Realization Of A Dedicated Synergistic Study Of The White Sea Based On Spaceborne, Shipborne And Ecological Modeling Means

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Abstract- A new satellite-nonspecific algorithm for a simultaneous retrieval of content of such water quality proxies as phytoplankton chlorophyll (*chl*), suspended minerals (*sm*) and dissolved organics (*doc*) has been developed and applied for the surveillance of spatial and temporal dynamic in the water quality and productivity in the White Sea. Infrared and visible data were used to investigate the spatial and temporal distribution of water surface temperature and expressions of some hydrodynamic dynamic phenomena. The spaceborne data were backed up by shipborne *in situ* data as well as by hydrodynamic and biological numerical modeling. As a result, the conjointly analyzed multifaceted data constituted a veritable synergistic approach providing a considerably more adequate insight into a variety of in-water processes inherent in such semi-enclosed water bodies as the White Sea.

1.0 INTRODUCTION

The White Sea has recently become a subject of inquiry for scientists of various disciplines because of a new stage of development of natural resources both of the White Sea *per se* and its watershed. (Berger *et al.*, 2001). Located within the subpolar climatic zone between 68° 40'N and 63° 18'N and 32° 00'E and 44° 30'E in the northwestern part of Russia, the White Sea is connected to the Barents Sea, and thus constitutes part of the Arctic Ocean Basin. The water surface area reaches 9 x 10^4km^2, the maximum depth is 350 m, the mean depth is 67 m, and the total volume is 6 x 10^3km^3. In terms of the geomorphological classification, the White Sea is a marginal shelf sea. (Terziev *et al.*, 2001). In mid-summer, the water temperature in the White Sea bays, especially in Onega and Dvina Bays, can be as high as 19-20°C in the river deltas, and 10°C at the exit from the bays. In summer, the concentration of phytoplankton chlorophyll (μg/1) in the surface waters of Onega and Dvina Bays generally does not exceed 2, whereas in the Bassein within the permanent gyre it can reach 4. In the Bassein and the Voronka the vertical profile of *chl* peaks in the euphotic zone, however in Onega, Dvina, and Mezen Bays as well as in the Gorlo the vertical distribution of *chl* is mostly homogeneous (Sapozhnikov, 1994). This is due to the fact that the bays are shallow and the Gorlo is well mixed. Diatoms are the dominant species in the open areas of the sea, whereas in Onega Bay, Dinophyceae and Chrysophyceae are more abundant. The waters of the White Sea are rich in dissolved organic carbon (Arzhanova *et al*., 1994) and can be categorized as marine eutrophic waters (Mordasova and Venzel, 1994). Therefore, they are definitely non-case I waters, according to the Morel classification (Morel and Prieur, 1977).

The continental character of the White Sea climate is accounted for by its geographical position, implying relatively warm summers and long severe winters. The air temperature may reach +30°C; however, it normally does not exceed 15-20°C. (Berger *et al.*, 2001, Filatov *et al.*, 2005).

The present knowledge of the White Sea ecosystem's intrinsic functioning and its dynamics remains insufficient and requires further extensive interdisciplinary studies. However, such investigations are seriously hampered by severe weather conditions and can only be performed during 4 – 5 months when there are sufficiently vast ice-free areas in the White Sea suitable for shipborne investigations. Under favorable weather and light conditions spaceborne remote sensing first of all in the visible and infrared, can efficiently contribute to exploring the spatial and temporal variations of the water quality and trophic status of the White Sea.

Since the primary productivity (which can be assessed from space via the concentration of *chl*) depends on nutrients and light availability an hence on river discharge and cloudiness, monitoring of the White Sea water quality alterations can be indicative of the regional climate change. Besides, the White Sea is part of the Arctic Basin which is known to be highly sensitive to climate change.

The data provided by SeaWiFS, MODIS and MERIS are widely used for natural water quality assessment. However, the period of operational exploitation of these satellites (the SeaWiFS was launched in 1998 and MODIS and MERIS even later) is rather short compared to the scale of climate variations. Notwithstanding this limitation, multi-year satellite monitoring can be a valuable complementary means in comprehensive studies of marine environment.

2.0 REMOTE SENSING METHODOLOGY

For processing satellite images obtained in the visible we applied our advanced operational algorithm for the retrieval of the so-called colour-producing agents (CPAs) encompassing first and foremost *chl*, suspended minerals (*sm*) and dissolved organic matter (*doc*) (Pozdnyakov *et al.*, 2004a). With a given accuracy threshold and for certain hydro-optical conditions the developed algorithm remains sufficiently robust to input data with the noise as high as 15%. To avoid inadequate retrieval results, the algorithm identifies and eventually discards the pixels with inadequate atmospheric correction and/or water optical properties incompatible with the applied hydro-optical model. The algorithm is based on a combination of the Levenberg-Marquardt multivariate optimization procedure and neural networks. (Pozdnyakov *et al.*, 1999).

Infrared images were processed by the algorithm developed by the MODIS Ocean Team Computing Facility (Brown *et al.*, 1999). The sea surface temperature (*sst*) determination is based on satellite infrared retrievals of ocean temperature, which are corrected for atmospheric absorption using combinations of several MODIS mid- and far-infrared bands.

3.0 THE UTILIZED REMOTE SENSING DATA

The visible data were downloaded from two satellite sensors, namely SeaWiFS and MODIS. The sea surface temperature data were downloaded as a ready for use product from MODIS (Morel, 1998). For the analyzed period of satellite monitoring extending from 1998 to 2004 the overall number of multispectral images is only 536 while the number of IR images is 152. Due to cloud screening and wrong atmospheric correction none of the images contain the CPA spatial distributions for the *entire* White Sea. To obtain continuous spatial distributions of the CPAs, the retrieval results were merged and image mosaics were created for each month during the entire phytoplankton vegetation cycle from May 1 till September 30.

The results of retrieval of *chl*, *sm*, *doc* and *sst* obtained through the application of our methodology to MODIS and SeaWiFS imageries are shown in Fig. 1. The averaged spatial distributions of CPAs and *sst* are arranged in the figure in the from of a “table”. The columns refer to the retrieved variables (*chl, doc, sm* and *sst*) and rows accommodate the mosaics for the respective months (May, June, July, August, September). The color scale for the mosaics is presented in Fig 2.

To obtain continuous spatial distributions of the CPAs, the retrieval results were merged and image mosaics were created for each month during the entire phytoplankton vegetation cycle from May 1 till September 30. Each mosaic was calculated using all satellite images that were taken within the corresponding month throughout all years of the sea spaceborne monitoring. The CPA concentration in each pixel of a mosaic was obtained as a mean value of nonzero pixels with the same position in all utilized satellite images.

4 ANALYSIS OF THE OBTAINED SPATIAL DISTRIBUTIONS

Concentrations of *chl* are most pronounced in Dvina, Onega and Mezen Bays throughout the entire vegetation period and especially high in spring and early summer. A high discharge rate of river waters containing ample amounts of nutrients determines the phytoplankton growth intensity in these regions during that time. The latter is proved by the fact that the river waters are also rich in *sm* and *doc* and clearly visible in satellites images in May and June. In mid-summer and early fall, due to a decreased river discharge rate and nutrient depletion, the *sm* and *chl* concentrations are low and *doc* is almost absent. Considerably high concentrations of *chl* in the Bassein in May are followed by low concentrations in June and July but they slightly increase in August and September.

The plume of enhanced *chl* and *sm* concentrations in the Gorlo Strait near the Zimny Coast originates from Dvina Bay. The bay water masses containing enhanced *sm* and *chl* concentrations are driven to the Gorlo by a coastal current (Berger *et al.*, 2001).

The similarity of *chl* and *sst* distributions in May, which disappears in June, reveals that water heating in the White Sea starts due to river discharge and continues due to the solar irradiation. The frontal zone, which occurs in Dvina Bay in May, is evident in all visible and IR images taken during that month. The other front between the Bassein and Gorlo is apparent only in the IR images taken in June, July and August. The low *sst* values in the vicinity of the Solovetsky Archipelago indicate the presence of a persistent upwelling in this area. The latter is in compliance with the known oceanographic data (Terziev *et al.*, 2001). A high variability of *sst* in different parts of the White Sea in spring and summer is followed by an almost homogeneous water temperature field in autumn.

5. ANALYSIS OF THE OBTAINED TIME SERIES

In order to quantitatively analyze inter-annual water quality variations in the White Sea we calculated two time-series of the averaged CPA concentrations. Each entry in the first time series was calculated as a *chl* concentration averaged over the entire sea for each year. In the second time-series *chl* concentrations were averaged solely over Dvina Bay. The time series are presented in Fig. 3 (for the entire White Sea) and Fig. 4 (for Dvina Bay only).

On both figures one can see a slight decrease of *chl* concentrations throughout the time period 1998 – 2004. In the entire marine basin the variability of *chl* mean concentration is less that it is in Dvina Bay. Such a decrease is in accordance with the known data on climate variations in the White Sea (Filatov et al., 2005).

6. VALIDATION OF THE RETRIEVAL RESULTS

The adequacy of the CPA concentrations retrieved by our algorithm was quantitatively proved through comparing *chl*, *doc* and *sm* field observations in the White Sea with the values retrieved from the satellite data. Qualitative comparisons of *in situ* and retrieved data indicate that the spatial patterns of CPA distributions and their development throughout the year comply closely with the known oceanographic data (Pozdnyakov et al., 2004a, Pozdnyakov et al., 2004b).

The validity of the obtained results was also checked though the comparison of the retrieved CPA and *sst* values with the values obtained in numerical simulations. (Bashmachnikov *et al.*, 2005). A qualitative validation, which was based on the visual comparison of both the average spatial distributions of the retrieved *chl* and simulated phytoplankton biomass contents, showed a good agreement between these sets of data.

In order to conduct a quantitative validation, we compared the temporal dynamics of the remotely observed *chl* and simulated phytoplankton abundance. The correlation between the time-series of *chl* and phytoplankton contents averaged over the entire White Sea amounts to 80% and over Dvina Bay it constitutes 85%.

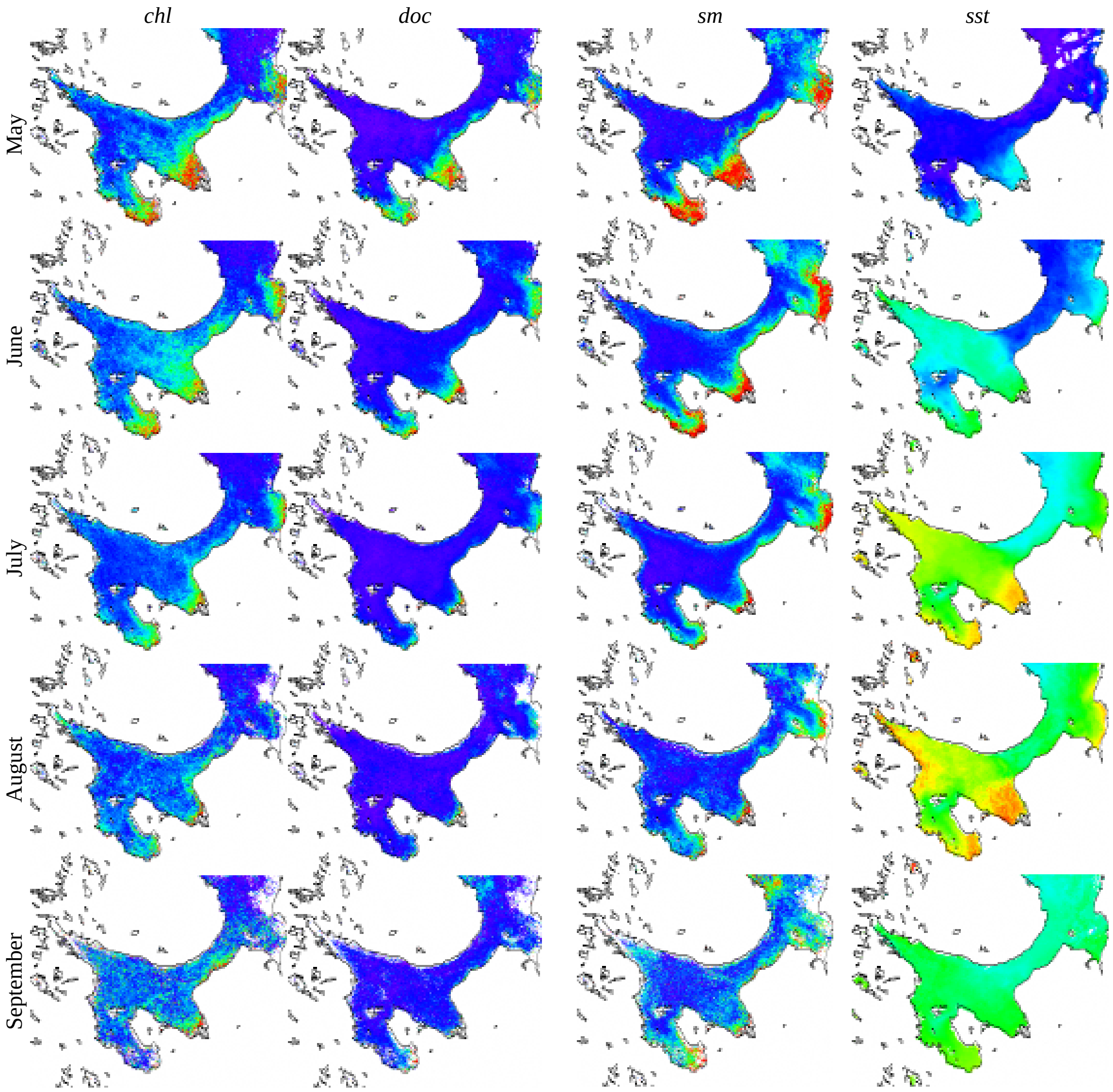
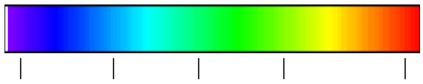


Figure 1. Spatial distributions of the retrieved CPA concentrations and *sst*.



chl	0	2.5	5	7.5	10	ug/l
doc	0	2.5	5	7.5	10	mCg/l
sm	0	0.75	1.5	2.25	3	mg/l
sst	0	5	10	15	20	^{0}C

Figure 2. Color scales for the images in Fig 2

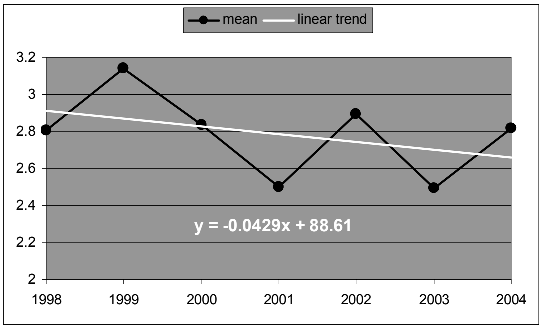


Fig. 3. *chl* concentrations averaged over the entire White Sea. Mean, maximum and minimum values for each year are presented. The revealed linear trend and the corresponding equation are also shown.

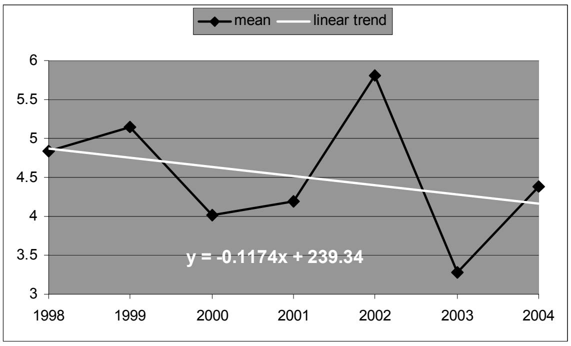


Fig. 4. *chl* concentrations averaged over Dvina Bay. Mean, maximum and minimum values for each year are presented. The revealed linear trend and the corresponding equation are also shown.

7. CONCLUSIONS

The data presented in Fig. 2 are believed to be the first mosaics obtained by averaging *chl*, *sm*, *doc* and *sst* spatial distributions in the White Sea throughout the year. A methodology for multi-year spaceborne data archiving and processing was developed in order to facilitate long-term studies of the climate change in the Arctic by means of multispectral remote sensing.

The applied synergistic approach, which consists in a combined use and analysis of satellite data obtained in the visible and IR as well as data from numerical simulations, was employed in this study and provided a considerably more adequate insight into a variety of in-water processes inherent in the White Sea.

Notwithstanding the shortness of the monitoring period, a distinct temporal trend of *chl* variability was revealed, and it was found that the *chl* concentrations only slightly decrease throughout 8 years. The observed trend indicates that climate change has not appreciably affected the White Sea ecosystem.

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