Upwelling Parameters From Bias-Corrected Composite Satellite SST Maps in the Gulf of Finland (Baltic Sea)

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Abstract—This letter proposes a method for using the operational ship of opportunity temperature data at a fixed depth for bias correction of satellite sea surface temperature (SST) images. The bias-corrected SST imagery from MODerate Resolution Imaging Spectroradiometer (MODIS) and Advanced Along-Track Scanning Radiometer (AATSR) sensors were used to calculate mean upwelling characteristics in the Gulf of Finland (GoF, Baltic Sea). First, we determined that the operational flow through temperature data at a 4-m depth can be used for validation and bias correction of satellite SST images in cases of wind speed over 5 m · s⁻¹. The composite sea temperature maps were calculated from bias-corrected images collected during upwelling events in the GoF, in 2000–2009. Mean upwelling characteristics were estimated from composite maps for both the northern and southern coasts of the gulf.

Index Terms—Advanced Along-Track Scanning Radiometer (AATSR), Baltic Sea, bias correction, MODerate Resolution Imaging Spectroradiometer (MODIS), oceanography, remote sensing, sea surface temperature (SST), upwelling.

I. INTRODUCTION

C OASTAL upwelling is an important physical process in the Baltic Sea, including the Gulf of Finland (GoF), influencing temperature, salinity, nutrient, and phytoplankton distribution through vertical and cross-shore water exchange [1]. The satellite sea surface temperature (SST) data carry substantial information about the spatial extent and mesoscale structures (filaments, fronts, and eddies) of summer upwelling [11]. The bias-corrected SST imagery from MODerate Resolution Imaging Spectroradiometer (MODIS) sensors is ±0.5 °C, MODIS/Aqua has a bias of 0.01 °C, with a standard deviation (STD) of 0.5 °C, for daytime SST retrievals, while MODIS/Terra has a mean bias of −0.20 °C, with the STD of 0.5 °C [4]. Different spaceborne sensors have biases of up to ±0.6 °C [10], particularly in the coastal sea areas [11]. In situ data (bulk temperature) and satellite SST (skin layer temperature) may have systematic biases due to diurnal warming [14], [15].

An important factor influencing temperature distribution in the near-surface layer is wind-induced mixing. Donlon et al. [16] showed that in situ temperature measured at a 5-m depth can be used in moderate wind (> 6 m · s⁻¹) conditions for determination of satellite SST bias.

In addition to daily remote sensing SST imagery provided by MODIS and AATSR, upper layer temperature measurements conducted regularly by ship of opportunity at a fixed depth are available in the GoF [17]. The daily temperature data collected on passenger ferries are the largest data set for evaluation of satellite SST in the GoF area. This data set enables provision of daily bias-corrected operational composite SST maps.

The objectives of the current study are described as follows: 1) to estimate the wind speed threshold for the use of in situ temperature for bias correction of MODIS and AATSR SST; 2) to calculate composite sea temperature maps representing the bulk temperature from multisensor SST imagery (representing skin layer temperature); and 3) to estimate mean upwelling parameters in the GoF from bias-corrected sea temperature maps.

II. DATA AND METHODS

A. In Situ Temperature and Wind Data

The high-spatial-resolution surface layer temperature data were collected along the shipping line between Tallinn and Helsinki (see Fig. 1) with a flowthrough system (FT) on passenger ferries [17], [18]. The data originated from two different

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measuring systems. The first data set, covering the years 2003–2005, was collected in the project Alg@line [18]. The second data set (2007–2009) was collected with the Ferrybox system (4H-Jena, Germany) installed on a passenger ferry [17]. The two measuring systems operated similarly, taking water from about a 4-m depth and recording data with 20-s intervals, i.e., horizontal resolution of about 150 m (vessel speed was about 27 km · h−1). The perturbation caused by vessel probably had minimal influence on skin–bulk temperature difference as the water intake located in the vessel head.

Wind data with 3-h temporal resolution measured at the Kalbådagrund weather station (Finnish Meteorological Institute) were used to evaluate the comparability of the satellite SST and the in situ temperature. The 6-h mean wind speed prior to satellite data acquisition was calculated.

B. Remote Sensing Data

The 10-year (2000–2009) SST data from MODIS and AATSR collected during the warm period of the year (June–September) and depicting well-expressed coastal upwelling events in the GoF were used in this paper.

The MODIS SST products were derived by NASA Ocean Biology Processing Group (OBPG) using “The Multi-Sensor Level-1 to Level-2 Code” (MS12). MODIS standard level-2 products (http://oceancolor.gsfc.nasa.gov) provide SST at 1 km × 1 km nominal spatial resolution. The pixels with the highest quality indicated by a standard flag were used. The set of MODIS SST images includes five upwelling events along the northern coast and three events along southern coasts. In total, 25 SST images acquired by MODIS (Terra and Aqua satellites) covered the in situ temperature measurements. Most of the MODIS matchups (85%) were in the 3-h time window from FT measurements, while 15% of MODIS data and all AATSR data were in the 4–5-h time window from FT measurements. In addition, 122 MODIS SST images (covering upwelling) were used to calculate upwelling characteristics (mean area, offshore extent, STD at each point, and upwelling centers) in the GoF.

The temporal and spatial coverage of AATSR is lower, with only one satellite compared to the two satellites carrying MODIS, and a swath width of 500 km compared to MODIS’ 2330 km. In total, five AATSR SST images, showing four upwelling events along the northern coast and one event along the southern coast of the GoF, were compared with the in situ temperature measurements. All five AATSR images coincided with one or two MODIS images. The AATSR images were acquired between 09:00 and 10:00 UTC, while the MODIS imagery was up to 1.5 h later. The AATSR is a dual-view instrument, i.e., it provides two SST products: nadir view and dual view. The AATSR level-1 brightness temperature was processed to level-2 SST products with BEAM software (http://www.brockmann-consult.de/cms/web/beam/) using dual-view and single-view SST retrievals for two channels [7], [10].

C. Comparison Methods

The data along the transect (see Fig. 1) were extracted from each image for the comparison with in situ temperature. As the spatial resolution of in situ measurements was higher (~150 m) compared to the satellite data (1 km), the average in situ temperature was calculated for each pixel area.

The root-mean-square temperature difference (RMSD), the correlation coefficient (r), and mean bias were calculated from the satellite SST and the corresponding in situ temperature.

The statistics were calculated using a different number of data matchups: 1) the in situ data collected within a 5-h time window covering satellite overpass; (2) the data collected at the wind speed of ≥ 5 m · s−1 within a 5-h time window covering satellite overpass.

III. RESULTS

A. Statistics of SST and FT Temperature Comparisons

The comparability of FT temperature and different satellite SST products was evaluated depending on wind speed (upper mixed layer depth). In the cases of wind speed at < 5 m · s−1,
the bias between FT temperature and SST started to increase (see Fig. 2). The threshold value of 5 m · s⁻¹ is lower compared to that in [16] and is in accordance with [19]. The mean bias and STD of data collected during low-wind-speed conditions were 1.17 °C and 1.05 °C, while the corresponding values for high-wind-speed conditions were −0.072 °C and 0.23 °C, respectively. Thus, the wind speed of 5 m · s⁻¹ can be treated as a threshold for the comparability of satellite SST and FT temperature measured at a depth of 4 m. The secondary maxima on bias distribution plots near 1.3 °C [see Fig. 3(a) and (b)] showed that remote sensing data were biased due to the stratified upper layer during low wind speed. By applying the wind speed criterion, the data collected in the stratified upper layer can be excluded and, therefore, the mean bias reduced. Fig. 3(a) shows that, in the case of wind speed of ≥ 5 m · s⁻¹, the distribution of biases between MODIS SST and in situ temperature became almost Gaussian, with the mean bias of −0.12 °C and RMSD of 0.37 °C (see Table I). In the case of MODIS data, the correlation improved slightly if the wind criterion was applied, from 0.92 to 0.95. The mean bias and RMSD of MODIS/Aqua were −0.22 °C and 0.42 °C, while the corresponding values for MODIS/Terra data were 0.04 °C and 0.29 °C (see Table I), respectively. The implementation of the wind speed threshold reduced the AATSR mean bias significantly for nadir- and dual-view SST, at −0.27 °C and 0.28 °C, respectively. Prior to implementation of the wind speed threshold, the corresponding values were 1.84 °C and 1.04 °C. In addition, RMSD values of AATSR data were reduced significantly. The improvement of AATSR bias distribution after implementation of wind speed criterion can be observed in Fig. 3(b). Fig. 3(c) shows that AATSR data collected in the upwelling region (low temperature values) tend to deviate more from the 1:1 line compared to MODIS data. In addition, the correlation between FT and AATSR data is lower, at 0.66 and 0.89, for dual- and nadir-view data, respectively (see Table I). The analysis earlier showed that wind conditions can significantly influence the bias between SST and in situ temperature. If the wind speed was sufficiently high (deeper upper mixed layer), SST values deviated slightly from the FT measurements, and the effect of bias correction on the composite map was low.

If FT data are available, then the SST imagery should be bias corrected using the FT data from the same day. In case FT data are not available, the SST imagery should be corrected using the mean bias, in case of wind speed at ≥ 5 m · s⁻¹ (see Table I). The imagery collected during low-wind (< 5 m · s⁻¹) conditions without corresponding FT data should not be used for calculation of bias-corrected composite map.

### B. Application Example of Bias Correction

For comparison, two different composite maps were calculated, in cases when data from different satellite sensors (22 images) and in situ measurements were available, to obtain a composite map best representing sea temperature along the northern coast of the GoF: 1) uncorrected composite maps and 2) bias-corrected MODIS and AATSR/Nadir sea temperature (wind speed of ≥ 5 m · s⁻¹).

As the AATSR nadir data have positive bias and dual-view data have negative SST bias compared to MODIS and in situ measurements (see also [20]), artificial effects can appear on the SST composite map if appropriate bias correction is not applied. In addition, cloud masks and spatial coverage, as well as bulk–skin temperature difference, can cause irregularities on composite maps. The bias correction reduced the values on sea temperature composite map [see Fig. 4(b)] compared to the noncorrected...
map [see Fig. 4(a)] because the effect of skin layer warming was considered. Histogram on Fig. 4(c) showed that the differences between the bias-corrected map and the noncorrected map varied in the range from 0 °C to 2 °C, with the peak value at 1.2 °C. Examples in Fig. 4 showed that the gradients in frontal zones and filaments, i.e., important upwelling parameters, can be preserved quite well even when using composite images, which generally tend to smooth out the gradients.

C. Mean Upwelling Parameters

The composite sea temperature maps were calculated from 147 bias-corrected images, i.e., 61 images covering upwelling along the southern coast and 86 images along the northern coast in the GoF during the period of 2000–2009 [see Fig. 5(a) and (b)]. The bias correction was applied to all images, according to the FT data availability and wind speed criteria, as well as mean bias values given earlier (see Section III-A and Table I). The method for upwelling front detection is described in [2]. The sea temperature maps were overlaid by isotherms with the fixed contour interval of 0.3 °C starting from the upwelling center(s). All sea surface isotherms either form closed contours or intersect the basin boundary. The contour of the warmest isotherm intersecting the basin boundaries is considered the upwelling water open sea border [2]. The upwelling area (detected from the mean map) along the northern coast and along the southern coast was 5642 km² and 3917 km², which is 19% and 13% of the GoF area (29 500 km²), respectively. In addition, the upwelling area was larger in the western GoF compared to the eastern region. More intensive upwelling events along the northern coast occurred in the western part of the GoF. The lower mean temperatures (13.5 °C) were in the upwelling centers between Hanko Peninsula and Helsinki [see Fig. 5(a)]. Along the southern coast, the intensive upwelling events with low mean temperature values (14 °C) occurred in the western part of the GoF, between Osmussaar Island and Aegna Island.

The mean cross-shore extent of the upwelling region along the northern coast of the GoF was 20–30 km. The cross-shore extent of upwelling along the southern coast varied from 7 km in the eastern part to 25 km in the western part.

To describe the variability of temperature during upwelling events, the STD was calculated for each pixel location [see Fig. 5(c) and (d)]. The regions with high STD (high temperature variability) due to filaments near upwelling centers along the northern coast are located in the western and central part of the GoF (Hanko, Porkkala, and Porvoo Archipelago). The STD values near upwelling centers were between 3.0 °C and 3.5 °C. The STD values of about 3 °C in the eastern GoF (Kotka) are caused by the seasonal course of the surface layer temperature and lower occurrence frequency of upwelling events [3]. Along the southern coast, the area of high temperature variability with STD values of 4°C–5.5 °C is between Osmussaar and Aegna Islands, which coincides with the mean low
temperature area (15°C–17.5 °C). The areas with high temperature variability (STD > 4 °C) in the eastern part of the southern coast are caused by an irregular coastline, resulting in the occurrence of upwelling events forced by wind from different directions.

IV. CONCLUSION

A method was proposed for using the operational ship of opportunity temperature data at a fixed depth and wind speed data as the mediation process to correct different satellite SST products. Composite sea temperature maps were calculated from the bias-corrected products to characterize upwelling events in the GoF.

The dependence of the mean bias between satellite SST and FT temperature on wind speed showed that the FT data measured at a 4-m depth can be used for validation of MODIS and AATSR SST retrievals when the wind speed is \( \geq 5 \) m \( \cdot \) s\(^{-1}\). MODIS SST data have a \( \sim 0.12 \) °C bias compared to \textit{in situ} temperature, while AATSR nadir- and dual-view SST products have \( -0.27 \) °C and \( 0.28 \) °C biases, respectively.

Bias-corrected composite sea temperature maps showed that upwelling events are more extensive on the northern coast of the GoF, with a mean upwelling area of 5642 km\(^2\) (19%), while along the southern coast, the mean area was 3917 km\(^2\) (13%). Four different regions were identified from sea temperature STD maps, with high variability during upwelling events. The high variability is caused by filament dynamics near upwelling centers in the western and central GoF, and by an irregular coastline, resulting in occurrence of upwelling events forced by wind from different directions in the eastern GoF.

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REFERENCES


