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Satellite evidence of ecosystem changes in the White Sea: A semi-enclosed arctic marginal shelf sea

Dmitry V. Pozdnyakov,[1,2] Ola M. Johannessen,[2] Anton A. Korosov,[1] Lasse H. Pettersson,[2]
Hartmut Grassl,[3] and Martin W. Miles[4,5]

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[1] Recent observations suggest an arctic climate system in broad transformation, yet the regional marine-ecosystem response is poorly known. Here, we develop and analyze a comprehensive biogeophysical dataset of key water constituents – chlorophyll (*chl*), suspended sediments (*sm*) and dissolved organic matter (*doc*) – using satellite ocean-color data from the White Sea in the Russian Arctic, for the period 1998–2004. The revealed changes in *chl*, *sm* and *doc* are more pronounced in the bays (e.g., the southeastern bay trends are −20%, +18% and +11%, respectively) than in the central basin (−5%, +5% and +3%, respectively). The chlorophyll decreases reflect the impact of enhanced runoff on *sm* and *doc*, which make the water more turbid and less favourable for phytoplankton growth, in contrast to other arctic seas where *increased* phytoplankton is expected. This case study supports our hypothesis that the marine ecosystems of semi-enclosed arctic shelf seas respond rapidly to climate change and are thus particularly vulnerable to future global warming.

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1. Introduction

[2] Observational data and numerical model experiments consistently indicate global climate change to be amplified in the Arctic, with a multitude of environmental effects [*Bobylev et al.*, 2003; *Arctic Climate Impact Assessment (ACIA)*, 2004]. Rising temperatures, increasing precipitation and river runoff, retreating sea ice and other ocean–atmosphere changes [e.g., *Johannessen et al.*, 2004] may drastically affect the marine ecosystems of the Arctic Ocean and its marginal seas. Recently, changes in species abundance and distribution have been observed within arctic–subarctic marine ecosystems, apparently in response to climate change, e.g., the ensemble of changes in the Bering Sea suggesting "a continued trend toward more subarctic ecosystem conditions" in its northern arctic region [*Grebmeier et al.*, 2006]. However, the regionally varying marine ecosystem response to climate change is generally poorly known, especially for the Russian Arctic.

[3] The White Sea is a semi-enclosed shelf sea in the Russian Arctic (Figure 1). There have been fragmentary indications of manifestations of climate change in the White Sea in recent years. The mean annual air temperature in the White Sea basin increased by 0.8°C from 1990–99 and continued to rise even more strongly (2.1°C) from 1998–2005 (our study period) also warming the seawater [*Filatov et al.*, 2005]. The mean annual and winter (snow) precipitation in the White Sea basin increased over the latter time period by 3% and 8%, respectively [*Filatov et al.*, 2005; Global Precipitation Climatology Centre database, http://www.dwd.de/en/FundE/Klima/KLIS/int/GPCC/GPCC.htm]. Accordingly, river discharge into the sea has increased particularly during the melting period in spring and early summer [*Filatov et al.*, 2005]. Marine macrofaunal changes have been observed concurrently, e.g., a massive die-out of starfish caused by increased seawater temperatures [*Smourov and Komendantov*, 2003], as well as unfavorable dwelling conditions for the Greenland seals (*Phoca groenlandica*) due to a reduced sea-ice cover [*Melentyev et al.*, 2000, *Dumanskaja*, 2004; Arctic and Antarctic Research Institute, 2006, Satellite information services: Sea charts (in Russian), available at http://www.aari.nw.ru/clgmi/sea_charts/sea_charts.html].

[4] Therefore, we hypothesize the White Sea ecosystem to be in a transitional state due to climate change. In this light, an investigation of the status and dynamics of its marine ecosystem is highly warranted in itself and to provide inter-regional perspective for other arctic shelf seas and the Arctic Ocean proper. Insight into ecological consequences of physical changes in the White Sea can be obtained at the level of microalgae phytoplankton, which are fundamental to hierarchical marine food-web interactions. In contrast to the aforementioned Bering Sea study [*Grebmeier et al.*, 2006] which analyzed the transitional response to climate change from benthic levels to pelagic ones, we focus on the specific response of the algal community.

[5] An important indicator of phytoplankton abundance is chlorophyll (*chl*), the photosynthetic pigment universally present in algae. In addition to *chl*, dissolved organic matter (*doc*) is an important ecological parameter that reflects the water-body trophic level and, hence, the balance between the primary production and decomposition processes. Suspended minerals (*sm*) affect water transparency and therefore their concentration controls the light regime and, hence,

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[1] Nansen International Environmental and Remote Sensing Centre, St. Petersburg, Russia.

[2] Mohn–Sverdrup Center for Global Ocean Studies and Operational Oceanography, Nansen Environmental and Remote Sensing Center, Bergen, Norway.

[3] Max Planck Institute for Meteorology, Hamburg, Germany.

[4] Bjerknes Centre for Climate Research, Bergen, Norway.

[5] Environmental Systems Analysis Research Center, Boulder, Colorado, USA.

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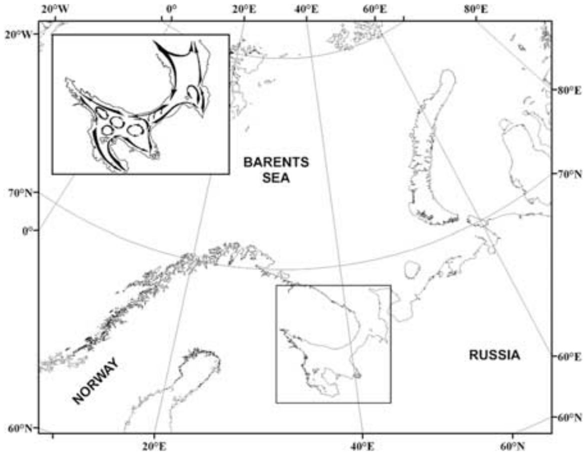

Figure 1. Location map of the White Sea and adjacent areas (lower box indicates study area). (inset) Schematic of mean surface-circulation features in the White Sea [from *Filatov et al.*, 2005].

ecology in the water column. Each of these water constituents affects water color, thereby providing the possibility to study the marine ecological status using optical sensors which measure the radiance upwelling from the water surface [*Jerlov*, 1976; *Pozdnyakov and Grassl*, 2003]. Given the sampling limitations of shipborne measurements, satellite remote sensing is the only feasible means to synoptically monitor and quantify biogeochemical changes across the White Sea over a multi-year period with high spatial and temporal resolution.

[6] Our objective is to identify the ecological state of the White Sea, through developing and analysing a comprehensive dataset comprised of *chl*, *sm* and *doc* retrieved from satellite ocean-color data. The research and results presented here are novel for at least two reasons. First, we develop the longest possible multi-year series based on Sea-viewing Wide Field-of-view Sensor (SeaWiFS) data. Second, we apply original and unparalleled methods of ocean-color data processing, namely: (1) an advanced bio-optical algorithm that simultaneously yields the concentrations of the three major color-producing agents (CPAs), which reflect not only the trophic state but also the light climate of the water body, and (2) an interpolation technique that mitigates data gaps due to clouds, thus providing a spatiotemporally complete water-quality dataset from which the intra-annual and interannual variability and trends in the White Sea can be identified.

2. Data and Methods

[7] The primary data are ocean-colour radiances from SeaWiFS for the period 1998–2004, obtained from the National Aeronautical and Space Administration (NASA) Goddard Space Flight Center (GSFC). The optical complexity of the White Sea waters (Case II) challenges the use of SeaWiFS data for retrieving the essential variables. In Case II waters, standard ocean-color algorithms developed for retrieving the content of *chl* and total suspended matter in clear open-ocean waters (Case I) haven proven to be invalid [*Kondratyev and Pozdnyakov*, 1999]. Moreover, standard *chl* algorithms cannot retrieve concentrations of *doc* and *sm*. We overcome these problems by using our recently developed algorithm that is capable of simultaneous retrieval of *chl*, *sm* and *doc* for both Case I and II waters [*Kondratyev and Pozdnyakov*, 1990]. The algorithm is based on a combination of neural networks and multivariate optimization procedures and outfitted with a number of quality-checking facilities that substantially enhance the retrieval accuracy and performance efficiency [*Pozdnyakov et al.*, 2005a, 2005b]. The algorithm has been validated quantitatively for the White Sea and other Case II waters in the Gulf of Finland, Lake Ladoga and the Great Lakes [*Pozdnyakov et al.*, 2005a, 2005b; *Shuchman et al.*, 2006] – see details in the auxiliary material[1]. The algorithm's efficacy has been further assessed qualitatively by thoroughly examining the conformance of the satellite-derived spatial and temporal distributions of the above variables with the fundamental hydrodynamic and hydrobiological processes inherent in the particular water body [*Korosov et al.*, 2006; *Shuchman et al.*, 2006].

[8] We also retrieved sea-surface temperature (SST) from the Advanced Very High Resolution Radiometer (AVHRR) using the most accurate-to date algorithm, taking into account the effect of surface film [*Robinson*, 2004]. For each of the parameters retrieved from both SeaWiFS and AVHRR, additional processing was performed, summarized as follows (and detailed in the auxiliary material). For each pixel, the satellite information for each variable was individually accumulated for the ice-free season of each year, yielding – through our recently developed spatiotemporal interpolation technique [*Korosov et al.*, 2006] – a continuous time series of 5-day averaged images at 1-km spatial resolution. The resulting sequences document the 7-year mean spatiotemporal variability of *chl*, *sm*, *doc* and SST through the seasonal cycle May 1 – September 30. (It should be noted that we were not able to investigate the effect of reduced sea ice in detail, due to retrieval limitations caused by ice-contaminated pixels during the melting period coinciding with the initial spring algal bloom.)

[9] Further, these data have also been aggregated into the seven regions commonly identified in the White Sea: Four are the principal bays (areas I, II, III, IV in Figure 2a), relatively shallow and with the estuaries of inflowing rivers; one is the transition zone (area V) to the Barents Sea; and two others are the central, deepest part of the sea (area VI) and the channel region (area VII). This could not be done for areas IV and V because of frequent cloud cover. The result is five regional time series of *chl*, *sm*, and *doc* concentrations for the ice-free season in each year 1998–2004, with the satellite data (300 images for each year, $\sim$ 2200 images in total) averaged for each year. These time series are the basis for identifying interannual variability and trends.

3. Results: Intra-Annual Variability

[10] The mean spatiotemporal variability of *chl*, *sm*, *doc* and SST in the White Sea through the phytoplankton vegetation seasonal cycle May 1 – September 30 is

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[1] Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2006gl028947. Other auxiliary material files are in the HTML.

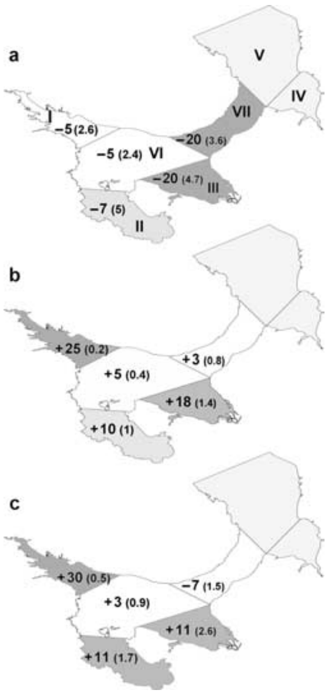

Figure 2. Linear trends (%) in regional variations of concentrations of (a) chlorophyll *chl*, (b) suspended minerals *sm*, and (c) dissolved organic content *doc*, in surface waters during the phytoplankton vegetation period, May 1–September 30, in the White Sea, as obtained from SeaWiFS data, 1998–2004. Numbers in parentheses are the mean annual baseline concentrations of *chl* (μg/l), *sm* (mg/l), and *doc* (mgC/l) for 1998. Shading indicates magnitude of trends. Roman numerals in Figure 2a indicate regions specified in the text. Light gray-shaded areas IV and V in the northeast indicate insufficient data due to frequent cloudiness.

revealed in Figure 3. Figure 3 depicts the –year spatiotemporal variability of *chl*, *sm*, and *doc* at 20-d intervals through the seasonal cycle. Dynamic versions of each sequence at 5-d intervals are available online as Animations S1–S3 in the auxiliary materials, in addition to SST at the same 5-d time steps.

[11] These image sequences reveal the dependence of the water quality parameters on river runoff and circulation in the White Sea. Due to persistent coastal currents, the riverborne *sm* and *doc* are advected from the bays into the central region and the channel and spread there due to mesoscale eddies and tidal currents (*Filatov et al.* [2005] and Figure 1 inset), an interpretation supported by high-resolution (5 km) numerical-model simulations for the same period [*Filatov et al.*, 2005].

4. Results: Interannual Variability and Trends

[12] The interannual variability of *chl*, *sm* and *doc* proved to be smooth enough (see auxiliary Figure S1) for some statistically significant (s = 0.01) linear trends to be identified (Figure 2). In the two southern bays (areas II and III), the content of *sm* and *doc* increased by respectively 10 and 18%, while the *chl* decreased by 20%. The northwesternmost bay (area I), relatively deep and previously with very clear water, shows an even higher increase of water turbidity due to *sm*, and opacity due to *doc*, whose concentrations grew by up to 25% and 30%, respectively (Figures 2b and 2c). These changes in *sm* and allochthonous *doc* are consistent with the increased river runoff due to the observed enhanced annual (3%) and winter (8%) precipitation over land (*Filatov et al.* [2005] and auxiliary Figure S3).

[13] The variation of the regional trends in the water constituents (*sm* and *doc*) also revealed their dependence upon both the river runoff and the water circulation in the White Sea, as described above. The central part, which is essentially the pelagic marine area of the White Sea, shows only a few percent increase in *sm* and *doc* – 5% and 3% respectively. Variations of *sm* and *doc* in the channel are governed partly by the advection of the southern bay waters (enriched in both *sm* and *doc*) due to counter clockwise coastal currents and the inflowing Barents Sea water [*Filatov et al.*, 2005].

[14] In contrast, the phytoplankton *chl* concentration decreases across the sea over the study period (Figure 2a, see also auxiliary Figure S1a). For instance, in area III with the maximum increase in the content of *sm* and *doc*,

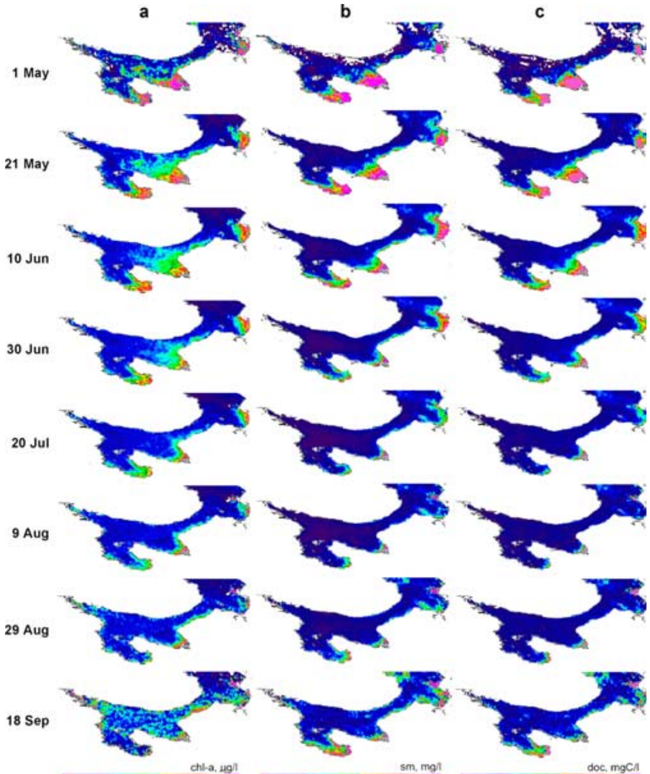

Figure 3. Spatiotemporal variability of satellite-retrieved concentrations of (a) chlorophyll *chl*, (b) suspended minerals *sm*, and (c) dissolved organic content *doc*, in the White Sea through the phytoplankton vegetation season, May–September, averaged over the 7-yr study period, 1997–2004. The seasonal progression is shown here at 20-d intervals: 1 May, 21 May, 10 Jun, 30 Jun, 20 Jul, 09 Aug, 29 Aug, and 18 Sep. Dynamic versions of each sequence at 5-d intervals are available as Animations S1–S3 in the auxiliary materials, in addition to sea-surface temperature (SST) at the same 5-d time steps.

the *chl* concentration decrease is as high as 20%. It decreases less in the northwesternmost bay (area I, 5%), the central area (area VI, 5%) and the southernmost bay (area II, 7%) because the river runoff influence is lower there [*Filatov et al.*, 2005]. For the bays, the decrease in *chl* can also be explained by the enhanced precipitation-driven river discharge that increases water turbidity and opacity due to *sm* and allochthonous *doc*, respectively [*Pozdnyakov et al.*, 2005b].

5. Conclusions

[15] We conclude that the observed decrease in *chl* in the White Sea – which is in contrast to other arctic–subarctic seas where *increased* phytoplankton is expected [*ACIA*, 2004; *Richardson and Schoeman*, 2004] – is caused by the enhanced concentrations of *sm* and *doc*, which are responsible for less light penetration into the water column, causing less favourable algal-bloom growth conditions. This conclusion is supported by the fact that the cloudiness, also assessed using the SeaWiFS data, did not increase significantly. Interestingly, the decrease of *chl* proceeds in spite of higher nutrient concentrations in the bay waters, due to the land- and river-runoff increases [*Filatov et al.*, 2005], again implying the dominance of the *sm* and *doc* in reducing the marine primary production.

[16] Thus, the present study reveals that marine ecosystem alterations driven by climate change are not necessarily triggered exclusively by direct warming of the water column. There is at least another mechanism of exertion of influence of this global process: increased precipitation and, hence, runoff can lead to significant enhancement of water turbidity. The consequences of this effect are at least twofold: (1) reduction of the indigenous phytoplankton photosynthetic activity and algal biomass accrual, and (2) impairment of the inherent trophic interactions when due to decreased underwater visibility, the fish fail to amply consume zooplankton, and thus unreduced population of the latter graze out more phytoplankton [*Asknes et al.*, 2004]. Therefore, the net result of this twofold effect is a reduction of primary production, which is a key parameter of all aquatic ecosystems.

[17] Importantly, this mechanism comes into action nearly immediately with increased runoff, whereas water column warming is a rather inertial process. Based on our study, we contend that the ecosystems of marginal, especially semi-enclosed arctic seas, exemplified by the White Sea, due to the revealed mechanism respond rapidly to regional climate change and therefore are particularly vulnerable to future global warming.

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H. Grassl, Max Planck Institute for Meteorology, Bundestrasse 53, D-20146 Hamburg, Germany.

O. M. Johannessen and L. H. Pettersson, Mohn–Sverdrup Center for Global Ocean Studies and Operational Oceanography, Nansen Environmental and Remote Sensing Center, Edvard Griegsvei 3a, N-5008 Bergen, Norway.

A. A. Korosov and D. V. Pozdnyakov, Nansen International Environmental and Remote Sensing Centre, B. Monetnaya, 26/28, St. Petersburg 197101, Russia. (dmitry.pozdnyakov@niersc.spb.ru)

M. W. Miles, Environmental Systems Analysis Research Center, 4450 Arapahoe, Suite 100, Boulder, CO 80303, USA.