period 1982-2019, which is more than 4 degrees over the 38 years. This linear trend is represented as the red line in the figure.

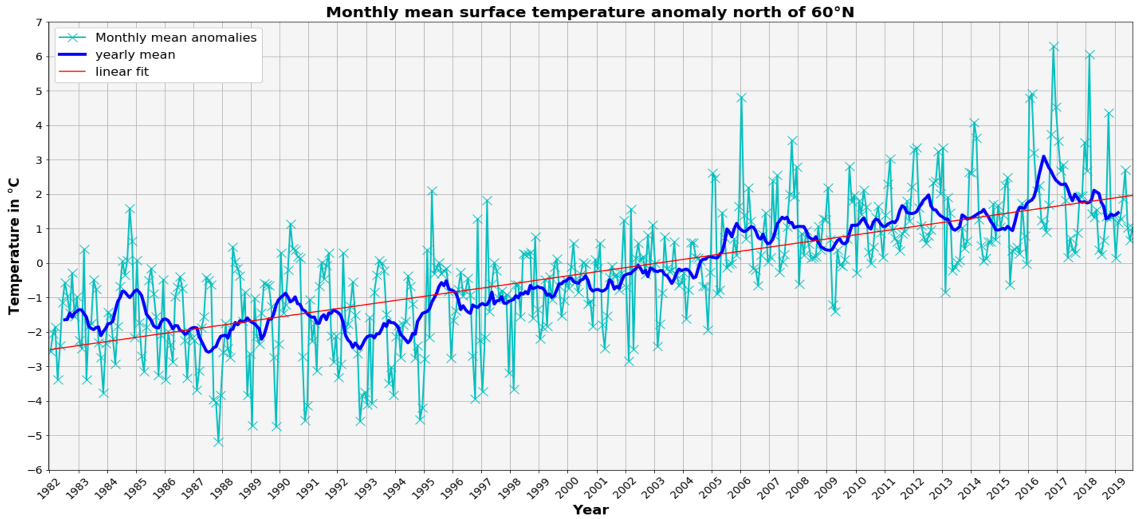

Figure 5.2: *The light blue curve shows the monthly temperature anomaly for the Arctic (> 60 N) for the time period 1982-2019. The anomaly show the difference between the monthly mean temperature and the monthly climatology for the reference period 1993-2014. The dark blue curve represent the yearly mean value, while the red line shows a linear fit through time.*

7 Conclusions

The work carried out within the NCKF work package 1.3.2, has contributed with an important and unique climate data record. It is the first time that such a satellite based CDR has been created that covers surface temperatures for all ocean and sea ice regions in the Arctic. The CDR has been extensively validated for both ocean and sea ice regions and allow for an improved estimation of the surface temperature changes in the Arctic since beginning of the 1980ies. A monthly and daily climatology of the surface temperatures have been constructed and examples of surface temperature indicators are also presented. Such climate indicators can be used to monitor the present conditions in the Arctic and easily assess how anomalous the situation is, based upon the derived climatology. The work has been carried out for the Arctic but can easily be extended to the Antarctica.

8 References

Atkinson, C. P., Rayner, N. A., Kennedy, J. J., and Good, S. A. (2014), An integrated database of ocean temperature and salinity observations, J. Geophys. Res. Oceans, 119, 7139– 7163, doi:10.1002/2014JC010053.

Dybkjær, G., R. Tonboe, and J. L. Høyer (2012). Arctic surface temperatures from Metop AVHRR compared to in situ ocean and land data. Ocean Sci., 8, 959–970, 2012, doi:10.5194/os-8-959-2012.

Dybkjær, G., J. Høyer, R. Tonboe and S. Olsen (2014) NACLIM Deliverable D32.28. Report on the documentation and description of the new Arctic Ocean dataset combining SST and IST.

Høyer, J. L. and She, J. (2007) Optimal interpolation of sea surface temperature for the North Sea and BalticSea, J. Mar. Sys., Vol 65, 1-4, pp.

Høyer, J. L., Le Borgne, P., & Eastwood, S. (2014) A bias correction method for Arctic satellite sea surface temperature observations. Remote Sensing of Environment, 146, 201-213.

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