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ATMOSPHERIC COLUMNAR CO_2 ENHANCEMENT OVER *E. HUXLEYI* BLOOMS: CASE STUDIES IN THE NORTH ATLANTIC AND ARCTIC WATERS

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Blooms of a coccolithophore *E. huxleyi* are generally huge, occur annually and in the oceans of both Hemispheres. As a calcifying algal species, *E. huxleyi* is known to enhance the partial pressure of dissolved CO_2 in the surface ocean, thus reducing its ability to absorb atmospheric CO_2. Here we report on the results of our satellite study of CO_2 enhancement in the atmospheric column over *E. huxleyi* blooms in the North, Greenland, Iceland and Barents seas. The study is based on OCO-2 and wind force and direction data, and *E. huxleyi* bloom masks developed by us earlier. Eight case studies are discussed herein relating to the time period 2015–2018. The results obtained are strongly indicative that, indeed, the phenomenon of *E. huxleyi* blooms noticeably affects the carbon fluxes between the atmosphere and the surface ocean: the quantified enhancement of CO_2 content in the atmospheric column over the bloom area in five out of eight case studies proved to be in the range of 0.6–3.0 ppm. It is also shown that the magnitude of CO_2 enhancement in the atmospheric column is significantly controlled by air advection in the boundary layer.

K e y w o r d s: satellite remote sensing; OCO-2 data; enhancement of atmospheric columnar CO_2 content over *E. huxleyi* blooms in Subarctic and Arctic seas; *Emiliania huxleyi*; wind and atmospheric advection.

Е. А. Морозов, Д. В. Кондрик, С. С. Чепикова, Д. В. Поздняков. УВЕЛИЧЕНИЕ КОНЦЕНТРАЦИИ CO_2 В АТМОСФЕРНОМ СТОЛБЕ НАД ОБЛАСТЬЮ ЦВЕТЕНИЯ *E. HUXLEYI*: КОНКРЕТНЫЕ СЛУЧАИ В ВОДАХ СЕВЕРНОЙ АТЛАНТИКИ И АРКТИКИ

В этой краткой статье сообщается о результатах спутниковых исследований по увеличению содержания CO_2 в атмосферном столбе над цветениями *E. huxleyi* в Северном, Гренландском, Исландском и Баренцевом морях. Исследование базируется на данных космической станции OCO-2 по содержанию CO_2 в атмосферном столбе, на спутниковых данных о силе и направлении приводного ветра, с использованием ранее нами разработанных масок цветений *E. huxleyi.* Всего было выявлено и исследовано восемь конкретных случаев за период с 2015 по 2018 гг., когда траектория пролета станции OCO-2 пролегала по области цветения и выходила за ее пределы, что позволяло оценивать влияние цветения *E. huxleyi* на содержание CO_2 в атмосферном столбе. Полученные результаты однозначно свидетельствуют о влиянии исследуемого явления на потоки углерода на границе раздела «атмосфера-океан». В пяти случаях из восьми увеличение CO_2 в атмосферном столбе над областью цветения *E. huxleyi* оказывалось в диапазоне 0,6–3,0 ppm. Выяснено, что конкретная величина увеличения в некоторых случаях существенно зависит от адвекции воздушных масс в приграничном слое.

Ключевые слова: спутниковое дистанционное зондирование; данные ОСО-2; увеличение концентрации CO_2 в атмосферном столбе над цветениями *E. huxleyi* в морях субарктической Атлантики и Арктики; *Emiliania huxleyi*; ветер и адвекция воздушных масс.

Introduction

Among marine biosystems, coccolithophores (class Prymnesiophycea) are the most productive calcite-producing organisms in the world's oceans [Thierstein, Young, 2013]. Dissolved carbon dioxide of atmospheric origin interacts with dissolved calcite with the formation of HCO_3^- and Ca^{+2}. Thus, any increase in the partial pressure of atmospheric CO_2 leads to a shift between the marine suspended organic and inorganic carbon. This, in turn, is bound to affect the carbon cycle in the atmosphere – ocean surface balance.

In addition to the production of particulate calcite, coccolithophores are capable of increasing dissolved CO_2 partial pressure within their blooming areas [Holligan et al., 1993; Kondrik et al., 2018].

Conjointly, these two mechanisms affect the carbon balance in surface ocean and tend to weaken marine carbon sinks, which has far-reaching consequences in terms of planetary climate change [IPCC, 2014].

Within the coccolithophore group, *E. huxleyi* is the most widespread species in the world's oceans [Westbroek et al., 1985; Moore et al., 2012]. It forms gigantic blooms with a surface of several thousand square kilometers [Kondrik et al., 2017], but sometimes exceeding one million square kilometers [Balch et al., 2014].

The aforementioned *E. huxleyi* bloom-driven enhancement of dissolved CO_2 partial pressure can reduce, nullify or even reverse the flux of CO_2 at the atmosphere-ocean interface. Indeed, Shutler et al. [2013] report on an average reduction in the monthly air-sea CO_2 flux by about 55 % across the marine tracts encompassing extensive *E. huxleyi* blooms in the North Atlantic, whereas the maximum reduction over the time period 1998–2007 was registered at 155 %.

Here we present our results on several case studies in the North, Iceland, Greenland and Barents seas. The study was designed to quantify the atmospheric columnar CO_2 over *E. huxleyi* blooms based on remote sensing data from the Orbiting Carbon Observatory OCO-2 that was put into orbit in 2014 to study CO_2 concentration and spatio-temporal distribution in the Earth's atmosphere [Crisp, 2015]. The areas targeted in the above seas were identified in advance making use of *E. huxleyi* bloom masks developed on the basis of ocean color data from the ocean-colour climate-change initiative OC CCI data archive [Sathyendranath, Krasermann, 2014].

Methodology

Previously, based on the developed bloom masking technology, i. e. the methodology *of E. huxleyi* bloom detection and contouring, the 1998–2018 time series of blooms of this alga were obtained for the Subarctic Atlantic and Arctic Seas [Kondrik et al., 2019; Selyuzhenok et al., 2019]. For the revealed locations of *E. huxleyi* blooms, the 2015–2018 OCO-2 data were subjected to sieve analysis in order to ascertain the cases of OCO-2 footprint trajectory crossing both the bloom area and adjoining bloom-free waters. The identified situations were further analyzed as case studies in order to investigate on a quantitative basis if there was any impact of *E. huxleyi* bloom areas on XCO_2 registered by OCO-2. Thus, to assess the impact, XCO2 values registered along the OCO-2 footprint both over the bloom area and beyond it (either prior to reaching the bloom area or after leaving it) were compared. The resultant change in XCO_2, i. e. ΔXCO_2, was considered as a measure of the *E. huxleyi* bloom impact on the CO_2 exchange at the atmosphere-sea water interface, and hence, of the change in the CO_2 atmospheric columnar content.

All case studies also included the analysis of above water surface wind force and direction over the bloom area in order to clarify the issue of air mass advection across the satellite footprint trajectory.

Data sources

Wind data. 8-day averaged satellite data from Cross-Calibrated Multi-Platform (CCMP) data http://www.rmss.com/measurements/wind/ were employed for the time period prior to 2016 (http: www.rems.com/measurements/ccmp/). CCMP gridded surface vector winds are generated through concatenation of satellite, moored buoy, Change of XCO_2 (ppm) over *E. huxleyi* bloom areas in the Barents, Iceland, Greenland and North seas as recorded with the OCO-2 instrument within the time period 2015–2018

Case number	Sea	Start of 8-day time interval	XCO_2 over bloom	XCO_2 beyond bloom	ΔXCO_2	Wind force (m/s) and direction
1	Barents	28.07.2015	393.6	393.0	0.6	4.6 E
2	South Iceland	12.07.2015	396.5	395.0	1.5	6.1 NNE
3	South Greenland	12.07.2015	397.0	394.0	3.0	3.0 WSW
4	South Iceland	24.05.2016	404.0	404.0	0	4.9 S
5	South Iceland	01.06.2016	404.0	402.0	2.0	3.3 ESE
6	North	17.05.2018	410.0	410.0	0	4.9 NE
7	North	18.06.2018	408.0	407.0	1.0	8.4 NW
8	North	26.06.2018	406.0	406.0	0	3.1 N

and simulated wind data. Thus conjoined, these mutually harmonized data qualify as Level-3 ocean vector wind analysis product. Through the involvement of improved and extended input data, the CCMP product was updated up to the CCMP V2.0 data set that is reachable at the Remote Sensing Systems (RSS) portal. This updated data set combines RSS-7 V. 7 radiometer wind speeds, QuikSCAT and ASCAT scatterometer wind vectors, wind speed actually measured from moored buoys, and ERA-Interim wind spatial distribution simulated with the Variational Analysis Method (VAM). The resultant product is four maps at a daily temporal and 0.25° spatial resolution.

In the case of the North Sea 2018, CCMP are unavailable, and in their stead ASCAT data, version 2.1 were exploited (http://www.remss.com/missions/ascat/). To better harmonize scatterometric and radiometric wind measurements, the ASCAT data were generated with the use of a new Geophysical Model Function, C-2015.

Thus, the wind vectors that are laid upon the maps illustrating our case studies represent 8-day wind force and direction averages specifically over the areas of *E. huxleyi* blooms.

Atmospheric CO_2 content. The column averaged dry air mole fraction, XCO_2 is defined as the ratio of "the altitude-dependent CO_2 number density integrated over the atmospheric column and the column abundance of dry air" [Crisp, 2015].

Having a 16-day ground-track repeat cycle, OCO-2 yields XCO_2 values with single-sounding random errors in the range of 0.5–1 ppm at solar zenith angles up to 70°, and at the spatial resolution of 3 km^2 in nadir, i. e. 1.25 km in width and ~2.4 km in length, which corresponds to a ~1.8 mrad instantaneous field of view and 3 Hz sampling. In 2018, the OCO-2 data processing algorithms were improved at NASA, and the current and retrospective products (L1B/L2 Version 8 and L2LiteFileVersion 9; October 10, 2018) were released (https://docserver.gesdisc.eosdis.nasa.gov/public/project/OCO/OCO2_DUG.V9.pdf).

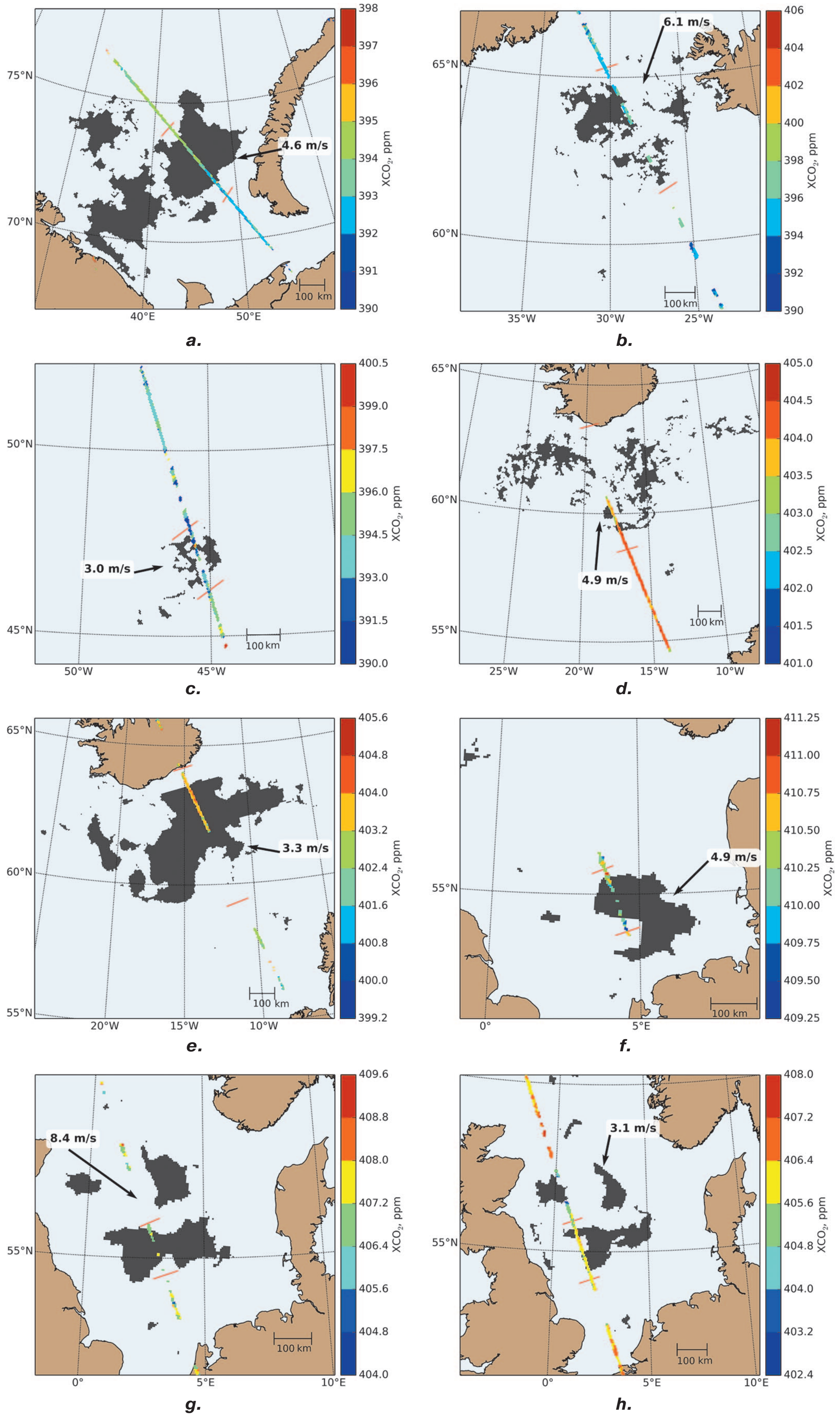
Only high quality data (i. e. unflagged data) were employed in our case studies. 8-day averaging of XCO_2 data was implemented in this study.

***E. huxleyi* bloom masking.** The 1998–2018 time series of *E. huxley* blooms in the Subarctic Atlantic and Arctic oceans was retrieved from Ocean Color Climate Change Initiative (OC CCI) data through the analysis of spectra of remote sensing reflectance, $R_{rs}(\lambda)$. The methodology is described in detail in [Kondrik et al., 2017, 2019]. Concisely, a typical R_{rs} spectrum from a *E. huxleyi* bloom exhibits a maximum at λ = ~490 nm at the late stage of its development, when the surface water is predominantly populated by coccoliths whereas *E. huxleyi* cells have already mostly died off. Accurate delineation of *E. huxleyi* blooms was based on fulfillment of the requirement that the spectral values of *Rrs* (sr^{-1}) in the OC CCI standard spectral channels exceed the following statistically established thresholds: 0.001 at 412 nm, 0.008 at 443 nm, 0.01 at 490 nm, 0.008 at 510 nm, and ~ 0 at 670 nm. On this basis, masks of *E. huxleyi* blooms were plotted for the target Subarctic and Arctic seas to restore the chronicle of spatio-temporal variations of the bloom areas between 1998 and 2018.

Results and discussion

Here we present the results of eight satellite-based case studies from the Barents, Iceland, Greenland and North seas (Table, Fig., *a–h*). Note that red lines show the limits of the beyond-bloom areas used in this study for assessing ΔXCO_2; black arrows indicate the force and direction of wind over the bloom area; black areas are *E. huxleyi* blooms.

As the Table shows, in 5 cases (The Barents, South Iceland, South Greenland, North seas) OCO-2 registered an increment of XCO_2 over *E. huxleyi* bloom areas ranging between 0.6



OCO-2 footprint trajectory and along XCO_2 (ppm) track values: *a–h* are 1–8 Cases, respectively (see Table) and 3.0 ppm. These numbers are fully consistent with the results we have obtained in the study of *E. huxleyi* -induced XCO_2 in the Black Sea as registered in 2016–2017.

However, in three cases (the South Iceland, and North seas), no XCO_2 enhancement was found. A combined OCO-2 and wind data analysis has shown that the explanation of the apparent absence of *E. huxleyi* blooming impact upon XCO_2 might reside in the effect of above water air mass advection. Indeed, for cases 4, 6, and 8 the meteorological and *E. huxleyi* blooming conditions were specific. In case 4 the blooming area was essentially inhomogeneous/fractionized, and the wind direction was southern, i. e. bringing air masses from the parts of the sea free of any *E. huxleyi* bloom influence.

In case 8 there were very similar conditions in terms of wind-driven advection of above-water air from marine tracts void of *E. huxleyi* blooming. It is also worth mentioning that the blooming area was also significantly fractionized.

A special consideration should be given to case 6. At first glance, it appears that the *E. huxleyi*-driven ΔXCO_2 signal should not be zero: the footprint trajectory traverses the bloom area, and the advected air comes from a large portion of bloom. However, the number of OCO-2 pixels within the bloom area is rather small, rendering the ΔXCO_2 retrievals insufficiently reliable.

Concluding remarks

Produced in the reaction of calcification inside the cell of *E. huxleyi*, CO_2 becomes available for the reaction of photosynthesis with a result of a reduced uptake of dissolved CO_2 from ambient water. Thus, surface marine waters within the bloom of *E. huxleyi* turn out to be less CO_2 depleted. Moreover, the thus enhanced partial pressure of dissolved CO_2 can either nullify the flux of atmospheric CO_2 or even reverse it. This has been proven in shipborne surveys, and through spaceborne observations over the Black Sea: the enhancement of CO_2 content in the atmospheric column proved to be within 1–2 ppm.

The eight case studies conducted with the employment of OCO-2 satellite data and presented in this concise report have shown that the impact of *E. huxleyi* blooming phenomenon on the atmospheric CO_2 partial pressure over the North, Iceland, Greenland, and Barents seas proved to be of the same order of magnitude as over the Black Sea (0.6–3 ppm). It is also shown that the magnitude of CO_2 enhancement in the atmospheric column is significantly controlled by the air advection in the boundary layer.

Arguably, this might be an indication of some inherent property of *E. huxleyi*, and the obtained results on the increment of CO_2 in the atmospheric column over the blooms of this alga can be considered as representative of this phenomenon across the oceanic tracts, at least, in the Northern Hemisphere.

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