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PREPARATION AND DISSEMINATION OF THE AVERAGED MAPS AND FIELDS OF SELECTED SATELLITE PARAMETERS FOR THE BLACK SEA WITHIN THE SeaDataNet PROJECT

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Abstract. Statistical sea surface temperature (SST) and chlorophyll *a* (Chl.*a*) maps and fields (monthly, seasonal and annual) have been prepared for the Black Sea region in the framework of the SeaDataNet project. Daily MODIS/Aqua (SST and Chl.*a*) and SeaWiFS (Chl.*a*) level 2 (L2) datasets were utilised to produce 1 km resolution final products, which are disseminated through the Internet. Data processing was done with the SeaDAS (SeaWiFS Data Analysis System) software package. Standard algorithms were used for calculation of Chl. *a* and SST. Only 'clean' pixels (i.e. pixels without any SeaDAS flag) were taken for averaging. Data interpolating empirical orthogonal functions (DINEOF) method was tested to reconstruct missing SST data, however, it did not work properly in conditions of insufficient data, producing some unrealistic results so it was not applied to the final products. In total, about 500 averaged maps and fields were prepared for period of September 1997 to December 2004 (Chl. *a* from SeaWiFS) and for period July, 2002, December 2007 (Chl. *a* and SST from MODIS).

Keywords: the Black Sea, remote sensing, satellite, SeaWiFS, MODIS, Chl. *a*, SST, data, statistical map.

AIMS AND BACKGROUND

One of the objectives of the SeaDataNet project is the preparation and dissemination of regional statistical products from recent data collected over the Black Sea to serve wide range of users: public, scientists, modellers, and decision-makers. According to this objective the averaged monthly, seasonal and annual maps and fields of chlorophyll *a* (Chl.*a*) and sea surface temperature (SST) were calculated from the satellite data derived from Level 2 (L2) datasets for SeaWiFS (Sea-viewing Wide Field-of-view Sensor) and MODIS/Aqua (Moderate Resolution Imaging Spectroradiometer) sensors available at the *Ocean Color* web site. Spatial resolution of the resulted maps and fields is 1 km. The products are disseminated through the web site http://www.ims.metu.edu.tr/SeaDataNet/. Being easier to interpret by non-specialist users, statistical maps and fields upon quality check and

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cross-validation expected to be used by final users, such as scientists-modellers, environmental projects and so on.

Since the Coastal Zone Colour Scanner success (1978–1986) satellite oceanography entered in an era of rapid growth. Within the last decade a number of SST, sea surface height and ocean colour sensors were deployed on satellite platforms for scientific and operational purposes. The resolution (250 m ÷ 1 km) and accuracy of the ocean colour and SST data from SeaWiFS and MODIS/Aqua platforms are among the best available to Earth scientists today. The global standard products from these platforms, such as Chl.*a* and SST monthly and seasonal composites, are available at the spatial resolutions of 9 and 4 km at http://oceancolour.gsfc.nasa.gov/cgi/climatologies.pl. In order to utilise the instrumental possibilities to a greater extent, in this work averaged monthly, seasonal and annual maps and fields were produced with a spatial resolution of 1 km.

EXPERIMENTAL

Level 2 (L2) satellite data from approximately 10 000 SeaWiFS and MODIS files have been processed with the SeaDAS (SeaWiFS Data Analysis System) software package. The pixel sizes in a satellite image are not equal so binning process was applied to the daily data files for obtaining 1 km resolution data. Usually the Black Sea is not covered in a single pass of the satellite, hence data files corresponding to the same day have to be combined and binned to obtain single data file for that day. In that way L2 data files were converted to daily L3 (binned and mapped) files, which consequently were binned to monthly composites. Monthly files then were utilised to produce seasonal and annual composites. Automated scripts used to process datasets at every step (Fig. 1) and produce ASCII and graphic outputs.

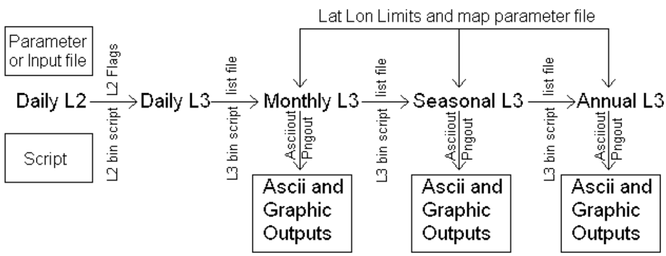

Fig. 1. Schematic representation of the data processing steps

Both Chl.*a* and SST data in L2 files are calculated using standard algorithms, so the resulted datasets are comparable with the global low resolution datasets available. Chl.*a* data have been processed by OC4 v.4 and OC3 algorithms for SeaWiFS and MODIS data, respectively (details of the algorithms can be found at http://oceancolour.gsfc.nasa.gov/DOCS/). Measurements in visible part of the spectrum are affected by artifacts like aerosols, sun glint, sun angle, high turbidity in water, so high number of quality flags (16) is needed to characterise Chl.*a* data. Quality flags like high sensor zenith angle, sun glint, etc., have been taken into account to improve data quality in Chl.*a* processing.

MODIS/Aqua SST is derived from the infrared measurements in the 11-μm range (bands 31 and 32 at 11 and 12 μm, daytime and nighttime) and 3–4-μm range (bands 22 and 23 at 3.959 and 4.050 μm, only nighttime). Only 'clean' pixels (i.e. pixels without any SeaDAS flag) were taken for further processing.

Like all passive sensors, SST and Chl.*a* sensors can not receive signal from the sea surface under cloudy conditions. In the Black Sea region SST and Chl.*a* measurements suffer from high level of cloud coverage, particularly during winter period. The amount of clear sky data obtained is relatively low. Since we are using only not flagged pixels, it decreases amount of data available for further processing even more: in case of SST, for example, all pixels in approximately 150 km zone from both sides of the satellite swath are rejected. For some the Black Sea passes data of required quality are totally absent. As a result, fields and maps in the monthly composites have gaps.

Attempt to reconstruct missing data to achieve full coverage of the Black Sea was undertaken with the DINEOF (Data INterpolating Empirical Orthogonal Functions) method[1,2]. The main advantages of this method are that it does not need *a priori* knowledge about the error statistics of the data, and that it can reconstruct big matrices in an accurate and fast way. From shortcomings of DINEOF is inability to reconstruct entirely clouded or missing images, and not well capturing of propagating features. The method was successfully applied for reconstruction of satellite SST images in the Adriatic Sea[2], sometimes in conditions of 75% cloudiness within several days.

DINEOF method was tested with SST datasets. Filling gaps in monthly fields by applying DINEOF directly to the temporal sequence of these fields would not be correct from the physical point of view, so missing values were reconstructed in daily fields (images), which then were average to obtain the monthly fields. Since spatial dimension of the images is quite large (730×1200), due to computing limitations it was not possible to fulfill calculations for the whole set of daily images at once. So for each month the separate sub-dataset was prepared consisting of about 40 sequential daily images from the corresponding month ±5 daily images from neighbouring months, and then DINEOF method was applied to these sub-datasets.

RESULTS

Resulting products contain two Chl. *a* datasets derived from SeaWiFS and MODIS sensors . The SeaWiFS dataset contains 88 monthly, 29 seasonal and 7 annual fields and maps for period September 1997, December 2004. The MODIS Chl.*a* dataset contains 66 monthly, 22 seasonal and 5 annual fields and maps for period July 2002 – December 2007. Chl.*a* field matrix has dimensions of 925×1500 points and covers the region of the Black Sea and Marmara Sea with approximate coordinates (48ºN, 24.5ºE) – (39ºN, 42ºE).

Totally three SST datasets (fields and maps) are included in the products: SST 11 μm day, SST 11 μm night, and SST 4 μm night. The reason of having 3 different SST datasets is as follows: the data obtained from the 'daytime' and 'nighttime' passes are kept separate because of the diurnal change in SST; the SST 11 μm and SST 4 μm data from 'nighttime' passes are not merged because even being obtained simultaneously they were calculated using different algorithms and still have differences which are investigated further on in this work. Each SST dataset contains 66 monthly, 22 seasonal and 5 annual fields and maps for period July 2002 – December 2007. SST field matrix has dimensions of 730×1200 points and covers only the Black Sea region with approximate coordinates (47.5ºN, 27ºE) – (40.5ºN, 42ºE).

RECONSTRUCTION OF MISSING SST DATA

The prepared SST sub-datasets were processed with DINEOF. Unfortunately, more or less satisfactory result was achieved only for summer months, which even without reconstruction are good enough. The main problem with DINEOF reconstructed fields is that missing values tend to be replaced with close approximations to the monthly means resulting in appearing of areas with overestimated SST at the northern part of the region and underestimated SST at the southern part of the region (Fig. 2).

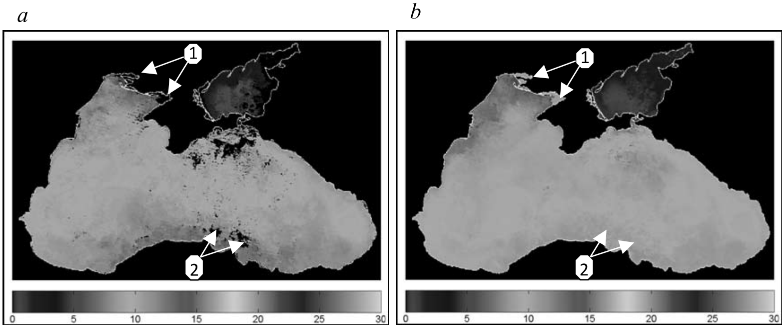

Fig. 2. Monthly SST 11 μm night, December 2004: *a* – original; *b* – reconstructed with DINEOF. In areas 1 SST is overestimated, in areas 2 SST is underestimated

Another problem is existing of long periods (up to ten days), when amount of good pixels in daily images does not exceed 10%. In such a situation DINEOF becomes not applicable, producing unreliable reconstructed daily images, which finally results in obtaining unrealistic monthly fields.

Detailed analysis of percentage of good pixels in initial data showed that its monthly average is only 24.3% for SST 11 μm day (Fig. 3), falling below 10% in winter and rising up to 50% in summer. So, for most time of year the DINEOF method is not applicable. The situation with availability of good pixels in 'night-time' SST is even worse. Changing time window for sub-datasets may improve DINEOF result, but finding optimal time window for every month is time-consuming and still does not ensure success. Since overall result of DINEOF reconstruction was not satisfactory, it was decided not to publish reconstructed maps and fields at the web site.

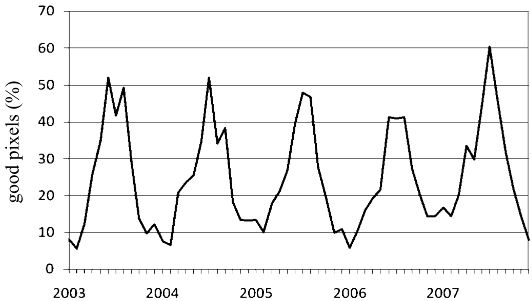

Fig. 3. Monthly average of good pixels in daily SST images (SST 11 μm day)

ANALYSIS OF SST DATASETS

Simple statistical characteristics. SST mean, standard deviation, minimum and maximum were calculated for each obtained monthly fields. The resulting graph for most representative SST 11 μm day is presented in Fig. 4. The statistical data for SST 11 μm night and SST 4 μm night are very similar and therefore are not provided here.

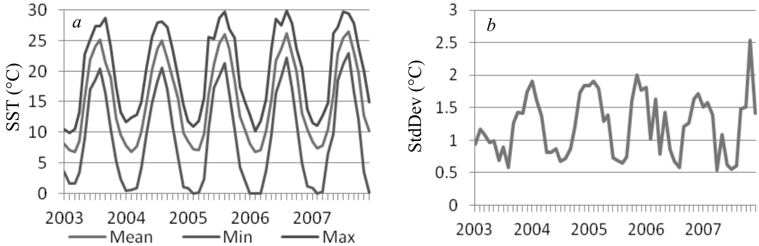

Fig. 4. Average SST 11 μm day for the Black Sea region: *a* – monthly mean, minimum and maximum; *b* – monthly standard deviation

The annual cycle of SST has minimum in January and maximum in August with global extreme values of 0 and 30.2ºC, correspondingly (due to processing software limitations possible negative values of SST were filtered from statistics). The standard deviation (SD) of regional SST has different annual cycle with minimum in July – August and maximum in November – January. Extremely high SD value of 2.54 was found in November 2007.

Inter-annual comparison of regional statistical characteristics revealed gradual rise of average monthly mean SST as well as average monthly minimum (except 2003) and maximim (Fig. 4 *a*, *b*).

Table 1. Regional yearly averages

Year	Annual mean	Average monthly minimum	Average monthly maximum
2003	15.04416	9.165608	19.18015
2004	15.26380	8.725108	19.84213
2005	15.51614	8.7356	20.30357
2006	15.53428	8.8838	20.46945
2007	15.96547	9.3927	20.78956

Annual mean increase of 0.92Cº within 5 years is observed, whereas average monthly maximum was rising faster and an increase of 1.6ºC is observed. Similar inter-annual course is observed for two other SST datasets as well. The representativeness of MODIS SST datasets is not enough to make conclusion about observing climatic changes in the region, however described above fact of gradual increasing of average SST in the region deserves to be further investigated in order to find its confirmation or disapproval using SST data obtained from other space platforms.

COMPARISON OF SST 11 μm DAY AND NIGHT

The main factor contributing to STT difference from the 'daytime' and 'nighttime' passes is diurnal variability in SST itself. Satellite-derived SST obtained in 10–12 μm spectral waveband represents the actual temperature of the water at a depth of approximately 10–20 μm, or skin SST. During the daytime, solar heating may lead to the formation of a near-surface diurnal warm layer, particularly in regions with low wind speeds, thus resulting in rising SST measured from satellites, whereas at nighttime skin temperature approaches the bulk temperature[3,4]. This effect can be clearly seen in maps, for the Black Sea particularly during summer period, when insolation is high and wind is low. For the event shown in Fig. 5, diurnal warming compared to the night is about 3.5ºC maximum, and >2ºC over a wide area in the western Black Sea.

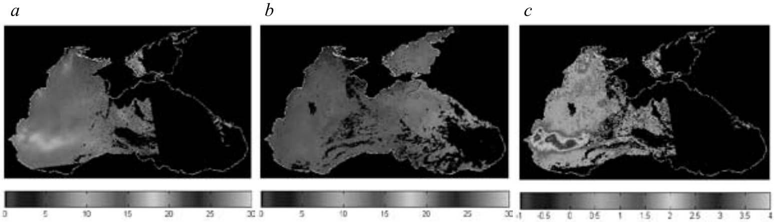

Fig. 5. Diurnal warming observed in the Black Sea on August 17, 2007: *a* – SST 11 μm day; *b* – SST μm night; *c* – SST difference (day – night)

Parameterisation of diurnal warming features is important for correct interpretation of satellite data, particularly if both day and night measurements are used to obtain daily temperature field. This task, which requires taking into account many factors such as diurnal variations of wind, solar radiation, air–sea interaction and so on, is being implemented by the Diurnal Variation Working Group (DV-WG) of the GODAE High Resolution SST Pilot Project (GHRSST-PP)[5].

In this work simple statistical approach was used to estimate diurnal STT magnitude. Daily means and standard deviations of differences between SST 11 μm day and night (ΔSST) were calculated for more than 1400 days when both passes were available. Preliminary analysis of the graph for obtained time-series revealed well-defined annual course of ΔSST, which is illustrated by scattering diagram in Fig. 6.

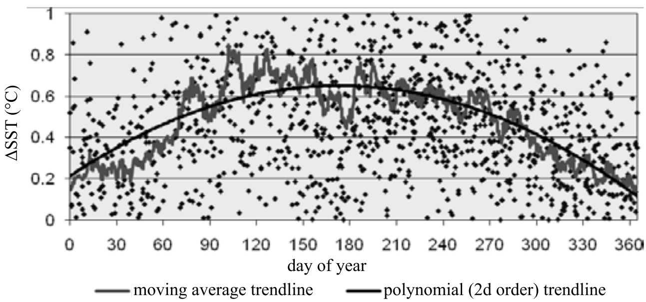

Fig. 6. Difference between SST 11 μm day and night (ΔSST) against day of year

The annual course of ΔSST has minimum in winter and maximum at the end of spring – beginning of summer, which corresponds to the Black Sea climatic conditions with relatively strong wind and low solar radiation in winter and low wind/high solar radiation in summer. Simple polynomial expression of second order describes statistical relationship between day and night SST:

$$SST_{night} = SST_{day} - 0.2133 - 0.0051d + 0.00001d^2, \text{ where } d \text{ is day of year.} \quad (1)$$

The SST_{night} from formula (1) can be used to estimate for bulk SST on the basis of MODIS SST 11 μm day data for the Black Sea.

Table 2 provides average for 5 years ΔSST statistics per months. The minimum ΔSST – about 0.2ºC – is in December, whereas maximum – about 0.7ºC – can be expected in April and May.

Table 2. Averaged monthly values of ΔSST

Month	1	2	3	4	5	6	7	8	9	10	11	12
Mean	0.24	0.32	0.55	0.71	0.70	0.58	0.65	0.60	0.55	0.41	0.28	0.19
SD	0.33	0.34	0.41	0.54	0.63	0.53	0.58	0.50	0.47	0.38	0.41	0.36

Comparison of SST 4 µm and SST 11µm night. Since both datasets are derived from simultaneous measurements, it was expected to find identical statistical for both of them. However, comparison of monthly means for the area of interest revealed bias of about 0.12ºC between SST 4 µm and SST 11µm (Fig. 7).

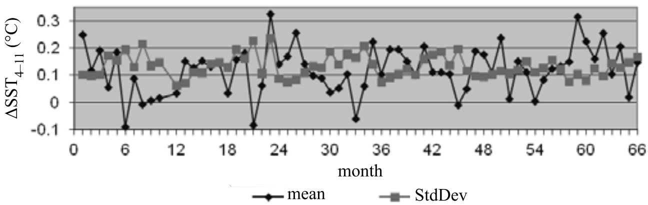

Fig. 7. Monthly means and standard deviations of difference between SST 4 µm and SST 11µm (ΔSST_{4-11})

Further investigations revealed that amount of good pixels in SST 4 µm and SST 11 µm datasets is not the same. In this case estimate of bias obtained from monthly fields is not correct because of different contribution of daily values into the monthly averages. Therefore, daily means and standard deviations of ΔSST_{4-11} were calculated (for 1480 days in total) and then frequency analyses (Fig. 8) was applied to estimate bias.

The ΔSST_{4-11} frequency function (the number of days with particular $\Delta SST_{4-1})_1$ has distribution close to normal with mean and median of 0.155ºC and standard deviation 0.2 (the standard normal distribution for current mean and standard deviation are also presented at the figure for comparison). Statistically SST 4 µm is warmer than SST 11µm on approximately 0.15ºC. It should be noted, that we did not find explanation to this fact in publications – perhaps it is localised in the Black Sea region only.

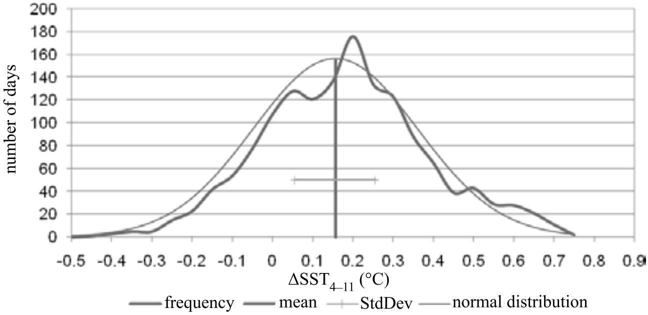

Fig. 8. $\Delta SST_{4\text{–}11}$ frequency

ANALYSIS OF CHL.*a* DATASETS

In contrast to the SST datasets, Chl.*a* datasets were derived from both SeaWiFS and MODIS sensors. These two platforms are designed for ocean colour studies but they are not the same. The algorithms used for derived Chl.*a* concentrations are different: SeaWiFS Chl.*a* is produced by using OC4, whereas OC3 is used for MODIS. Thus, the concentrations obtained are not exactly the same. While showing the same trends over the time (June 2002 to December 2004) in the Black Sea (Fig. 9), MODIS sensor gives higher values compared to SeaWiFS – about 0.13 or 7%.

The Black Sea average Chl.*a* concentrations over the years are fluctuating between 1998 and 2007 (Fig. 10). There are three periods appeared between 1998 and 2007. In 1999 the Chl.*a* concentration was at its peak level. After this year decreasing trend occurred until 2003, when it changed to increasing trend until 2007. Thus, fluctuations seem to have half-cycle of 4 years; however, this pattern needs to be confirmed by next years data.

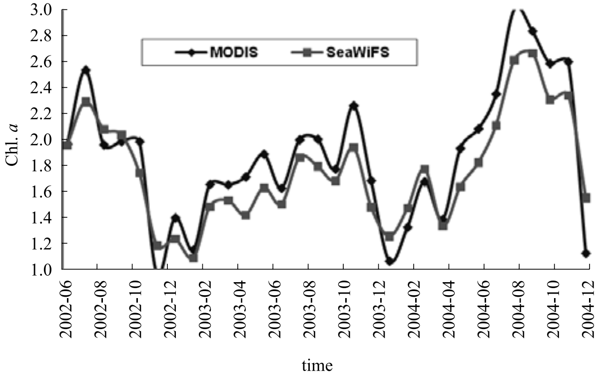

Fig. 9. Comparison of MODIS and SeaWiFS basin mean Chl.*a* in the Black Sea

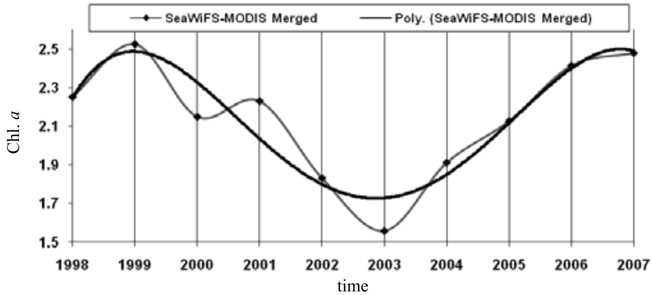

Fig. 10. Merged yearly averaged Chl.*a* concentrations of SeaWiFS and MODIS in the Black Sea and polynomial fit of the data (MODIS data shown here are normalised according to the mean difference from SeaWiFS)

CONCLUSIONS

Averaged monthly, seasonal and annual Chl. *a* and SST fields and maps with spatial resolution 1 km were produced for the Black Sea region and disseminated through Internet. DINEOF method was tested to reconstruct missing SST data in monthly fields. However, positive result was achieved only for summer months not resolving the problem for other seasons due to insufficiency of data required for this method, therefore reconstructed fields were not disseminated through the web site.

The obtained Chl.*a* and SST fields were statistically analysed and the following results were received:

• Chl.*a* is fluctuating in the region with half-cycle of 4 years;

• According to the data, bloom events in the Black Sea tend to occur in August–November;

• There is a slight (0.13 or 7%) difference between MODIS and SeaWiFS Chl.*a* concentrations;

• Effect of gradual rising of annual SST mean for the Black Sea region is observed (0.92ºC within 5 years from 2003 to 2007);

• Simple formula is proposed for statistical correction of MODIS SST_{day} affected by diurnal warming;

• There is a bias between SST 4 μm and SST 11 μm equal to ~ 0.15ºC.

Update of all obtained datasets is planned to be done yearly.

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