Remote Sensing of Environment xxx (2013) xxx–xxx

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

A bias correction method for Arctic satellite sea surface temperature observations

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ARTICLE INFO

Article history:
Received 28 September 2012
Received in revised form 6 March 2013
Accepted 15 April 2013
Available online xxxx

Keywords:
Sea surface temperature
Optimal Interpolation
Arctic Ocean
Multi-sensor

ABSTRACT

A multi-sensor bias correction method has been developed using satellite sea surface temperature (SST) products from one microwave and five infrared sensors that cover the Arctic Ocean. The correction method has been used to construct improved single sensor and multi-sensor, merged and interpolated satellite SST products from January to December 2008.

The validation of the satellite products ingested in the level 4 production shows that large biases can persist for months in this region. The SST products from the AATSR sensor on ENVISAT and the NAVOCEANO AVHRR GAC are the most stable and reliable products for the Arctic region. These products have therefore been used to construct the reference product against which the other satellite products have been corrected. The bias correction method has been developed using detailed error characteristics and thorough time-space analysis, and the bias corrected fields are validated against in situ observations from drifting buoys. All the individual satellite products show improvement in both bias and standard deviation after correction. Largest improvements are found for the Modis sensor on the Terra satellite, where biases are improved from −0.46 K to 0.02 K with the correction method. Temporal validation statistics reveal that extended periods with significant biases are also removed by the bias correction method.

A significant improvement is seen when the corrected satellite products are used for the SST analysis. When compared against drifting buoys, not included in the analysis, the corrected level 4 satellite SST product shows a bias of −0.04 K and standard deviation of 0.54 K, compared to an original bias of −0.28 K and standard deviation of 0.61 K. The effect of a missing reference sensor is assessed for the full period. Level 4 test runs using only one reference sensor demonstrates that improvements can be obtained with a single sensor bias correction method, and that the AATSR sensor gives the largest improvements. However, using both reference sensors in the bias calculation gives significantly better performance than using just one.

1. Introduction

The sea surface temperature (SST) of the global oceans is an important parameter to quantify due to the wide range of applications within e.g. climate change detection, air-sea heat flux calculations and assimilation into operational ocean and atmospheric models (e.g., Carton, Chepurin, Cao, & Giese, 2000; Larsen, Høyer, & She, 2007; Oke, Brassington, Griffin, & Schiller, 2008; Rayner et al., 2003). The decrease in sea ice extent in the recent years (Comiso, 2012; Comiso, Parkinson, Gersten, & Stock, 2008; Lindsay, Zhang, Schweiger, Steele, & Stern, 2009) has led to much larger areas with open waters in the Arctic during summer and fall. The large areas with water and the positive ice-albedo feedback (Lindsay & Zhang, 2005; Walsh, Kattsov, Chapman, Govorkova, & Pavlova, 2002) make the Arctic Ocean SST a very important parameter to monitor and predict.

Satellites provide a unique coverage of the global ocean and constitute an important part of the observational network for sea surface temperature. Extreme atmospheric and oceanographic conditions make the Arctic Ocean a very challenging region for retrieving the satellite surface temperature from satellites (Donlon et al., 2010; Høyer et al., 2012 and specialized retrieval algorithms have been demonstrated under some conditions to outperform the traditional global algorithms (Vincent, Marsden, Minnett, & Buckley, 2008; Vincent, Marsden, Minnett, Creber, & Buckley, 2008).

The polar orbits of the earth observation satellites result in frequent satellite passages in the high latitude regions and several satellites in the present observing system are capable of observing the sea surface temperature. The satellite observations range from infrared, which is cloud limited, to microwave observations that can be performed in cloudy conditions. The individual satellite products have typically higher error levels in the Arctic Ocean compared to the global ocean and the error characteristics are different from one product to another. Examples of persistent biases over months have been presented for both infrared and microwave satellite SST products (Høyer et al., 2012).

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http://dx.doi.org/10.1016/j.rse.2013.04.020

The number of in situ observations in the Arctic Ocean is smaller compared to the other regions of the global oceans (see e.g. Emery, Baldwin, Schlüssel, & Reynolds, 2001). This means that in situ observations cannot be used alone to effectively bias correct the different satellite products on an operational basis. Single sensor satellite based bias correction methods have been developed using the AATSR observations from ENVISAT as a reference sensor (Blackmore, O'Carroll, Fennig, & Saunders, 2012; Donlon et al., 2012; Le Borgne, Marsouin, Orain, & Roquet, 2012; O'Carroll, Blackmore, Fennig, Saunders, & Millington, 2012; Stark, Donlon, O'Carroll, & Corlett, 2008). The observations from the AATSR instrument are the preferred reference data due to the low overall noise on a global scale and the advantages for the two way observation technique in aerosol contaminated regions. The largest corrections for the AVHRR observations are typically found in the tropics and in periods with large atmospheric aerosol contents (O'Carroll et al., 2012).

No detailed studies have been performed to quantify the effect of the bias correction methods on the performance of the merged, gap free and interpolated level 4 (L4) products in the Arctic Ocean, despite the large differences between the L4 products (Dash et al., 2012; Martin et al., 2012). The persistent cloud cover in the Arctic (Yinghui, Key, Ackerman, Mace, & Zhang, 2012) and the narrow swath of the AATSR sensor result in a very low data return for this particular SST product. This poses a challenge for the AATSR based bias referencing methods. In addition, it was recently shown that the AVHRR Global Area Coverage product from NAVOCEANO (NAVO-GAC) performed very well in the Arctic Ocean when compared to drifting buoys (Høyer et al., 2012). There is therefore a need to examine the potential of using other satellite SST products as a reference and for developing and validating a multi-sensor satellite bias correction method. The method developed here uses the AATSR and NAVO-GAC products as a reference and bias correct the satellite products from Metop-A, AMSR-E, and the Modis Aqua and Terra satellites. The bias adjustment is performed as an individual step, separated from the OI generation. This gives the advantage that the performance of the bias correction is independent of the performance of the OI algorithm and that individual bias adjusted products can be made available to users that wish to apply them directly.

The recent loss of ENVISAT and AMSR-E underline that all satellites fail eventually, and that alternatives to AATSR observations should be sought. The AATSR and AMSR-E data are included in this study, even though we also aim for an operational bias correction method, because plans exist to replace these instruments and to produce operational microwave SST observations from the AMSR2 instrument on the Global Change Observation Mission (GCOM-W1) satellite (Imaoka et al., 2010). In addition, the Sentinel 3 satellite will carry the Sea and Land Surface Temperature Radiometer (SLSTR), which resembles the AATSR instrument in terms of a dual view capability (Donlon et al., 2012).

The purpose of this paper is to develop a multi-sensor bias adjustment method for satellite sea surface temperature observations in the Arctic Ocean, to be used in the DMI Optimal Interpolation (OI) L4 production (Høyer & She, 2007). The Optimal Interpolation method is developed to take into account the random noise on the observations to produce an estimate of the true value with minimum error variance (see e.g. Gandin, 1963; Thiebaux & Pedder, 1987). All systematic errors are assumed to be removed from the satellite data prior to ingestion in the OI method. Extended periods with significant biases as observed are thus not favorable and therefore make it important to bias correct the input data. The DMI OI L4 scheme follows Høyer & She, 2007 with the modifications that we use the previous days OI field as a first guess field for the present day analysis to produce one merged, gap-free interpolated L4 SST product every day, with a spatial resolution of 0.05° in latitude and longitude. The DMI OI L4 processing setup is currently applied to produce the Baltic Sea and Arctic Ocean SST products within the Global Monitoring for Environment and Security (GMES) MyOcean project. The L4 SST processing is ingesting 6 of the most widely used global operational satellite products ranging from infrared (AATSR, AVHRR and Modis) to microwave (AMSR-E) sensors and accounts for the noise levels on each of the satellite products.

The bias correction method developed in this paper also uses the DMI OI L4 pre-processing system for the Arctic Ocean to construct the single sensor daily fields with gaps (L3) from the level 2 (L2) swath observations. The bias correction method is thus easy to implement in the production and the improvements will be demonstrated for both L3 and L4 SST fields.

The paper is organized with an introduction to the satellite and in situ observations in Section 2, followed by an error characterization in Section 3. Section 4 presents the multi-sensor bias correction method with the validation of the corrected satellite products in Section 5. The improvements on the L4 OI analysis are assessed in Section 6 and Section 7 contains summary and conclusions.

2. Satellite and in situ data

2.1. Satellite data

The satellite SST observations used for this study are all operational L2 products that have been processed and made available in near real time. The products are listed in Table 1 and follow the GHRSST Data Specification (GDS) for L2P (Donlon et al., 2007). For this study we have used the variable called "sea_surface_temperature" from the L2P files.

The NAVOCEANO product is a Global Area Coverage (GAC) and is abbreviated NAVO-GAC in the rest of the paper. All L2P products have been obtained as part of the operational DMI-OI L4 processing chain (see e.g. Høyer & She, 2007).

The SST retrieval algorithms for the individual satellite products will not be described in detail here, but the IR satellite products are based upon the multichannel linear and nonlinear algorithms (see e.g., Barton, 1995; McClain, Pichel, & Walton, 1985; Walton, Pichel, Sapper, & May, 1998). During daytime, all the IR algorithms use observations from two spectral windows in the 10–12 μm part of the electromagnetic spectrum, where the difference between two spectral channels is used to correct for atmospheric effects, such as water vapor (Kumar, Minnett, Podestá, & Evans, 2003). Night time algorithms can also include observations from a 3–4 μm spectral window, which cannot be used during daytime due to contamination from reflected sunlight. The AATSR, NAVO-GAC and Metop-A products include the 3–4 μm spectral window in a 3-channel night time SST estimate, whereas the Modis products use observations from the 11 and 12 μm spectral windows both day and night. The AATSR instrument observes the same waters two times with different incidence angles and therefore different path through the atmosphere. This dual view capability is used to perform a more sophisticated correction for atmospheric effects, such as water vapor and aerosols (Merchant, Harris, Murray, & Zavody, 1999; Zavody, Mutlow, & Llewellyn-Jones, 1995).

All the IR algorithms provide a skin or subskin SST value depending upon whether in situ observations or radiative transfer modeling has been used to tune the parameters in the algorithm (Merchant & LeBorgne, 2004). In situ observations have been used to determine the NAVO-GAC and Metop-A IR algorithms, whereas the AATSR and Modis algorithms use radiative transfer modeling for determining the coefficients. The Modis and the AATSR products are thus provided as skin SST observations whereas the other products are subskin (see e.g. Donlon et al., 2007). The technique for SST retrievals in the microwave part of the spectrum is fundamentally different (see e.g. Wentz & Meissner, 2000; Wentz & Meissner, 2007). The MW radiometer observations of the sea surface are corrected for the sea surface roughness and atmospheric attenuation and data influenced by precipitation are discarded.

The L2P data files also include a field with quality flags ("proximity confidence") from 0 to 5, where 5 is the best (Donlon et al., 2007). According to the GDS definition, the satellite error levels and the quality levels should be consistent within the same satellite product but not

Please cite this article as: Høyer, J.L., et al., A bias correction method for Arctic satellite sea surface temperature observations, *Remote Sensing of Environment* (2013), http://dx.doi.org/10.1016/j.rse.2013.04.020