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Comparison of satellite sea surface temperature with in situ surface layer temperature

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Abstract. Shipborne measurements of sea surface layer temperature in the western Gulf of Finland in July 2002 were compared with four different MODIS sea surface temperature (SST) products. The root mean square difference of the satellite and shipborne temperature series was calculated. According to the calculations the MODIS Aqua SST products were closer to the shipborne temperature measurements than the MODIS Terra SST products. A criterion of 0.4 °C temperature differences was found to detect upwelling regions from MODIS SST products. Comparison of images showed that surface accumulation of cyanobacteria causes a local increase of the sea surface temperature on the SST images.

Key words: sea surface temperature, MODIS Aqua, MODIS Terra, upwelling, Gulf of Finland.

INTRODUCTION

One of the most frequent variables retrieved from satellite sensors used for oceanographic studies is the sea surface temperature. The distribution of the sea surface temperature provides significant information for monitoring the relevant key ocean structures, e.g. fronts, eddies, and upwellings (Gidhagen, 1987; Sur & Ilyin, 1997; Borzellia et al., 1999; Kartushinskaya, 2000; Bricaud et al., 2002; Tang et al., 2002). The sea surface temperature is observed from the space by the thermal infrared imagery during cloud-free conditions using the thermal and infrared satellite channels. A wide range of different satellite systems and sensors providing the sea surface temperature (SST) data is and will become available during the next decade (Johannessen et al., 2000). In the Gulf of Finland (Baltic Sea) the summer coastal upwellings caused by the time-variable wind forcing bring up cold and phosphate rich waters from the deeper layers to the surface thus

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increasing the biomass of cyanobacterial blooms (Laanemets et al., 2004; Vahtera et al., 2005). Therefore, statistical analyses of upwelling parameters (horizontal scales of the upwelled water and the upwelling-related filaments, temperature differences between the upwelled and the surrounding water) as well as the frequency of upwelling events during summer by using SST from satellite remote sensing images is an important task.

The aim of this study is to compare (1) different images obtained within a short time window (Aqua and Terra products) and (2) MODIS products in terms of algorithms (SST and SST4) used for the calculation of the sea surface temperature for the same images.

This comparison shows which MODIS product gives the best results in the Baltic Sea region. The sea surface temperatures calculated by using different MODIS products are compared with the respective shipborne measurements to establish quantitative measures for defining uncertainties of the SST from remote sensing. The results can be used for developing quantitative criteria for the detection of upwelling parameters.

DATA AND METHODS

Shipborne measurements

A field study trip for measurements of the surface layer temperature was made on 29 July 2002 using a flow through (FT) system while the ship was moving. The length of the ship track from Tallinn to Hiiumaa Island (Fig. 1) was about

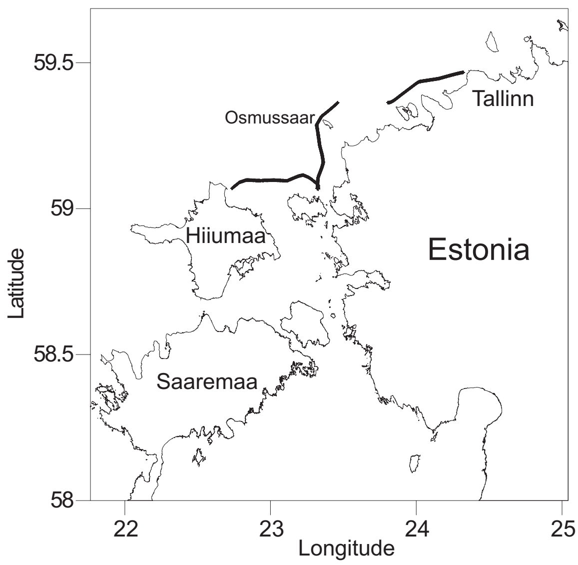

Fig. 1. Study site. Ship track from Tallinn to Hiiumaa.

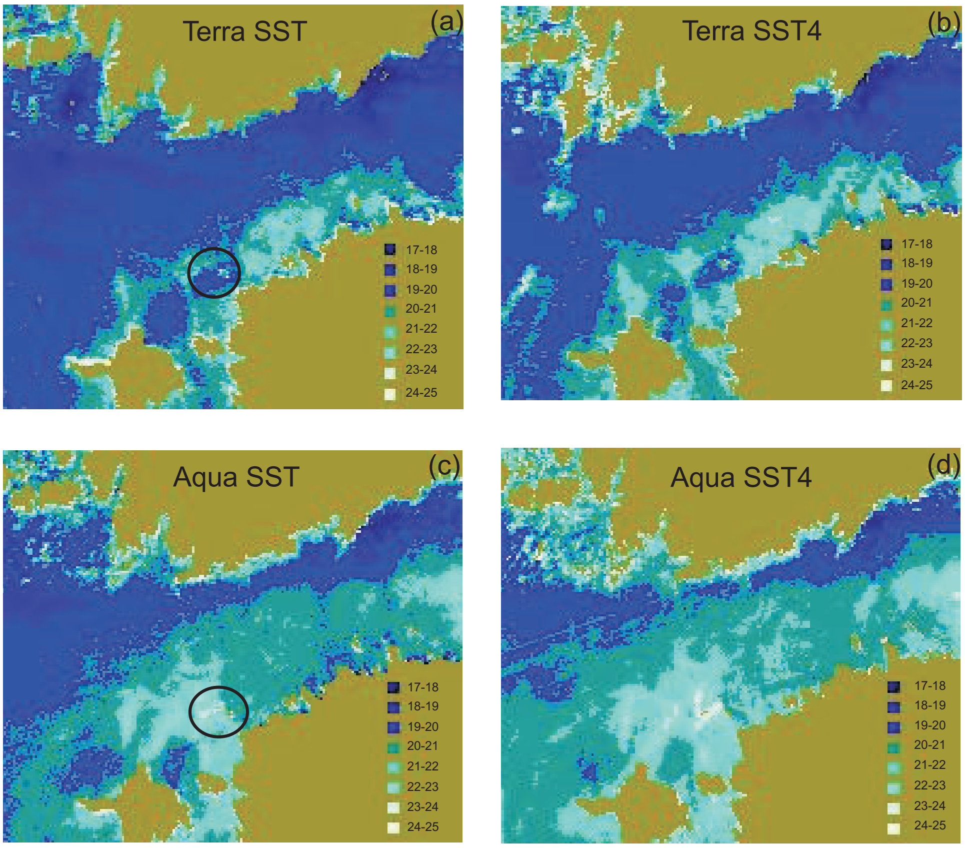

Fig. 2. Sea surface temperature products from satellite images Terra SST (a), Terra SST4 (b), Aqua SST (c), and Aqua SST4 (d). The region of surface accumulation of cyanobacteria is encircled (c).

130 km and it was passed in 7 h. Measurements started at 10.30 UTC. The FT system comprised a Seabird CTD recording temperature and conductivity at 1 s intervals. The ship location was determined by GPS. Seawater was pumped into the FT system from a depth of 20 cm. During the cruise the wind speed and direction were measured once per hour.

Remote sensing images

MODIS (**MOD**erate Resolution **I**maging **S**pectroradiometer) is a key instrument aboard the Terra (EOS AM) and Aqua (EOS PM) satellites. Terra MODIS and Aqua MODIS view the entire Baltic Sea area daily, acquiring data in 36 spectral bands. MODIS Level 2 Sea Surface Temperature Product, MOD28L2, provides a long wavelength (11–12 μm, SST) and a short wavelength (3–4 μm, SST4) sea surface temperature at 1 × 1 km resolution over the global oceans (Satellite-based Information System on Coastal Areas and Lakes, http://www.siscal.net/documents/EOP_SST_MOD_V03.pdf and GES Distributed Active Archive Centre, http://disc.gsfc.nasa.gov/data/dataset/).

Both MODIS Terra (overflight at 9.15 UTC) and MODIS Aqua (overflight at 11.05 UTC) SST products of 29 July 2002 were downloaded from GES Distributed Active Archive Centre (http://disc.gsfc.nasa.gov/data/dataset/). Geocorrection was applied to each obtained image. The digital number (DN) values were converted to SST by using the following values of calibration coefficients:
MODIS SST = 0.01 × DN-300 (GES Distributed Active Archive Centre).

RESULTS AND DISCUSSION

Comparison of images

The SST images of MODIS standard products are shown in Fig. 2. Differences between the products are evident. The major difference in the temperature fields is between the MODIS Aqua and MODIS Terra products (cf. Fig. 2a, b and Fig. 2c, d). The MODIS Aqua SST and SST4 products give generally higher values and the area with a temperature of 20–21 °C is much wider than the temperature fields on MODIS Terra products. This disparity can be partly explained by the surface layer solar heating because the overflight of Aqua took place 1 h and 45 min later. The Aqua SST value averaged along the ship track was 0.183 °C higher than the Terra SST value while the difference between the averaged SST4 values was 0.149 °C. The difference was smaller within the Aqua and Terra products (Fig. 2).

Small-scale areas with significantly higher temperature anomalies can be seen on the north-west Estonian coast in all four MODIS SST images (Fig. 2a, c). The maxima can be explained by the visible massive surface cyanobacteria patches

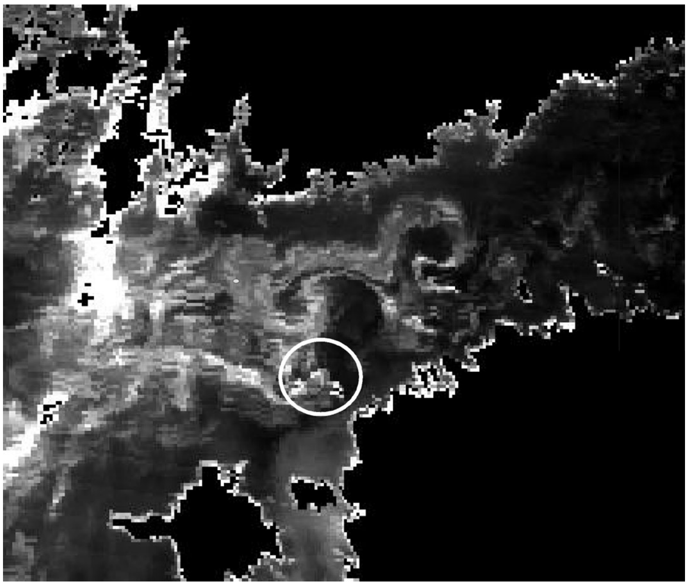

Fig. 3. Radiance data at a waveband of 662–672 nm. The area of measurements that was affected by a cyanobacterial bloom is encircled.

near Osmussaar Island. Kahru et al. (1993) assumed that the massive surface accumulation of cyanobacteria can cause a local increase of the sea surface temperature up to 1.5 °C on the SST images for low wind speed (about 2 m s^{-1}). We suggest that this effect was also intermittently present in the area covered by our data (temperature difference between two neighbouring pixels was up to 2 °C), in the region encircled in Fig. 2a, c. In the same region maximum values were also observed in the radiance data at the waveband 662–672 nm, which is the range that describes surface accumulation of cyanobacteria (Fig. 3). Therefore in the following data analysis the pixels for which the cyanobacteria surface accumulation was visible were discarded.

Estimation of the Ekman layer depth

To evaluate the correspondence of the shipborne temperature measurements with the satellite SST data the depth of the turbulent Ekman boundary layer h_m was estimated by the formula $h_m = 0.1u_*/f$ for a homogeneous water column (Csanady, 1982). Here $u_* = (\tau/\rho_w)^{1/2}$ is friction velocity, $\tau = \rho_a C_a u^2$ is wind stress, ρ_a is air density, ρ_w is water density, $C_a = 1.2\times10^{-3}$ is dimensionless wind drag coefficient, u is wind speed, and $f = 1.3\times10^{-4}\ s^{-1}$ is Coriolis parameter. The mean wind speed during the measurement was 2.8 m s^{-1} and the corresponding estimated Ekman layer depth was 2.5 m. The stratification due to the surface heating certainly reduces the depth of the surface shear layer but probably not as much as by an order of magnitude and we assume that the FT temperature is representative for the sea surface temperature.

Calculation of the root mean square difference

The SST products were compared with the FT temperature data. Using the ship track coordinates from satellite SST images the pixels covering the ship track were extracted. The average FT temperature was calculated for each pixel area. The number of FT temperature readings within a pixel varied between 50 and 300. The correspondence between FT data and four different MODIS SST products is shown in Fig. 4. The Terra products (Fig. 4a, b) differ more from the FT data than the Aqua products (Fig. 4c, d). As the SST and SST4 products are calculated using different algorithms, the differences in temperature that can be seen in Fig. 4c (ranges 90–100 km and 120–130 km) may be caused by the Aqua SST4 algorithm. For the evaluation of the coincidence of the MODIS SST products and FT temperature measurements the root mean square (RMS) difference (ΔT) of the satellite and FT temperature series was calculated as follows:

$$\Delta T = \sqrt{\sum \frac{(T_{\text{sat}} - T_{\text{ship}})^2}{n}},$$

where T_{sat} is the temperature from a MODIS product, T_{ship} is the pixel-averaged temperature of FT data, and n is the number of pixels on the ship track. The calculated RMS differences are presented in Table 1. For the MODIS Terra products the RMS differences are larger than for the Aqua products. The Aqua SST product has the smallest ΔT_1 and is the most compatible with the FT data (Fig. 3c). We also calculated the RMS differences for the ±0.5 h time interval around the overflight of Aqua (Table 1). At the time of the Terra overflight there were no shipborne measurements. As expected, the RMS differences were smaller for the shorter time intervals.

Table 1. The RMS differences of all MODIS products and FT temperature calculated for the total length of the series (ΔT_1) and the RMS differences of the MODIS Aqua products and FT temperature series for the time interval ±0.5 h around the overflight (ΔT_2)

MODIS product	ΔT_1	ΔT_2
Terra SST	0.753	–
Terra SST4	0.766	–
Aqua SST	0.572	0.312
Aqua SST4	0.578	0.524

– No relevant measurements made.

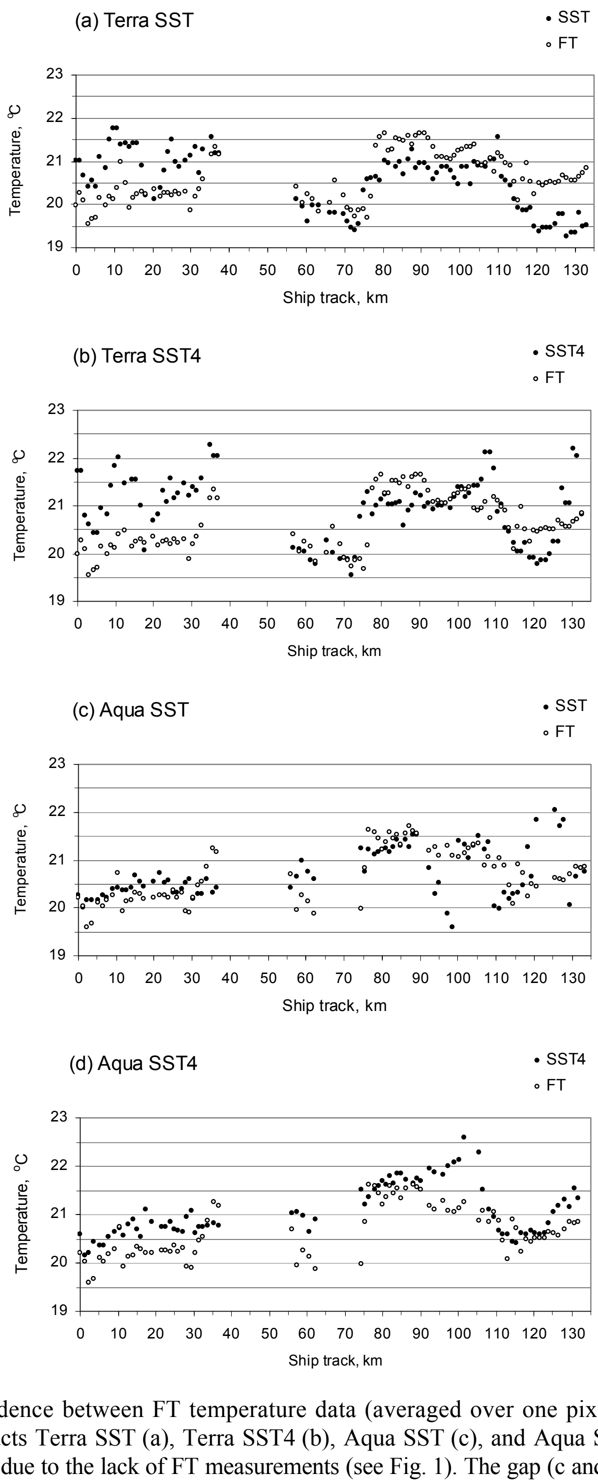

Fig. 4. Correspondence between FT temperature data (averaged over one pixel) and sea surface temperature products Terra SST (a), Terra SST4 (b), Aqua SST (c), and Aqua SST4 (d). The large gap (36–56 km) is due to the lack of FT measurements (see Fig. 1). The gap (c and d) near Osmussaar Island (62–74 km) is due to the accumulation of cyanobacteria.

CONCLUSIONS

Generally the Aqua products show a better correspondence with the FT temperature data than the Terra products. The correspondence between the shipborne data and satellite data is the best in the case of the Aqua SST product. The RMS difference in the case of 1 h interval around the satellite overflight time was ~0.4 °C. Therefore it is assumed that the criterion of 0.4 °C temperature differences can serve for detecting upwelling regions. Finding a criterion for spatial variability needs to be studied.

Comparison of the images showed that massive surface accumulation of cyanobacteria can cause a local increase of the sea surface temperature on the SST images for low wind speed.

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REFERENCES

Bricaud, A., Bosc, E. & Antoine, D. 2002. Algal biomass and sea surface temperature in the Mediterranean Basin. Intercomparison of data from various satellite sensors, and implications for primary production estimates. *Remote Sens. Environ.*, **81**, 163–178.

Borzelli, G., Manzella, G., Marullo, S. & Santoleri, R. 1999. Observations of coastal filaments in the Adriatic Sea. *J. Mar. Syst.*, **20**, 187–203.

Csanady, G. T. 1982. *Circulation in the Coastal Ocean*. D. Reidel Publishing Company, Dordrecht, Holland.

Gidhagen, L. 1987. Coastal upwelling in the Baltic Sea – satellite and in situ measurements of sea-surface temperatures indicating coastal upwelling. *Estaurine Coastal Shelf Sci.*, **24**, 449–462.

Johannessen, O. M., Sandven, S., Jenkins, A. D., Durand, D., Pettersson, L. H., Espedal, H., Evensen, G. & Hamre, T. 2000. Satellite earth observation in operational oceanography. *Coastal Eng.*, **41**, 155–176.

Kahru, M., Leppänen, J. M. & Rud, O. 1993. Cyanobacterial blooms cause heating of the sea surface. *Mar. Ecol. Prog. Ser.*, **101**, 1–7.

Kartushinskaya, V. A. 2000. Time–space structure and variability of surface temperature frontal zones in the ocean (based on AVHRR satellite data). *Adv. Space Res.*, **25**, 1107–1110.

Laanemets, J., Kononen, K., Pavelson, J. & Poutanen, E.-L. 2004. Vertical location of seasonal nutriclines in the western Gulf of Finland. *J. Mar. Syst.*, **52**, 1–13.

Sur, H. I. & Ilyin, Y. P. 1997. Evolution of satellite derived mesoscale thermal patterns in the Black Sea. *Progr. Oceanogr.*, **39**, 109–151.

Tang, D., Kester, D. R., Ni, I., Kawamura, H. & Hong, H. 2002. Upwelling in the Taiwan Strait during the summer monsoon detected by satellite and shipboard measurements. *Remote Sens. Environ.*, **83**, 457–471.

Vahtera, E., Laanemets, J., Pavelson, J., Huttunen, M. & Kononen, K. 2005. Effect of upwelling on the pelagic environment and bloom-forming cyanobacteria in the western Gulf of Finland, Baltic Sea. *J. Mar. Syst.*, **58**, 67–82.

Satelliidi merepinna temperatuuri võrdlus alusmõõtmistega

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29. juulil 2002 teostati Soome lahe läänepoolses regioonis merepinna temperatuuri mõõtmised, kasutades läbivoolusüsteemi. Saadud andmeid võrreldi MODIS-e nelja erineva merepinna temperatuuri (SST) produktiga (Terra SST, Terra SST4, Aqua SST ja Aqua SST4). Kokkulangevuse uurimisel hinnati satelliidipiltide erinevusi. Võrreldi läbivoolusüsteemiga mõõdetud merepinna temperatuuri ja satelliidi merepinna temperatuuri produkte (Terra SST, Terra SST4, Aqua SST ja Aqua SST4) graafiliselt ning arvutati ruutkeskmised hälbed. Saadud tulemused näitasid, et Aqua merepinna temperatuuri produktid (Aqua SST ja Aqua SST4) on läbivoolusüsteemiga mõõdetud pinnakihi temperatuuridega paremas vastavuses kui Terra merepinna temperatuuri produktid (Terra SST ja Terra SST4). Läbivoolusüsteemiga mõõdetud temperatuuri ja satelliidi merepinna temperatuuri andmete kokkulangevus oli kõige parem satelliidi produkti Aqua SST korral. Ruutkeskmine hälve ajavahemiku jaoks 30 minutit enne ja pärast satelliidi ülelendu oli 0,312 °C. Saadud tulemusi arvestades võib eeldada, et nii temperatuuri kui ka temperatuuri muutuste määramiseks tõusuhoovuse piirkonnas võib kasutada kriteeriumi 0,5 °C.