KLAIPĖDA UNIVERSITY

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WIND-INDUCED COASTAL UPWELLING IN THE SOUTH-EASTERN BALTIC SEA: SPATIO-TEMPORAL VARIABILITY AND IMPLICATIONS FOR THE COASTAL ENVIRONMENT

DOCTORAL DISSERTATION

Natural sciences,
ecology and environmental sciences (N 012)

Klaipėda, 2019

Doctoral dissertation was prepared during the period 2014–2019 at Klaipėda University, based on the conferment a doctorate right which was granted for Klaipėda University by the order of the Minister of Education and Science (Republic of Lithuania) No. V-1019, signed on 8 June 2011, by the order of the Minister of Education, Science and Sport (Republic of Lithuania) No. V-160, signed on 22 February 2019.

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The dissertation will be defended in a public meeting of the Board in Ecology and Environmental Sciences, Klaipėda University Marine Research Institute conference hall (201 a.) at 2 p. m., 30th of October 2019.
Address: University Avenue 17, LT-92294, Klaipėda, Lithuania.

The doctoral dissertation was sent out on 30th September 2019.
The doctoral dissertation is available for review at the Library of Klaipėda University.

KLAIPĖDOS UNIVERSITETAS

Toma DABULEVIČIENĖ

VĖJO SUKELTAS PRIEKRANTĖS APVELINGAS PIETRYČIŲ BALTIJOS JŪROJE: KITIMAS LAIKE IR ERDVĖJE BEI JO POVEIKIS PRIEKRANTĖS APLINKAI

DAKTARO DISERTACIJA

Gamtos mokslai,
ekologija ir aplinkotyra (N 012)

Klaipėda, 2019

Disertacija rengta 2014–2019 metais Klaipėdos universitete pagal Lietuvos Respublikos švietimo ir mokslo ministro 2011 m. birželio 8 d. įsakymu Nr. V-1019 ir Lietuvos Respublikos švietimo, mokslo ir sporto ministro 2019 m. vasario 22 d. įsakymu Nr. V-160 Klaipėdos universitetui suteiktą Ekologijos ir aplinkotyros mokslo krypties doktorantūros teisę.

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Daktaro disertacija ginama Klaipėdos universiteto Ekologijos ir aplinkotyros mokslo krypties taryboje:

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Daktaro disertacija bus ginama viešame Ekologijos ir aplinkotyros mokslo krypties tarybos posėdyje 2019 m. spalio 30 d. 14:00 val. Klaipėdos universiteto Jūros tyrimų instituto Konferencijų salėje (201 a.).
Adresas: Universiteto al. 17, LT-92294, Klaipėda, Lietuva.

Daktaro disertacija išsiųsta 2019 m. rugsėjo 30 d.
Disertaciją galima peržiūrėti Klaipėdos universiteto bibliotekoje.

Abstract

This study provides the first comprehensive research of wind-induced coastal upwelling in the South-Eastern (SE) Baltic Sea based on the analysis of satellite and conventional monitoring data over a period of 2000–2015. The analysis of multi-spectral satellite data enabled the analysis of both physical and biological properties of the coastal upwelling in a broad range of spatial and temporal scales. The detailed statistical information on upwelling properties in this region and the impact of the upwelling-induced inflows on the hydrological conditions of the Curonian Lagoon together with an insight of its possible impact on the marine environment of this region is provided. Additionally, for the first time an Ekman-based upwelling index (UI) is used over the study region to better understand the upwelling response to the background meteorological conditions, and to assess the effectiveness of satellite data in the upwelling studies over the SE Baltic Sea.

The study results indicate that the upwelling-induced SST drop and its spatial properties are larger than were previously registered with the SST drop up to 14 ˚C and the total affected area up to 16000 km^2 during extreme upwelling events. The analysis of satellite optical data shows a clear upwelling-induced decline in chlorophyll-*a* (Chl-*a*) concentration in the coastal zone and in the shallow Curonian Lagoon. It was also demonstrated that coastal upwellings might significantly influence water salinity and air temperature.

The study outcomes suggest that satellite data is an effective tool for coastal upwelling detection in the Baltic Sea under relatively cloud-free summer conditions enabling the analysis of the coastal upwelling intensity, its biological and atmospheric response and, moreover, yielding significant information about the sea-lagoon interaction. This thesis also demonstrates the benefits of integrating multi-spectral satellite data for the monitoring of the Baltic Sea and the Curonian Lagoon environment.

Key words

SST, Chl-*a*, MODIS, the Curonian Lagoon

Reziumė

Šiame darbe pirmą kartą yra pateikiami išsamūs vėjo sukelto priekrantės apvelingo Pietryčių (PR) Baltijos jūros regione tyrimai, remiantis palydoviniais ir įprastinių stebėjimų duomenimis 2000–2015 m. periodui. Daugiaspektrinių palydovų duomenų analizė įgalino išanalizuoti fizines ir biologines priekrantės apvelingų savybes plačioje erdvės ir laiko skalėje. Darbe pateikiama išsami statistinė informacija apie regionines PR Baltijos apvelingų savybes, jų poveikį Kuršių marių hidrologinėms sąlygoms, taip pat pateikiamos įžvalgos apie galimą apvelingo poveikį Baltijos jūros priekrantės bei Kuršių marių gamtinei aplinkai. Be to, siekiant geriau suprasti, koks yra apvelingo reagavimas į palankias meteorologines sąlygas bei įvertinti palydovinių duomenų taikymo efektyvumą priekrantės apvelingo tyrimams PR Baltijos jūros regione, čia pirmą kartą buvo panaudotas Ekmano teorijos pagrindu sukurtas „Apvelingo Indeksas“.

Tyrimo rezultatai rodo, kad apvelingo sukeltas jūros paviršiaus temperatūros pažemėjimas bei apvelingo erdvinės savybės yra didesni, nei iki šiol buvo fiksuota. Itin intensyvių apvelingo metu vandens temperatūra gali staiga pažemėti net per 14 ˚C, o apvelingo paveiktas PR Baltijos jūros priekrantės plotas gali apimti net iki 16000 km^2. Palydovinių optinių duomenų analizė rodo akivaizdų apvelingų sukeltą chlorofilo-*a* (Chl-*a*) koncentracijos sumažėjimą pakrantės zonoje, o įtekėjimų į marias metu – ir sekliose Kuršių mariose. Darbe taip pat parodyta, kad priekrantės apvelingas gali daryti didelę įtaką vandens druskingumui ir oro temperatūrai.

Tyrimo rezultatai rodo, kad palydoviniai duomenys yra efektyvi priemonė apvelingų PR Baltijos jūros regione identifikavimui šiltuoju metų periodu ir esant santykinai mažam debesuotumui. Be to, palydoviniai metodai įgalina tirti priekrantės apvelingo erdvines savybes, jo intensyvumą bei poveikį gamtinei aplinkai, suteikia naudingos informacijos apie jūros ir marių sąveiką. Šios disertacijos rezultatai taip pat parodo daugiaspektrinių palydovinių duomenų integravimo naudą Baltijos jūros ir Kuršių marių aplinkos stebėsenai.

Reikšmingi žodžiai

SST, Chl-*a*, MODIS, Kuršių marios

Contents

1

Introduction

1.1 Relevance of the dissertation

Coastal upwelling, a phenomenon during which deep and cold water rises toward the surface, is commonly found in large stratified lakes, estuaries, and coastal ocean (Myrberg and Andrejev, 2003; Plattner et al., 2006). The combination of wind stress and the Earth's rotation drives a near-surface layer of water offshore resulting in the upwelling of relatively nutrient-rich water from below (Kampf and Chapman, 2016), which stimulates the growth of microscopic phytoplankton forming the base of the marine food web (Jacox et al., 2018). The interactions between abiotic and biotic factors during the upwelling events have significant implications for the entire marine environment, including the physical-biological processes and the socio-economic activities (Rossi et al., 2009; Saldívar-Lucio et al., 2016). Coastal upwelling ecosystems are among the most productive ecosystems in the world (Xiu et al., 2018) meaning that upwelling regions are important fishing areas (Hu and Wang, 2016), and have a certain significance to fishermen. The role of upwelling in the atmosphere-ocean CO_2 exchange, carbon recycling, and offshore water transport is of a high interest for researchers as well (McGregor and Mulitza, 2007). The detailed information on coastal upwelling conditions is, therefore, crucial for physical climatology and environmental biology (Barzandeh et al., 2018). Moreover, upwelling is also an important aspect for the coastal managers (Jiang et al., 2010) as the recognition of upwelling spatio-temporal patterns might allow for some reasonable forecasting capacity, potentially useful for the regional marine resources management (Saldívar-Lucio et al., 2016).

Coastal upwelling also plays an important role in the ecologically sensitive regions of the global ocean, like the Baltic Sea. The specific geography of the region makes coastal upwelling quite a common process here (Lehmann and Myrberg, 2008; Bychkova and Viktorov, 1987) as it can occur with a sustained wind over the Baltic Sea in almost any direction (Sproson and Sahlee, 2014). Comprehensive studies of coastal upwelling are, therefore, also important when assessing regional variability of water and energy exchange in the Baltic Sea region, as it is one of the key factors affecting the circulation through the mixing of water masses (Zhurbas et al., 2008), modifying vertical stratification (Sproson and Sahlee 2014), and contributing to the coastal water exchange with an open sea (Kahru et al., 1995; Levy, 2008). Besides, upwelling induces the changes in sea surface temperature (SST), salinity and nutrient concentrations that are very closely related to the near-shore ecosystem functioning (Fisher and Mustard, 2004; Kowalewski, 2005; Krężel et al., 2005). Thus, upwelling can greatly accelerate primary production and hence set up an enhanced food chain of secondary producers, together with grazers from zooplankton up to fish, marine birds and mammals (Orren, 1995).

Owing to its significance, upwelling in the Baltic Sea has been a subject in numerous studies. However, most of the existing works have typically addressed coastal upwelling and its impact across the entire Baltic Sea basin, providing limited information about its development and implications for the environment in the SE Baltic region and Curonian Lagoon. Here, the main problem of upwelling studies was the lack of spatially and temporally detailed observations. However, the availability of multispectral remote sensing data having wide spatial coverage and relatively high temporal resolution proved to be advantageous for monitoring of the upwelling-induced changes in the surface water properties. This is, therefore, the first detailed study of wind-induced coastal upwelling along the SE Baltic Sea coast and the Curonian Lagoon using a combination of satellite remote sensing and *in situ* monitoring data for the period of 2000–2015 that provides the detailed statistical information on upwelling properties and its possible impact on the marine environment of this region.

1.2 Aim and objectives

The aim of this work is to assess the spatio-temporal properties of the wind-induced coastal upwelling and its impact on the environment of the South-Eastern Baltic Sea and the Curonian Lagoon.

The following tasks and objectives have been set:

1. To assess the suitability of satellite optical and infrared data for the coastal upwelling detection and quantification of its properties.

2. To analyse the meteorological conditions favourable for the coastal upwelling development along the southeast (SE) coast of the Baltic Sea.
3. To analyse the spatial-temporal variability of the coastal upwelling properties based on the joint use of satellite observations and *in situ* measurements over the SE Baltic Sea.
4. To assess the impact of the upwelling-induced inflows on the hydrological conditions of the Curonian Lagoon.
5. To assess the impact of the coastal upwelling on the distribution of chlorophyll-*a* in the coastal waters of the SE Baltic Sea and in the Curonian Lagoon.

1.3 Novelty

The study presents novel results on the coastal upwelling properties in the SE Baltic Sea, its effect on the coastal environment and the Curonian Lagoon waters. This research, to this day, is the first comprehensive study of the coastal upwelling over a long time period in the study region combining both satellite observations and *in situ* measurements. In addition, an Ekman-based upwelling index is used for the first time over the study region to better understand the upwelling response to the background meteorological conditions, and to assess the effectiveness of satellite data in the upwelling studies over the SE Baltic Sea. Finally, the combination of multi-spectral satellite data provides a valuable insight about the upwelling impact on the environmental conditions not only of the SE Baltic Sea, but also of the shallow Curonian Lagoon.

1.4 Scientific and applied significance of the results

This study makes a significant advancement in understanding the regional causes, properties and implications of the coastal upwelling in the SE Baltic Sea and the Curonian Lagoon, as most of the previous works typically addressed this process on a basin-scale, i.e. across the entire Baltic Sea basin, providing limited information about its development and fate in the SE Baltic. Based on multi-spectral satellite data enabling to analyse both physical and biological properties of the coastal upwelling in a broad range of spatial and temporal scales, the study also increases scientific knowledge about the main oceanographic characteristics of the coastal upwelling over the study region, and sea-lagoon interactions. Moreover, the study provides a framework to examine upwelling-induced Chl-*a* variability in the coastal zone using remote sensing data. The detailed statistics of upwelling events and their properties presented in this thesis might be used for the evaluation of the ecosystem response to the sudden biogeophysical gradients induced by the coastal upwelling development.

1.5 Scientific approval

Results of this study were presented in 10 international conferences/workshops and 2 national conferences:

1. The Baltic Sea Science Congress, 2015, Riga, Latvia
2. Baltic Earth Doctoral Conference, 2015, Tartu/Vilsandi, Estonia
3. Baltic Earth/Gulf of Finland PhD Seminar in connection to the Gulf of Finland Year's Final Scientific Forum, 2015 Tallinn, Estonia
4. EOS-COST Workshop on the use of new satellite datasets in marine climate applications, 2016, Porto, Portugal
5. The Baltic Earth conference, 2016, Nida, Lithuania
6. EO4Baltic Workshop 2017, Helsinki, Finland
7. The Baltic Sea Science Congress, 2017, Rostock, Germany
8. IEEE 2018, Klaipeda, Lithuania
9. Jūros ir Krantų tyrimai, 2018, Klaipėda, Lithuania
10. Open Readings, 2019, Vilnius, Lithuania
11. Jūros ir Krantų tyrimai, 2019, Klaipėda, Lithuania
12. 2019 Living Planet Symposium, 2019, Milan, Italy

The material of this study was presented in 2 original publications, published in peer-reviewed scientific journals. One of the publications is written under the author's maiden name Mingelaite, T.:

1. Delpeche-Ellmann, N., **Mingelaite, T.**, Soomere, T., 2017. Examining Lagrangian surface transport during a coastal upwelling in the Gulf of Finland, Baltic Sea, Journal of Marine Systems, Vol. 171, p. 21-30, https://doi.org/10.1016/j.jmarsys.2016.10.007
2. **Dabuleviciene, T.**; Kozlov, I.E.; Vaiciute, D.; Dailidiene, I., 2018. Remote Sensing of Coastal Upwelling in the South-Eastern Baltic Sea: Statistical Properties and Implications for the Coastal Environment. Remote Sens. 10(11), 1752; https://doi.org/10.3390/rs10111752

1.6 Thesis structure

The dissertation includes seven chapters, including Introduction, Literature review, Materials and methods, Results, Discussion, Conclusions and References. The material is presented in 81 pages, 29 figures and 4 tables. The dissertation refers to 195 literature sources. Dissertation is written in English with an extended summary in the Lithuanian language.

1.7 Acknowledgements

Spending 1/3 of my life at university so far is a long time, therefore I owe where I am today to a lot of amazing people who have been there for me during all these years: for giving me the opportunities, encouraging me, for supporting me during weak moments and for sharing the happiness during the joyful ones.

First and foremost, I have to thank my parents whom I deeply love: Elena and Aloyzas. Without their endless love and support I would not be where I am today. And I would not be the person I am today. I will never be able to thank my Mom enough for working days and nights so I could pursue my dreams. My late father, sadly, did not stay in this world long enough to see this, but I know I have a guardian angel in heaven. I call him Dad.

I also want to express the gratitude to my supervisor prof. dr. Inga Dailidienė for involving me into the Academia from the very beginning of my Bachelor's studies thus inspiring my interest in science. She has always been supportive and has given me the freedom to follow various projects during my PhD, allowing me to grow as a research scientist. Thank you for believing in me.

I would like to say the biggest thank you to dr. Igor Kozlov and dr. Diana Vaičiūtė for playing a major role in the success of my PhD. Their scientific advice, knowledge, many insightful discussions and suggestions made it possible for this thesis to reach the daylight. Dear Igor, thank you for your time and patience polishing my research writing skills, for your countless e-mails and careful attention to detail. Dear Diana, thank you for letting me be a part of your team, for your comprehensive support and all the experience you shared with me.

I would also like to recognize the members of the Doctoral School in Ecology and Environmental Sciences of Klaipeda University for their helpful advice and guidance through the PhD. I sincerely appreciate the supervision of the Head of Doctoral School, prof. dr. Darius Daunys, who has constantly reminded us to keep the PhD 'pulse' and move forward. Also my special thanks goes to prof. habil. dr. Sergej Olenin for his time and valuable comments on how to improve the thesis.

I am deeply grateful to prof. dr. Kai Myrberg for his scientific expertise and friendly advice that guides me through the PhD and life in general.

I greatly appreciate the countless experts and colleagues from Natural Sciences Department and Marine Research Institute who have offered the guidance, feedback and suggestions along the way. With a special mention of dr. Loreta Kelpšaitė-Rimkienė, who is my "first aid" in many stressful situations. Also thanks to prof. habil. dr. Olegas Pustelnikovas, prof. habil. dr. Marija Eidukevičienė and prof.dr. Albertas Bitinas for being the inspiring examples.

I would also like to express the gratitude to the members of Tallinn University of Technology Wave Engineering Lab, especially prof.dr. Tarmo Soomere and dr. Nicole

Delpeche-Ellmann for giving me the opportunity to become a part of their Lab and the possibility to learn from them.

All the friends I made during my PhD years are too numerous to name. But I am really grateful to all of them for small talks, coffee breaks and lunches together. There are a few, however, that cannot go unmentioned. My sincere thanks goes to Rūta – for the enriching of not only dolphins, but my life as well; to Greta S. – for spending her evenings and weekends together in the Institute and for all the talks and sushi's we ate and calories we burnt; Edvardas V. and Vitalijus – for standing at the corner and for all the vitamin C we made; Viktorija and Elena – my PhD "sisters" for their understanding, and Artūras – for reminding me that sometimes it is good to be a little like Honey Badger. Also many thanks go to Eglė N., for guiding us all through the PhD maze, for comforting and for cat videos and pictures.

I also thank my friends from JBG – even though we are all scattered around the Globe, I know I can always count on you.

My dear HOKs, thank you for all the fun we had during study years. Especially Ieva, Paulius and "who's that Marius" for becoming friends out of group-mates.

I would also like to say a heartfelt thanks to my sisters Aušra and Ernesta – for always believing in me and supporting me spiritually throughout writing this thesis and my life in general. All WhatsApp messages makes the distance between us disappear. I love you both for being there for me. I also thank my lovely nephew, who is always capable of cheering me up. P.S. Aušra, maybe the Pythagorean Theorem led me to where I am now?

Finally, I would really like to thank my beloved husband Domas – I will always be grateful for your unconditional support, care and love. For all the times you made me laugh. Even though you have had to put up with me being stressed, grumpy, messy, sleepy, travelling, working evenings / weekends / holiday – you have always been there for me. And let's not forget our cats – the furry balls of happiness comforting me with no words.

This study was partly supported by the EOMORES project belonging to the EU Horizon 2020 research and innovation programme (grant agreement No.°730066) and TODAY project funded by the European Space Agency (No. 4000122960/18/NL/SC). The author is also grateful to the Lithuanian Hydrometeorological Service under the Ministry of Environment for providing the meteorological data and to the Lithuanian Environmental Protection Agency (LEPA) Environment Research Department (former Department of Marine Research) for providing the *in situ* monitoring data.

1.8 Abbreviations

Abbreviation	Explanation
AMSR	Advanced Microwave Scanning Radiometer-EOS
AVHRR	Advanced Very High Resolution Radiometer
CDOM	Coloured or chromophoric dissolved organic material
Chl-a	Chlorophyll-*a* concentration
CUI	Cumulative upwelling index
DIN	Dissolved inorganic nitrogen
DIP	Dissolved inorganic phosphorus
EBUS	Eastern Boundary Upwelling Systems
EM	Electromagnetic
ESA	European Space Agency
EU	European Union
FUB	Processor, developed by the German Institute for Coastal Research, Brockmann Consult and Freie Universität Berlin
GMT	Greenwich Mean Time
HELCOM	HELsinki COMmission (Baltic Marine Environment Protection Commission)
IR	Infrared
LAC	Local Area Coverage
LEPA	Lithuanian Environmental Protection Agency
L2	Level 2
MABL	Marine Atmosphere Boundary Layer
MERIS	Medium Resolution Imaging Spectrometer
MODIS	MODerate-Resolution Imaging Spectroradiometer aboard Terra and Aqua satellites
MSFD	Marine Strategy Framework Directive
MVIRI	Meteosat Visible and Infrared Imager
NASA	National Aeronautics and Space Administration

NOAA	National Oceanic and Atmospheric Administration
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SEB	South-Eastern Baltic
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SST	Sea Surface Temperature
SLSTR WST	The Sea and Land Surface Temperature Radiometer Water Surface Temperature
TSM	Total Suspended Matter
UI	Upwelling Index
WBCs	Western Boundary Currents
WFD	Water Framework Directive

2

Literature review

2.1 Description of the Coastal Upwelling Process

The term "Coastal upwelling" describes the vertical flux of water moving upwards at the coast, which, in the case of a thermally stratified water column, brings cooler, nutrient-rich subsurface waters to the surface (Leppäranta and Myrberg, 2009). It is, in general, a result of wind forcing parallel to the coastline, Coriolis effect and Ekman transport. The combination of the latter creates a divergence of the flux, and due to the conservation of mass, upward vertical velocities are produced as a replacement of the surface water loss (Pitcher et al., 2010, Pardo et al., 2011, Mazzini and Barth, 2013). Although, for the Ekman theory to apply, the timescale of the wind forcing has to be long enough for the Coriolis force and Ekman layers to fully establish and the water body has to be deep enough for a spatial separation of the surface and bottom Ekman layers (Kämpf, 2015; Kämpf, 2017). Though, on the scales too small for the Coriolis forces to dominate upwelling can still be triggered by an off-shore wind blowing directly from the land interior (Bednorz et al., 2019).

The evolution and transport of water masses in the coastal upwelling are also influenced by multitude of drivers e.g., the geographic features, atmospheric forcing, characteristics of water masses or other oceanic processes (Lehmann & Myrberg, 2008; Delpeche-Ellmann et al., 2018). The extent of upwelling, in general, is scaled by the baroclinic Rossby radius (Fennel and Lass, 2007, Leppäranta and Myrberg, 2009, Gurova et al., 2013) while the specific regional bathymetric features has been found to have a significant effect on the upwelling characteristics, i.e., formation of offshore jets, filaments or eddies (Pitcher et al., 2010). The reverse of upwelling is called "downwelling", but it does not have such physical and biological importance as upwelling (Leppäranta and Myrberg, 2009).

Swedish oceanographer V. Wilfrid Ekman was the first to explain the dynamics of wind-driven coastal upwelling theoretically (Ekman, 1905). According to Ekman's theory, the wind induces a shear stress on the sea surface while the vertical turbulent friction transfers the momentum of the wind downwards. Due to the Coriolis effect, the spiralling pattern of currents is produced, when the current direction is deflected 45° to the right of the wind at the surface, and changes increasingly towards right with depth, while current speed decreases exponentially. At the same time, the net transport is directed 90° to the right in the Northern Hemisphere, as shown in Figure 1. However, the Ekman spiral is a theoretical consideration, which has only been qualitatively verified by direct measurements (Lehmann and Myrberg, 2008).

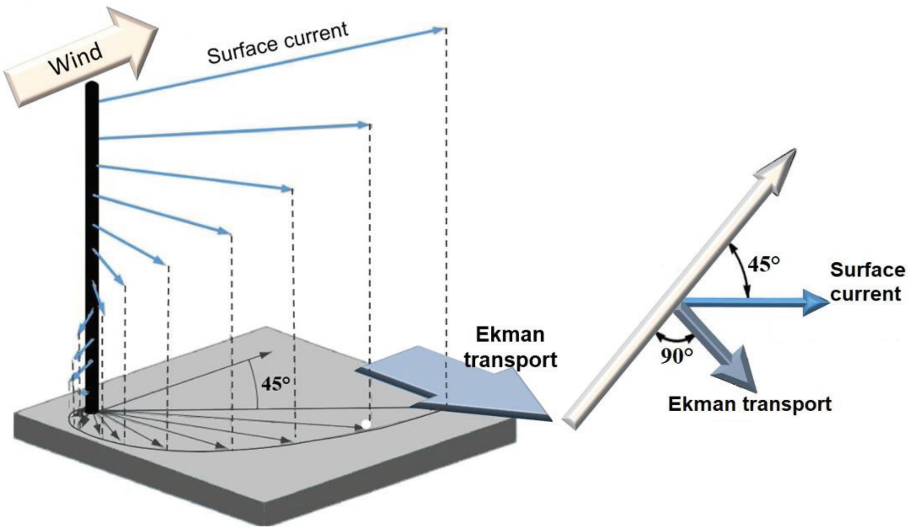


Figure 1. Ekman Spiral in the Northern Hemisphere. (Modified from: Offshore Engineering https://www.offshoreengineering.com/education/oceanography/ekman-current-upwelling-downwelling).

1 paveikslas. Ekmano spiralės schema Šiauriniame pusrutulyje. (Adaptuota pagal: Offshore Engineering https://www.offshoreengineering.com/education/oceanography/ekman-current-upwelling-downwelling).

Based on the location, upwelling can be categorised into two broad types of wind-driven upwelling – an open ocean divergence, and the coastal upwelling (Ibe and Ajayi, 1985). The main types of upwelling are (i) coastal upwelling, (ii) equatorial upwelling, and (iii) ice-edge upwelling (Kampf and Chapman, 2016). The coastal upwelling type is closely related to human activities in the coastal zone, has a considerable economic significance affecting fisheries, weather, and oceanic currents in many parts of the world (Barua, 2005). It is, therefore, of great global relevance. Even though the coastal upwelling is regionally more limited than the open ocean upwelling, its stronger vertical motion results in a greater climatic and biological impact (Leppäranta and Myrberg, 2009).

Upwelling, in turn, is typically characterised by an increase of primary production (Kowalewski, 2005; Krężel et al., 2005, Gonzalez-Rodrıguez et al., 2012; Vidal et al., 2017); hence, influencing the coastal pelagic communities and higher trophic levels (Vahtera et al., 2005). Even though coastal upwelling regions cover about 5% of the World Ocean, approximately 25% of the total global marine fish catch comes from five main upwelling sites (Krauss and Nies, 2015).

Depending on regional wind conditions, coastal upwelling can be classified as a (quasi-) permanent feature, i.e. major coastal upwelling systems; or as a seasonal coastal upwelling system (Kampf and Chapman, 2016). The major upwelling systems in the Global Ocean are driven by persistent winds blowing alongshore toward the equator, while seasonal upwelling is related to the periodic changes of wind direction. There are also sporadic coastal upwelling events (Rossi et al., 2013) usually restricted in space and time, and highly depending on the configuration of the coast and variable wind conditions. In the Baltic Sea region, wind conditions are dominated by westerlies (Leppäranta and Myrberg, 2009), however, there are no clearly defined permanent winds or winds that reverse their direction seasonally here. The coastal upwelling in the Baltic Sea is thus considered to have a more sporadic nature.

Though the mechanism of coastal upwelling formation was described already a century ago, the upwelling studies were rather superficial for a long time due to insufficient number of monitoring stations and oceanographic expeditions not enabling to perceive a full view of upwelling dynamics. The turning point in the upwelling studies was the start of the remote sensing era. In early 1960s, it was recognized that aerial sensors could be used for deriving useful oceanographic information (Wilson, Lindstrom and Apel, 2008). Since then, the use of remote sensing lead to a great boost in oceanographic research. The utilization of remote sensing data for the upwelling studies started in the early 1980s (Leppäranta and Myrberg, 2009), and is widely used now to tackle various aspects of the process.

2.2 Remote Sensing for the coastal upwelling

In general, the capability of remote sensing to gather the information about the sea is limited to four primary quantities that can be observed from space. These are primarily the properties of the sea surface, namely *colour*, the *temperature*, the *roughness* and the *height*. Nevertheless, it is surprising how much knowledge can be recovered from these four primary parameters (Robinson, 2004).

A variety of sensing instruments mounted on satellites and other platforms measure the amount of radiation at various wavelengths reflected from the water's surface. This reflected signal is used directly or indirectly to measure various parameters such as sea surface temperature (SST) or chlorophyll-*a* (Chl-*a)* concentration (Gholizadeh et al., 2016) widely used for upwelling studies. In general, the most commonly-used sensors are multi-spectral sensors mounted on the Earth-orbiting satellites (Al-Tahir et al., 2009). Since the 1980's the dynamics of coastal upwelling is frequently investigated using infrared- (IR) and visible-band satellite images (Leppäranta and Myrberg, 2009). Such data with relatively high spatial resolution can provide rather frequent coverage of the study site, allowing the upwelling-induced frontal dynamics to be studied in detail (Njoku, 1990).

2.2.1 Infrared Remote Sensing of SST

SST is widely recognized as being one of the key physical properties that possesses a clear imprint of coastal upwelling on the sea surface. This work is primarily based, therefore, on the utilization of satellite IR data frequently used nowadays in coastal upwelling studies (e.g., Bychkova and Viktorov, 1987; Plattner et al., 2006; Gurova et al., 2013; Delpeche-Ellmann et al., 2017). SST has a very long history in the study of the ocean and its interchange with the atmosphere. It is directly related to, and often dictates the exchanges of heat, momentum and gases between the ocean and the atmosphere (Emery et al., 2001). Thus, from the beginning of satellite environmental remote sensing, efforts have been made to measure the sea surface temperature from space with scientifically useful accuracy. In the early 1970s, environmental satellites carried IR radiometers mostly for meteorological purposes, but they also had capabilities of SST computation (Njoku, 1990; Emery et al., 2001).

In order to understand the principles of satellite IR sensors, one needs to understand the physical principles that apply in the nature. One of them is that all bodies having temperatures higher than the absolute zero (-273.15 °C) emit thermal radiation, the strength of which depends on the body's surface temperature. The higher is the temperature, the greater the radiant energy of the body. This is the fundamental basis of IR remote sensing of SST (Robinson, 2004) implying that the temperature of the body can be determined by measuring the thermal radiation energy coming from it.

The accuracy of measuring SST using satellite IR radiometers is limited primarily by uncertainties in the correction for atmospheric effects upon the measured radiance (Llewellyn-Jones et al., 1984). The constituents of the atmosphere such as CO_2, H_2O, CH_4, NO_2 and aerosols absorb some of the radiation emitted by the sea before it reaches the detector in space, and at the same time they re-emit radiation (Robinson, 2004). Therefore, IR radiometry of the sea surface is restricted to two spectral windows in the approximate ranges 3.5–4.1 µm and 10.0–12.5 µm that are used for IR sensing of the ocean, as shown in Figure 2.

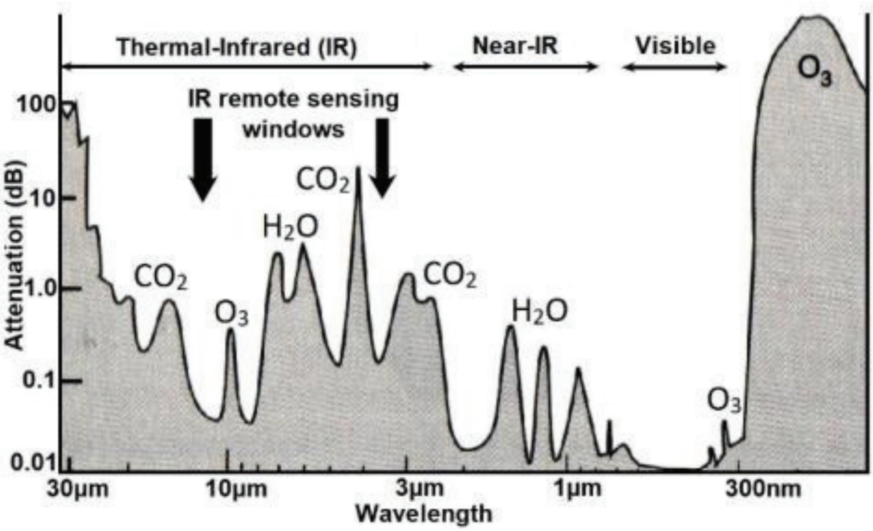


Figure 2. Attenuation in the IR part of the spectrum. Absorption peaks associated with a particular gas are labelled accordingly (redrawn from Robinson, 2004)

2 paveikslas. Infraraudonųjų spindulių spektro slopinimas. Dujų absorbcijos pikai pažymėti atitinkamai. (pagal Robinson, 2004)

In turn, before SST derived from infrared satellite data can be estimated, the data must be carefully screened for cloud contamination while specific SST algorithms are to be applied to correct for absorption and re-emission effects of atmospheric water vapour (Wick et al., 2002). In general, SST is a difficult parameter to define precisely, as the upper ocean (~10 m) has a complex and variable vertical temperature structure related to the turbulent regime and air-sea fluxes of heat, moisture and momentum in this layer (Garcon et al., 2014, p. 256). Moreover, IR SST measurements represent only approximately 10 microns within the oceanic skin layer, as shown in Figure 3.

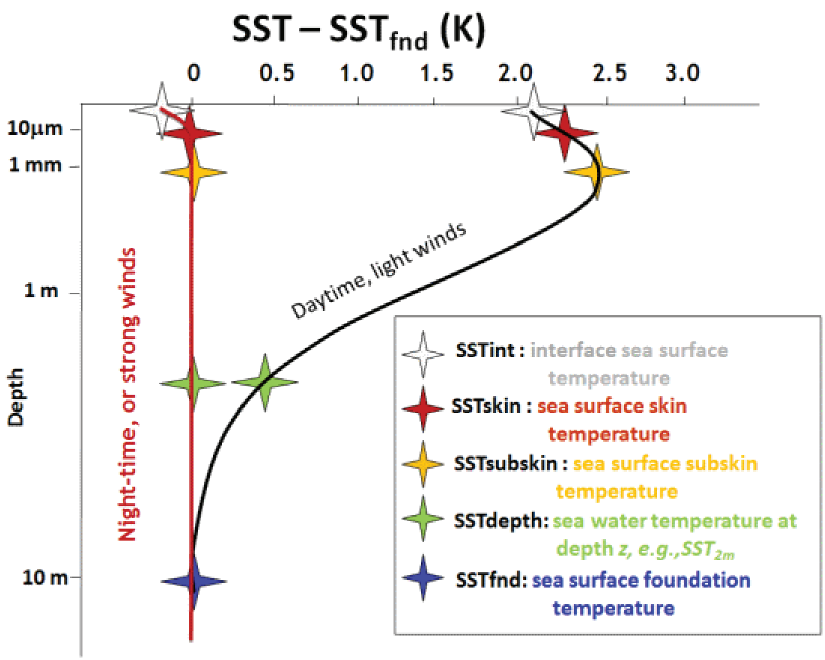


Figure 3. The schematic diagram summarising the definition of SST in the upper 10 m of the ocean in strong wind conditions / night time (red) and low wind speeds during the day (black) (© GHRSST – The Group for High Resolution Sea Surface Temperature, 2019, https://www.ghrsst.org/ghrsst-data-services/products/)

3 paveikslas. Scheminė diagrama, kurioje apibendrinama jūros paviršiaus temperatūros (SST) apibrėžtis viršutiniame 10 m sluoksnyje. Raudona spalva žymi SST esant stipriam vėjui / nakties metu. Juoda spalva – esant silpniems vėjams dienos metu. (© GHRSST – The Group for High Resolution Sea Surface Temperature, 2019, https://www.ghrsst.org/ghrsst-data-services/products/)

The skin temperature (SST_{skin}) is defined as the temperature measured by an IR radiometer typically operating at wavelengths 3.7–12 µm (Garcon et al., 2014, p. 256). It is generally several tenths of a degree cooler than the temperature measured just below, because of the heat loss from the ocean to the atmosphere (Minnett, 2001, p. 293). Thus, it is different from the bulk SST measured by conventional methods, as the SST_{skin} corresponds to the very skin of the sea surface and is influenced by diurnal warming, cool-skin effect and surface films (Robinson, 2004), while the bulk SST may or may not be influenced by the effect of diurnal thermocline depending on the measurement depth (Kozlov et al., 2014). However, despite of small inaccuracies

(±0.3 to ±0.5 K) between the skin SST and the bulk SST, the greatest advantage of satellite remote sensing is a large spatial and temporal coverage (Minnett, 2001, p. 293) making it possible to study temperatures of large ocean basins and coastal areas, which are difficult to monitor with ships and buoys alone (Klemas, 2011). Moreover, SST is one of the key climate and weather measurements acquired by satellite sensors.

As a parameter, SST is particularly important for the Baltic Sea, as the average water depth here is only 54 m, and its surface water is directly related to the bottom water by the mixing in the shallow sub-basins (Liu and Fu, 2018). In the Baltic–North Sea region, at present the satellite SST data can be retrieved from infrared sensors like Moderate Resolution Imaging Spectroradiometer (MODIS) of NASA and Advanced Very High Resolution Radiometer (AVHRR of NOAA), as well as microwave sensors like Advanced Microwave Scanning Radiometers (AMSR-E and AMSR-2) (She et al., 2007). In addition, water surface temperature from Sentinel-3 Sea and Land Surface Temperature Radiometer (SLSTR) became recently available (Bonecamp et al., 2016). However, MODIS is still amongst one of the most frequently used satellites for SST acquisition in the Baltic Sea. It has a much longer data record compared to the recently-launched Sentinel-3, spanning from year 2000 to this day. MODIS observations allow obtaining spatially detailed, regularly and continuously repeated datasets for the Baltic Sea and its coastal lagoons (Kozlov et al., 2014), and, therefore, are widely used for the coastal upwelling analysis.

2.2.2 Optical Remote Sensing

The first earth-orbital Gemini and Apollo missions in the 1960's released some spectacular over-water photography taken by the astronauts, proposing a number of potential applications for optical remote sensing of the oceans (Austin, 1993). In the upper ocean layer, the presence of living plant cells, dissolved organic material, and particulates influences the colour of sunlight scattered out of the sea, thus, the measurements of light leaving the water can be used to interpret the information it conveys about constituents in the surface layer of the sea (Robinson, 2004).

In an overview of Optical Remote Sensing provided by Teodoro (2016), it is summarized, that electro-optical imaging sensors operate in the optical region of the electromagnetic (EM) spectrum defined as radiation with wavelengths between 400 and 15000 nm and convert collected EM radiation to a stored representation useful for remote-sensing analysis. Different materials in the water, dissolved and suspended, reflect and absorb differently at different wavelengths, thus changing the colour of the ocean. Their spectral reflectance signatures can differentiate the targets/elements in the remotely sensed images. This is as a basis for optical remote sensing, which serves as a powerful source of information for monitoring the coastal environment.

Most current ocean colour sensors (e.g., Medium Resolution Imaging Spectrometer (MERIS), Sea-viewing Wide Field-of-view Sensor (SeaWiFS), MODIS Aqua and Terra) are able to provide global coverage of the earth roughly every 3 days at the equator and more frequently at the poles. Although the ability of the sensor to view the ocean colour is obscured due to the presence of clouds and in reality temporal sampling for any given region is much smaller (Dierssen and Randolph, 2013). The remote sensing of ocean colour, having a wide field of view has an important role to play as a cost-effective tool for global and frequent observations of the surface water properties, including ones resulting from the coastal upwelling. As the upwelling-induced vertical mixing and displacement of water masses (Myrberg and Andrejev, 2003) results in changes of bio-optical water properties, visible band satellite data is able to monitor detectible changes in water surface, such as Chl-*a* concentration.

One of the most scientifically relevant and commonly used applications to aquatic coastal systems is the estimate of chlorophyll concentrations, although the complexity of coastal waters makes this task quite challenging (Schalles, 2006). The combinations of water constituents are different in the open ocean and coastal waters, so from the perspective of remote sensing, waters can be divided into two classes: Case I and Case II as it was first suggested by Morel and Priour (1977). They described oligotrophic waters, open oceans and seas as Case I waters, having concentration of phytoplankton and other biogenic components high compared to that of other particles, whereas Case II waters, such as turbid coastal waters and lakes are characterised with dominance of inorganic particles (Coloured or chromophoric dissolved organic material (CDOM) and other mineral particles). In Case I waters, concentration of Chl-*a* can be quite satisfactorily estimated, while remote sensing in Case II waters mainly due to complex interactions of four optically active substances (phytoplankton, suspended particulate matters, CDOM, and water) has been far less successful (Chen et al., 2017, p.48). It is interesting to note, that the Baltic Sea is optically complex and the entire sea falls within the optical Case II waters. Standard algorithms for marine waters tend to overestimate the concentration of Chl-*a* in the Baltic Sea, therefore, specific algorithms need to be developed here (Kratzer et al., 2017, p.532).

The first attempts of calibration/validation activities for satellite MERIS data aimed at estimating Chl-*a* and CDOM in the Curonian Lagoon was performed by Giardino et al. (2010) and later, by Bresciani et al. (2012). Then, a comprehensive work of validation of satellite-derived and *in situ* measured concentration of optically active components (Chl-*a*, CDOM, Total Suspended Matter (TSM)) and applicability of remote sensing for the water quality assessment in the SE Baltic Sea Lithuanian waters was performed by Vaiciute (2012). The results of Vaiciute (2012) provided the key information about the most suitable processor for monitoring the coastal waters of the SE Baltic Sea with Envisat/MERIS data. The aforementioned works serve as a basis for Chl-*a* analysis in the SE Baltic Sea and Curonian Lagoon and therefore are used in this study to analyse upwelling induced Chl-*a* changes.

2.3 Investigation of coastal upwelling

In general, the coastal upwelling received considerable attention in the literature mainly because of its practical interest, and economic, oceanographic and ecological significance (Barua, 2005; Cropper et al. 2014; Casabella et al., 2014; Varela et al., 2015). The upwelling phenomena were already mentioned during Darwin expeditions (1831-1836) as in one of the chapters of *"The Voyage of the Beagle"* low temperatures of the surrounding waters near Galapagos Islands were observed during daily sea surface temperature records by the *Beagle*'s crew; that is now known to be the Humboldt Current, i.e. one of the major upwelling systems of the world (Grant and Estes, 2009). However, the mechanism of upwelling itself was described only in the beginning of the 20th century after the observation of Nansen on the movement of ice floes blown by wind, expatiated on the effect of wind on oceanic circulation (Ibe and Ajayi, 1985). After Nansen's observations one of the most important contributions to upwelling studies was done by Swedish oceanographer V. Wilfrid Ekman, who was the first one to describe mathematically the dynamics of wind-driven coastal upwelling more than 100 years ago. What is more, even nowadays Ekman's theory stands as the basis for our understanding of wind-driven ocean circulation (Leppäranta and Myrberg, 2009; Jasox et al., 2018). Another important contributor to the upwelling studies is Andrew Bakun, the developer of methodology for calculating cumulative upwelling index (CUI) to represent variations in upwelling along the coast and now, according to Schwing et al. (1996) more than 400 publications refer to the Bakun (1973) technical memorandum describing the upwelling indices.

2.3.1 Upwelling in the World Ocean

There are a number of upwelling systems existing throughout the global ocean. Some of them are year-round features, others occur on a seasonal basis (Kampf and Chapman, 2016) whereas in other regions a sporadic occurrence of wind-driven upwelling events might be observed (Rossi et al., 2014).

Eastern ocean boundaries are some of the most productive areas on the Earth as a result of wind-driven coastal upwelling systems, which supply nutrient-rich subsurface waters to the surface layer (Aguirre et al., 2018). The California Current Upwelling System, the Peruvian-Chilean Coastal Upwelling System, the Canary/Iberia Current Upwelling System and the Benguela Current Upwelling System are known as the four major Eastern Boundary Upwelling Systems (EBUS) in the Global Ocean (Tomczak, 1981; Pegliasco et al., 2015). In these systems, coastal upwelling is regulated by Ekman dynamics, where winds blowing alongshore towards the equator transport surface waters offshore, causing them to be replaced by cold and nutrient-rich waters from depth, thus increasing phytoplankton production (Xiu et al., 2018). The EBUSs span a wide range of latitudes: at higher latitudes, coastal upwelling is characterized by a marked seasonal cycle while the length of the upwelling season increases progressively as latitude decreases, becoming mostly a year-round phenomenon at tropical–subtropical latitudes and are, therefore, spatially heterogeneous environments (Wang et al., 2015). Upwelling also occurs in the Western Boundary Currents (WBCs), but is more of a sporadic nature, weaker in intensity and of moderate spatial extent (Azis Ismail et al., 2019).

Besides the aforementioned major upwelling systems, there are other important upwelling regions, such as the Indian Ocean, which is characterized by the unique seasonally reversing monsoon wind systems acting as the major physical drivers for the coastal and open-ocean upwelling processes. In the Indian Ocean, the main coastal upwelling systems are located at the western Arabian Sea, Sri Lanka Dome and the Java and Sumatra coast. The production and its variability over these upwelling systems are a key concern for the fishing community and are important for the Indian Ocean rim countries (Sreeush et al., 2018). Seasonal upwellings are also observed in the Pacific Ocean East Asian marginal seas, i.e., the South China Sea, the Taiwan Strait, the East China Sea or the Yellow Sea. Here, rich upwelling occurs mostly in response to the southwesterly summer monsoon and has become increasingly important because the potential changes in the upwelling may have a dramatic ecosystem, socioeconomic, and climate impacts (Hu and Wang, 2016).

Coastal upwelling is also quite frequently observed in the enclosed or semi-enclosed seas such as the Mediterranean Sea (Johns et al., 1992; Mamoutos et al., 2017). For example, vigorous upwelling zones are found in the eastern Aegean Sea, off the west coast of Greece, and in the Gulf of Lyons; also in the Gulf of Sidra during the spring and summer seasons and along the Algerian coast during summer (Bakun and Agostini, 2001). Wind-driven upwelling is also a common event in the Black Sea coastal zones (Mikhailova et al., 1997; Silvestrova et al., 2017) playing a significant role for the biogeochemistry of the marine ecosystem of the Black Sea (Stanichnaya, et al., 2004). In addition, upwelling phenomena is frequently observed in the large lakes, such as the Great Lakes as due to their large horizontal and depth scales they behave much like an inland seas in terms of coastal dynamics (Rao and Murthy, 2001; Plattner et al., 2006; Valipour et al., 2019). Upwelling events are ecologically important here, as, for example, in Lake Ontario they were observed to cause rapid shifts in the species composition of zooplankton communities (Haffner et al., 1984).

2.3.2 Upwelling in the Baltic Sea

The Baltic Sea is a large brackish water body having a very limited water exchange with the open ocean through the narrow and shallow Danish straits (Lehmann et al., 2012). Its extensive coastlines oriented in many directions mean that coastal upwelling can occur with a sustained wind over the Baltic Sea in almost any direction (Sproson and Sahlee, 2014). Therefore it is quite a common phenomenon and especially during a warm season becomes frequently visible all along the coast, depending on prevailing wind conditions (Lehmann and Myrberg, 2008). Besides, coastal zone plays a specific role in the Baltic Sea, as its extent is relatively large compared with the area of the Sea (Leppäranta and Myrberg, 2009) making coastal upwelling an important phenomena for the entire region.

The first documented observation of upwelling in the Baltic Sea appeared almost at the same time when the first records of upwelling in the Global Ocean were recorded by Darwin expeditions (1831–1836). As described in Matthaus (2010), the famous German naturalist and traveller Alexander von Humboldt (1769–1859) observed the Baltic Sea temperatures along the Prussian coast and noticed them to decrease suddenly up to 11–12 °C near Leba and to increase again to 22.2 °C close to Hela during the voyage from Stettin to Königsberg and return in August/September 1834. In his short report, Humboldt described for the first time a phenomenon off the Prussian coast, which is now well known as coastal upwelling. A more detailed description on Humboldt's contribution to the temperatures in the Baltic Sea is given by Kortum & Lehmann (1997) (cited in Myrberg and Lehmann, 2008).

However, even though upwelling in the Baltic Sea was first recorded in the 19th century the first studies of coastal upwelling were to some extent random in character and not the results from well-prepared measurement campaigns (Leppäranta and Myrberg, 2009). The main problem of water temperature, and at the same time upwelling studies, was the lack of spatial and temporal data. Then, the availability of satellite data has given a great technological advancement for many oceanographic studies since the spatial and temporal coverage allowed overcoming restrictions of *in situ* point monitoring (Vahtmäe et al., 2006). Nowadays with the help of satellite remote sensing, spatially detailed, regularly and continuously repeated datasets for the Baltic Sea and its coastal lagoons became available and are widely used in various upwelling studies (e.g. Krężel et al., 2005; Kozlov et al., 2012; Lehmann et al., 2012; Bednorz et al., 2013; Sproson and Sahlee 2014; Delpeche-Ellmann et al., 2017, Dabuleviciene et al., 2018).

In general, the Baltic Sea coastal upwelling received considerable attention in scientific literature (e.g. Bychkova and Viktorov, 1987; Myrberg and Andrejev, 2003; Uiboupin and Laanemets, 2009; Lehmann et al., 2012; Gurova et al., 2013) with one of the earliest studies involving satellite visible and IR data for description of main upwelling regions in the Baltic Sea done Bychkova and Viktorov (1987). According to analysis of available satellite data for 1980–1984 done by Bychkova et al. (1988), 22 upwelling zones were distinguished in the Baltic Sea (Figure 4)

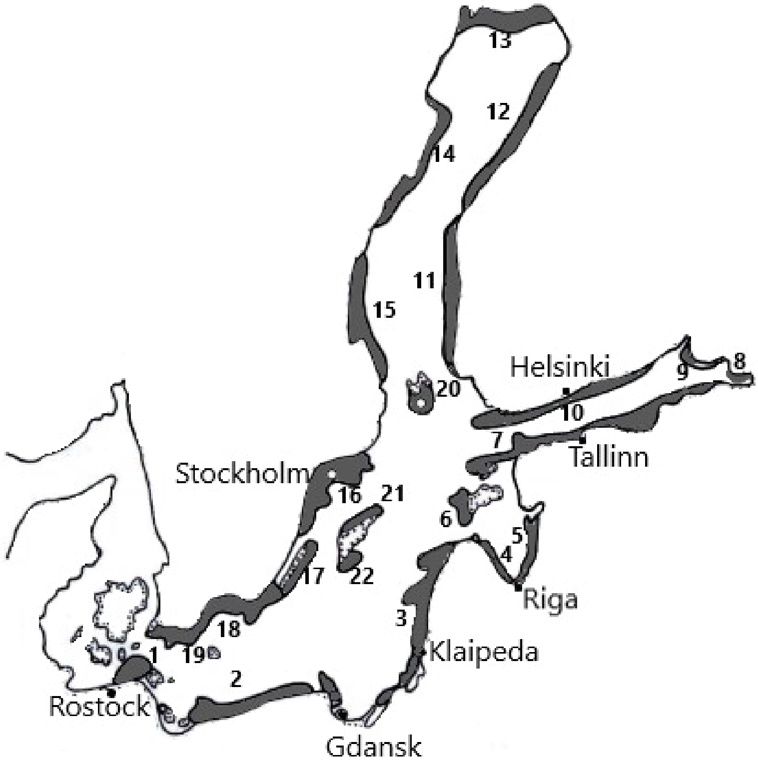


Figure 4. Main upwelling regions in the Baltic Sea according to Bychkova et al. (1988) (redrawn from Lehmann et al., 2012)

4 paveikslas. Pagrindiniai apvelingo regionai Baltijos jūroje pagal Bychkova ir kt. (1988) (adaptuota pagal Lehmann ir kt. 2012)

According to many investigations, the signatures of upwelling in the Baltic Sea are generally observed when the strongest thermal vertical stratification (with warm surface water and colder water below) occurs, i.e. from spring to autumn with the coastal upwelling as frequent as 25–30% of the time in some areas (Gidhagen, 1987; Lehmann et al., 2012). Although in different parts of the Baltic Sea upwelling has some regional features, depending on the local topography, orientation and shape of the coastline (Leppäranta and Myrberg, 2009).

Lehmann et al. (2012) analysed the upwelling frequency in the Baltic Sea for the period of 1990–2009 from May to September. Based on the results of the aforementioned study the most favourable upwelling regions are located off the southernmost coast of Sweden where upwelling can take place in 30–40% of cases. The steep west coast of Gotland Island is another well-known upwelling area (Lehmann and Myrberg, 2008). In May the main upwelling regions are located in the southern and eastern Baltic, where upwelling is generated by easterly winds with upwelling frequencies of 0–25% off the German and Polish coasts. In a review given by Lehmann and Myrberg (2008) it is summarised that near Poland most often upwelling takes place offshore Hel Peninsula, Leba and Kolobrzeg area and might potentially cover even 30% of the Polish economic zone (Krężel et al., 2005). At the German coast, upwelling is most pronounced stretching from the west coast of Hiddensee Island in north-northwesterly direction with an offshore length up to 60 km and 20 km basis at shore (Lehmann and Myrberg, 2008). At the Gulf of Riga south-easterly winds favour upwelling at the west coast and northerly winds – at the east coast (Bychkova and Viktorov, 1987; Lehmann and Myrberg, 2008).

In the northern Baltic upwelling is only observed from June, as there is usually no pronounced temperature stratification in May (Lehmann et al., 2012). Therefore in summer months, when the water masses are already well-stratified, upwelling becomes also apparent in the Gulf of Finland with prevalence of the south-westerly winds at the Finnish coast; and easterly winds – off the Estonian coast. In the Gulf of Bothnia northerly winds trigger upwelling at the Finnish coast and south to south-westerly at the Swedish coast (Lehmann and Myrberg, 2008).

In July, another area with the high frequency of upwelling is off the southern tip of Saaremaa at the mouth of the Irbe Strait, most probably induced by westerly winds or by the adjoining elongated coasts. As for the frequencies in September, the most remarkable change compared with previous months is a sudden weakening of upwelling near the Swedish coasts and a high frequency of it in the entire Gulf of Finland, the study of Lehmann et al. (2012) suggests.

Northerly winds are responsible for upwelling along the Baltic east (Lithuanian and Latvian) coast with its frequency between 0 and 20% (Lehmann et al. (2012)) with the length-scale of upwelling about 250 km and 5 to 20 km width (Bychkova and Viktorov, 1987; Lehmann and Myrberg, 2008). Several model studies analyzed the upwelling generation and evolution process and its vertical structure in the SE Baltic Sea region (e.g. Zhurbas et al., 2004; Zhurbas et al., 2006; Golenko and Golenko, 2012); however, their results appear to underestimate horizontal upwelling parameters when compared to satellite-derived sea surface temperature maps.

From the previous studies it is known that the typical upwelling event in the Baltic Sea has a vertical motion of 10^{-5}–10^{-4} m s^{-1} or 1–10 m day^{-1}; a horizontal scale of 10–20 km offshore and 100 km alongshore; a typical temperature change of 1–5 °C day^{-1}; a horizontal temperature gradient of 1–5 °C km^{-1}; and a lifetime from a few days to 1 month (Gidhagen, 1987; Krężel et al., 2005; Lehmann and Myrberg, 2008; Leppäranta and Myrberg, 2009). However, these characteristics are generalised for the whole Baltic Sea, and in different areas, they might fluctuate.

2.3.3 Implications to the environment

2.3.3.1 World Ocean

The environmental context has a large effect on the ecosystem functioning (Reddin et al., 2015; Boyer et al., 2009), thus, the elevated coastal upwelling activity occurring in the eastern ocean boundary regions has a strong physical, biogeochemical, and ecological relevance and is responsible for the remarkable biological productivity, which is unusually high relative to the rest of the ocean (Bakun, 1990; Saldívar-Lucio, 2016; Jacox et al., 2018). Upwelling systems are associated with increased pelagic productivity because the nutrients that normally limit phytoplankton production become readily available forming the base of the marine food web (Reddin et al., 2015; Jacox et al., 2018). In turn, the major Eastern Boundary Upwelling Systems are among the most productive ecosystems in the global ocean and have long been recognized for supporting some of the world's major fisheries, having significant impact to biological and socio-economical roles (Carr and Kearns, 2003; Rossi et al., 2009; Reddin et al., 2015; Varela et al., 2015).

Upwelling can influence higher trophic levels directly through exposure to physical and chemical signatures of the deeper ocean (e.g., higher salinity, lower temperature, oxygen concentration, and pH) (Aguirre et al., 2018; Jacox et al., 2018). It also influences the diet, distribution, and population dynamics of predators including seabirds (Thompson et al., 2012) and marine mammals (Croll et al., 2005; Benoit-Bird et al., 2018). Thus, upwelling zones are characterized by massive populations of small pelagic fishes such as sardines and anchovies, and support large populations of seabirds and marine mammals as well as important coastal fisheries (Bakun et al., 2010).

When cold-water upwelling filaments are generated they play a key role in cross-shelf exchanges of water masses (Bettencourt et al., 2017), and can transport water and biogenic material at large distances (Pelegrí et al., 2006; Sanchez et al., 2008). Upwelling systems are also widely believed to transport larvae far offshore in the surface currents resulting in larval wastage, limited recruitment, and increased population connectivity (Morgan, 2014). Although, upwelling filaments could also maintain a unidirectional gene flow between the invertebrate populations playing a significant role in dispersal and connectivity (Landeira et al., 2012).

Through the changes of SST, upwelling is also known to influence the coastal weather as the overlying air becomes chilled, contributing to the formation of fog banks (Diffenbaugh et al., 2004; Garrison, 2006) and leading to decreased temperatures and increased moisture flux over land. Some coastal terrestrial ecosystems could, thus, benefit from such changes (Snyder et al., 2003).

2.3.3.2 Baltic Sea

The all aforementioned literature suggests that coastal upwelling is commonly known to enhance the biological productivity along the continental shelves (Kampf and Chapman, 2016). Yet, the biological importance of upwelling is still poorly recognised in the Baltic Sea (Zalewski et al., 2005). Although upwelling can take place in the Baltic Sea throughout the year, the thermal effects may not be noticeable during thermally non-stratified conditions (Bednorz et al., 2013). On the other hand, during warm season wind-driven coastal upwelling is an important mesoscale phenomenon redistributing heat and salt in the coastal regions (Laanemets et al., 2011) that might also drastically change the euphotic layer temperature and nutrient conditions in the Baltic Sea (Vahtera et al., 2005).

Because of its frequent nature and spatial extent, coastal upwelling may be considered as one of the main factors, affecting the circulation of the Baltic Sea, and thus, its ecosystem functioning. Comprehensive upwelling studies are important assessing regional variability of water and energy exchange, salinity dynamics and response of marine ecosystems to extreme events. In turn, the aforementioned are among some of the "Grand Challenges" of the Baltic Earth Science Plan, established in 2016.

Typically, the upwelling structure consists of two main features: the core and the filaments, while the process itself can be divided into two phases: active and relaxation (Zhurbas et al., 2008; Gurova et al., 2013; Delpeche-Ellmann et al., 2017). During the active phase, cold water reaches the surface and the temperature may drop by >10 °C with horizontal temperature gradients reaching values of 1–5 °C km^{-1} (e.g., Leppäranta and Myrberg, 2009). This, in turn, shows that upwelling is modifying biotic and abiotic conditions of marine ecosystems by bringing cold, nutrient rich waters from the depth to the euphotic layer (Fuchs et al., 2013). For example, as was observed by Kowalewski (2005), the measured nutrient concentrations in the Hel upwelling tended to increase near the upwelling centre. In some cases, upwelling-induced inflow of nitrates and ammonia to the surface layer and the phosphate loads raised by the vertical current exceeded many times the load carried by the Vistula River. The latter is the main source of nutrient salts in the Gulf of Gdańsk (Kowalewski, 2005) and discharges alone 15% of total nitrogen and 19% of total phosphorus from all land-based sources to the Baltic (HELCOM, 1998). Through the transport of water masses with relatively high CO_2 concentration from the ocean interior to the sea surface, upwelling alters the surface water CO_2 concentration thus influencing the air–sea CO_2 fluxes (Norman et al., 2013). In addition, the formation of upwelling fronts also importantly modifies the vertical stratification and turbulent regime in the marine-atmosphere boundary layer, resulting in change in the surface wind stress and direction in the coastal zone (Kozlov et al., 2012; Sproson and Sahlee, 2014).

During the relaxation phase, when the upwelling-favourable wind decreases or changes its direction, various hydrodynamic instabilities, like jets, meanders, filaments, or eddies may develop at the upwelling front (Delpeche-Ellmann et al., 2017; Dabuleviciene et al., 2018). These could result in advection of irregular protrusions of upwelled water far beyond the coastal zone (Brink, 1983). Cold-water filaments/ squirts are narrow mesoscale structures of cold water that stretch seaward with origin in the coastal upwelling zone (Navarro-Pérez and Barton, 1998; Relvas et al., 2014; Troupin et al., 2012). They are associated with strong offshore currents and might propagate tens of kilometres seawards (Zhurbas et al., 2008; Laanemets et al., 2011) extending the domain of influence of upwelling from a narrow coastal zone into the basin interior (Laanemets et al., 2009). In satellite images, they are visible as cold tongues and meanders with enhanced pigment concentration compared with ambient levels (Davenport et al., 1999). They are also responsible for transporting coastal species to the open waters as coastal taxa occur offshore in higher abundances in cold upwelling filaments than in the surrounding warm ocean waters (Keister et al., 2009). Again, this shows that upwelling in the Baltic Sea is an efficient contributor to the coastal water exchange with an open sea (Kahru et al., 1995; Levy, 2008), and is responsible for the mixing of water masses (Zhurbas et al., 2008), and the formation of frontal zones with strong cross-front property gradients (Kahru et al., 1995; Alenius et al., 1998).

However, in the shelf seas, like the Baltic Sea, the initial effect of upwelling might be somewhat different and the influence on the ecosystem productivity may not be as obvious as in the oceanic environment (Suursar and Aps, 2007). A rapid drop of SST strongly influences the coastal ecosystem through the direct effects of temperature on species performance, and indirectly through the species interactions (Iles et al., 2012). Only after the upwelling relaxation phase temperature-sensitive organisms begin to thrive and most likely because of the proliferation of phytoplankton promoted by the nutrient input, the Chl-*a* concentration starts to increase, becoming highest in about two weeks after the upwelling event (Uiboupin et al., 2012; Vahtera et al., 2005).

The upwelled waters being rich in nutrients might also trigger changes in the phytoplankton community, productivity and species composition (Nommann et al., 1991; Laanemets et al., 2004; Lips and Lips, 2010; Kratzer et al., 2011). Observations by Vahtera et al. (2005) or Lips and Lips (2010) demonstrated that in some cases upwelling might be responsible for the displacement of populations such as *Aphanizomenom sp.*, which could have been residing in the thermocline before upwelling event. Besides, events such as upwelling are important in replenishing phosphate concentrations during the nutrient depletion growth season (Vahtera, 2007). So species, having a high requirement for nutrients might also have a competitive advantage during upwelling events (Lips and Lips, 2010). The combination of low DIN/DIP ratio in the upwelled waters with the access to nutrients from below the seasonal thermocline could create favourable conditions for the nitrogen-fixing cyanobacteria growth (Lips et al., 2011). In addition, interactions between physical and biological processes during upwelling in the coastal areas have significant implications for coastal pelagic communities (Vahtera et al., 2005; Aceves-Medina et al., 2009), higher trophic levels and biogeochemical cycling (Tapia et al., 2009; Capone and Hutchins, 2013).

During summer-time holiday season coastal upwelling might also have a negative impact on particular tourist areas due to rapid drop of water and air temperatures nearshore (Lehmann et al., 2012). Furthermore, bathing tourism depends on a good water quality while post-upwelling phytoplankton blooms might significantly reduce it, making coastal waters unattractive for recreation (Schernewski et al., 2008).

Up to now, the Baltic Sea upwelling and its impact to coastal environment has been studied using various techniques. Conventional *in situ* sampling for phytoplankton dynamics studies during coastal upwelling events in the Gulf of Finland was used in (Lips and Lips 2010). Upwelling-induced primary production and chlorophyll-*a* concentration changes were analysed in (Zalewski et al., 2005; Kuvaldina et al., 2010). Modelling tools came in handy for analysing upwelling dynamics as well (e.g. Myrberg and Andreejev, 2003; Zhurbas et al., 2006). Then, the availability of satellite data has given a great boost for upwelling studies since the spatial and temporal coverage allowed to overcome restrictions of *in situ* point-wise measurements (Vahtmäe et al., 2006). The remote sensing methods are now widely used in various upwelling studies (e.g. Krężel et al., 2005; Kozlov et al., 2012; Lehmann et al., 2012; Bednorz et al., 2013; Sproson and Sahlee, 2014, Delpeche-Ellmann et al., 2017). In addition, remote sensing can provide frequent data with large spatial coverage for studies of water quality parameters that might be influenced by the coastal upwelling, such as chlorophyll-*a* (Bresciani et al., 2011) that are often available at no cost (Geller et al., 2017).

3

Materials and methods

3.1 Study area

The Baltic Sea is a landlocked, shallow shelf sea (Kulinski and Pempkowiak, 2011) with the mean depth of 54 m and maximum depth in Landsort Deep, 459 m (Leppäranta and Myrberg, 2009). Typically, the coastal area in the most parts is quite shallow (20–40 m); only the central parts of the SE Baltic Sea region (max. depth 249 m) and the Bay of Gdansk (max. depth 114 m) are somewhat deeper. As can be seen in Figure 5, the coastline of the study site (SE Baltic Sea) is relatively strait and oriented so that northerly and north-easterly winds favour upwelling development here, thus coastal upwellings are rather frequently observed in the region (Lehmann and Myrberg, 2008; Lehmann et al., 2012), especially during warm season, when the vertical temperature stratification is strongest. Besides, upwelling might be often accompanied by the plume of highly productive waters from the Curonian Lagoon as the Ekman transport during upwellings produces a sea-level fall at the coast (Leppäranta and Myrberg, 2009).

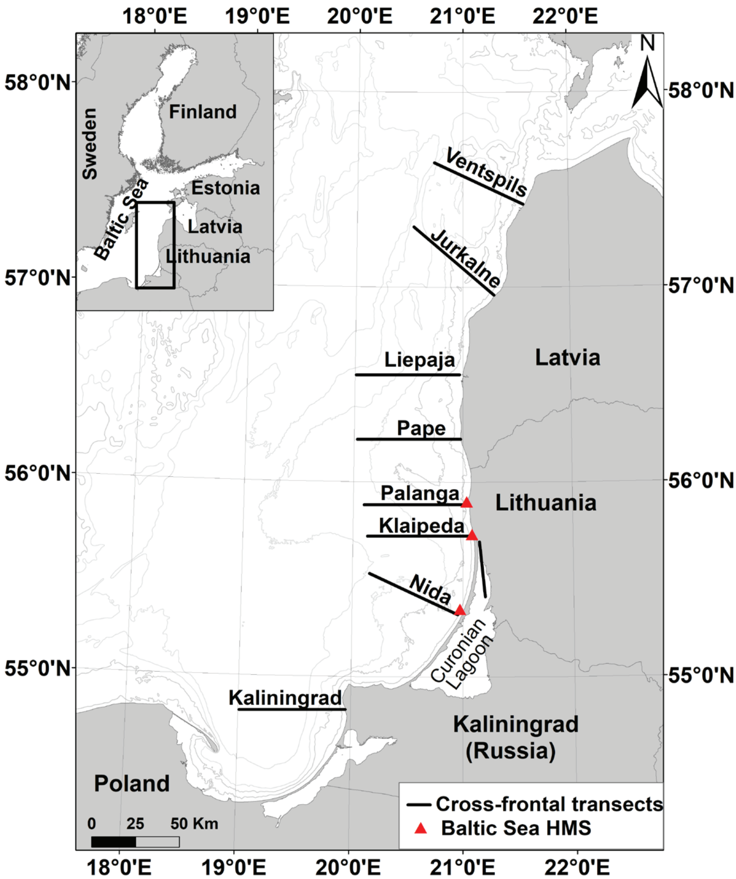


*Figure 5***.** Map of the study site in the SE Baltic Sea showing the locations of cross-frontal transects and hydrometeorological stations (HMS).

5 paveikslas. Tyrimo regionas su SST profilių vietomis bei pažymėtomis hidrometeorologinių stočių (HMS) vietomis.

In the Baltic Sea, seasonal differences in phytoplankton growth are observed between the east-west and north-south gradient (Gasiunaite et al., 2005) while the horizontal distribution is mainly associated with the changes in trophic conditions, nutrient availability, salinity and temperature, also with large scale marine gradients of decreasing salinity from Kattegat to the Bay of Bothnian, as summarised in Wasmund and Siegel, (2008). According to a detailed study at Gasiunaite et al. (2005), in the Lithuanian coast the phytoplankton succession is characterised by the dominance of dinophytes in April, cyanophytes in July-August and diatoms in late autumn and winter. Besides, the Curonian Lagoon plays an important role in the Lithuanian coastal zone as the freshwater plume from the lagoon is rather frequently observed, changing the hydrodynamics of the coastal waters. In addition, buoyant plume regions are usually characterized as having high phytoplankton biomass (Franks, 1992), thus, enhancing the activity at a higher trophic levels (Vaiciute, 2012).

The Curonian Lagoon – a shallow, highly eutrophied and mainly freshwater basin, is the largest (1,584 km^2) Baltic Sea lagoon, separated from the open sea by relatively narrow sandy Curonian Spit (0.5–3 km wide) and connected to the sea through the narrow (0.4–1.1 km) Klaipeda Strait at the northern end of the Lagoon. The strait is ca. 11 km long, with artificially deepened waterways down to 14 m depth (Gasiunaite et al., 2008) while the mean depth of the lagoon is approximately 3.8 m (Žaromskis 1996). Water exchange between the Baltic Sea and Curonian Lagoon is mainly governed by the river inflow to the Lagoon and the difference of water levels between the sea and lagoon (Jakimavicius et al., 2018). The northern part of the Lagoon is a transitory riverine-like system (Zemlys et al., 2008) with an active interaction with the Baltic Sea so annual average water salinity of 2.45 g kg^{-1} can fluctuate up to 7 g kg^{-1} due to Baltic water intrusions (Dailidiene and Davuliene, 2008).

In general, biological diversity is higher in the Curonian Lagoon than in the open coastal waters of the Baltic Sea (Olenina and Olenin, 2002). The lagoon is dominated by the freshwater phytoplankton species that generally follows a pattern typical of the eutrophic ecosystems with a prevalence of diatoms from January until June followed with the dominance of cyanophytes and diatoms until the biomass peak is generally reached in August–September and again, with diatoms abundant in late autumn (Gasiunaite et al., 2005; 2008). Only during seawater intrusions, marine species enter the lagoon and the overall abundance of phytoplankton is observed to markedly decrease with the increasing salinity (Gasiunaite et al., 2008).

3.2 Data and approach

3.2.1 Data

This work compiles several case studies with different objectives, therefore different data sets and analysis methods were used (Table 1). The main methods and data sets used are presented in the following subsections (3.2.1–3.2.4).

Table 1. **Summary of data used in different case studies of the thesis.**

1 lentelė. **Disertacijoje naudotų duomenų apžvalga.**

Data	Data Source	Time period
MODIS Level 2 SST products (In total about 1700 satellite SST images)	SST data retrieved from the moderate resolution imaging spectroradiometer (MODIS) on board Terra and Aqua	2000–2015
MERIS/Envisat Chlorophyll-*a* concentration (in total 144 cloud-free maps)	Chl-*a* data retrieved from the Medium Resolution Imaging Spectrometer (MERIS) on board ENVISAT	2005–2011
3-hourly wind speed and direction from Klaipeda station	Lithuanian Hydrometeorological Service under the Ministry of Environment of the Republic of Lithuania	2000–2015
Water temperature and salinity from Klaipeda, Palanga and Nida hydrometeorological stations	Former Department of Marine Research (Lithuanian Environmental Protection Agency), now – Environment Research Department	2000–2015
Water level from Nida (lagoon) and Klaipeda Strait	Former Department of Marine Research (Lithuanian Environmental Protection Agency), now – Environment Research Department	2000–2015
Nemunas Discharge	Lithuanian Hydrometeorological Service under the Ministry of Environment of the Republic of Lithuania	2005–2010
Solar Radiation	Surface incoming shortwave radiation, MVIRI/SEVIRI on METEOSAT, Daily, Mean	2005–2010

SST. In this work we used Terra/Aqua Moderate Imaging Spectrometer (MODIS) SST maps (available from year 2000) for the period of 2000–2015 to characterize the SE Baltic Sea coastal upwelling from the distribution and evolution of its surface thermal signatures. MODIS Level 2 daytime (MODIS thermal bands 31 (11 μ) and 32 (12 μ) imagery (L2_LAC_SST product) covering the study site with spatial resolution of about 1 km (Brown and Minnet, 1999) were obtained from the NASA OceanColor website. Validation of this product against *in situ* observations in the SE Baltic and the Curonian Lagoon carried out by Kozlov et al. (2014) showed a very good correspondence between space-borne and conventional SST measurements suggesting that MODIS-based SST retrievals can be used further to analyse the SST development over the study region.

MODIS SST images were processed using the ESA BEAM, Mathworks © Matlab software and ArcGIS 10.5.1 software by Esri. Visual inspection was used to eliminate cloud-covered images. In total about 1700 satellite images covering 16 years of observations between April–September were processed, from which 239 satellite images were used further to analyse statistical properties of coastal upwelling in the SE Baltic Sea.

Chl-a. For the analysis of coastal upwelling impact on the spatial distribution of chlorophyll *a* (Chl-*a*) concentration during upwelling events MERIS/Envisat full resolution (300 m) cloud free images were used. The Level 1b images firstly were corrected to account for the difference between actual and nominal wavelengths of the solar irradiance in each channel (Fomferra and Brockmann, "The BEAM project web page") with the Smile tool (1.2.101 version) of the BEAM VISAT (4.8.1) software provided by Brockmann Consult/ESA, in order to perform an irradiance correction for all bands. Chl-*a* concentration in the coastal waters of the Baltic Sea was retrieved after application of FUB processor (1.2.4 version) developed by the German Institute for Coastal Research (GKSS) and Brockmann Consult and Freie Universität Berlin. The FUB processor is designed for European coastal waters and uses MERIS Level 1b top-of-atmosphere radiances to retrieve the concentration of the optical water constituents (Schroeder et al., 2007). More details in Vaiciute et al. (2012). The retrieval of Chl-*a* concentration in the Curonian Lagoon was based on Giardino et al. (2010) and Bresciani et al. (2012) after revision in (INFORM). MERIS data was atmospherically corrected by using the Simulation of the Satellite Signal in the Solar Spectrum (6S) code (Vermote et al., 1997). Chl-*a* concentration was estimated by semi-empirical Near Infrared/Red band ratio algorithm that was calibrated with *in situ* data collected in the Curonian Lagoon (Bresciani et al., 2012).

In situ. 3-hourly wind speed and direction data sampled at 10 m height at Klaipeda coastal monitoring station provided by the Lithuanian Hydrometeorological Service under the Ministry of Environment of the Republic of Lithuania were used for the analysis of the upwelling favourable meteorological conditions. Klaipeda station was chosen as a representative point of wind conditions along the SE Baltic Sea coastline. Water temperature and salinity data from Nida and Palanga hydrometeorological stations provided by the Department of Marine Research (Lithuanian Environmental Protection Agency) were used to trace upwelling signatures in these records.

3.2.2 Satellite-based analysis of upwelling parameters

Following the methodology of previous researches (Gidhagen, 1987; Myrberg and Andrejev, 2003) 2 °C threshold was used (temperature drop ≥2 °C relative to ambient waters) to identify coastal upwelling events in satellite SST images and exclude other processes with temperature changes not associated with coastal upwelling, e.g. diurnal temperature changes, etc.

The primary upwelling parameters derived from the analysis of satellite data include upwelling frequency and duration, upwelling-related SST drop and cross-frontal horizontal SST gradient, as well as main spatial parameters of upwelling front – its cross-shore and alongshore extent, and total area. The upwelling frequency was calculated as the number of upwelling events per single thermally-stratified period from April to

September for any given year. Duration of a single upwelling event was calculated as the sum of days when upwelling signatures were detectable in SST maps (Plattner et al., 2006). In order to evaluate modulation of sea surface temperature during coastal upwelling events, it was defined in terms of SST drop (ΔT) and horizontal SST gradient. Upwelling-induced SST drop (ΔT) was defined as a difference between the mean SST of ambient (upwelling-free) waters and the minimum SST value over the particular transect across the upwelling front (Figure 5), while the total area of upwelling-affected waters was calculated from the corresponding low-temperature pixels.

Horizontal SST gradient, SST drop and cross-shore extent of upwelling front were retrieved from SST data taken along eight transects perpendicular to the SE Baltic Sea coast (shown in Figure 5). One transect is located next to the Sambian peninsula (denoted as Kaliningrad), three transects – along the Lithuanian coast (close to Nida, Klaipeda and Palanga), and four – along the Latvian coast (near Pape, Liepaja, Jurkalne and Venstpils). To evaluate upwelling impact on the shallow hypereutrophic coastal lagoon, one transect was also located in the northern part of the Curonian Lagoon (Figure 5).

3.2.3 Statistical analysis

To analyse if the changes in Chl-*a* concentration induced by the upwelling were significant, 30 points in each case were randomly selected using ArcGIS 10.5.1 software both in the upwelling zone and in the reference zone. Before the analysis, data was tested for normality and met the conditions, therefore no transformations were applied. Statistical comparison between the two groups (Chl-*a* concentration in the upwelling zone and in the reference zone) was performed by using *t*-test with R 3.5.1 software. To analyse the changes in Chl-*a* concentrations the descriptive statistics (means, medians, minimum, maximum values and standard deviations) were used in the study to represent the estimated parameters and their variability in the upwelling zone and in the reference zone. The areas affected by the plume from Curonian Lagoon were excluded from the further analysis.

Nonlinear regression analysis (Generalized Additive Modelling, GAM) was used to find the set of environmental factors that explain the variation of Chl-*a* concentration in the upwelling zone. Prior to the analyses, a Pearson's correlation analysis was conducted to test for correlations among quantified environmental parameters. It revealed a strong positive correlation between Upwelling SST and ΔT (rPearson = 0.73) and, therefore ΔT was excluded from the subsequent multivariate analyses. Environmental variables examined were: Nemunas discharge, upwelling SST, Solar radiation, average wind speed and direction while the dependent variable was the median value of Chl-*a* concentration. The regression analysis was performed using the Brodgar, version 2.7.5, software (www.brodgar.com/index.php/download).

3.2.4 Ekman-based upwelling index

The computations for deriving the upwelling indices were described by Bakun (1973) and since then are widely used to estimate the upwelling strength, seasonal variability, also for a better understanding of physical-biological coupling (e.g. Gomez-Gesteira et al., 2006; Bograd et al., 2009; Chenillat et al., 2012; Cropper et al., 2014).

As an additional tool for the identification of upwelling events in observational data and the analysis of upwelling response to meteorological conditions, the upwelling index (UI) was used. UI represents a measure of the volume of water that upwells (positive values) or downwells (negative values) at the coast, owing to the coastal divergence of geostrophic winds (Chenillat et al., 2012, Bograd et al., 2009).

Based on the proposal by (Gomez-Gesteira et al., 2006) the Ekman transport was calculated in terms of the wind speed at the 10 m level, W, the seawater density, ρ_w = 1025 kg m^{-3}, a dimensionless drag coefficient, C_d=0.0012(0.066|W|+0.63) adapted for the Baltic Sea (according to Myrberg and Andrejev, (2003)), and the air density, ρa (assumed constant at 1.22 kg m^{-3}):

$$Q_x = \frac{\rho_a C_d}{\rho_w f}(W_x^2 + W_y^2)^{1/2} W_y \qquad (1)$$

$$Q_y = -\frac{\rho_a C_d}{\rho_w f}(W_x^2 + W_y^2)^{1/2} W_x \qquad (2)$$

where f is the Coriolis parameter defined as twice the vertical component of the Earth's angular velocity, Ω, about the local vertical given by f = 2Ω sin (θ) at latitude θ. Finally, subscript corresponds to the zonal component and the subscript to the meridional one. Then UI can be defined as the Ekman transport component in the direction perpendicular to the shoreline:

$$UI = Q \perp = -\sin(\theta)\, Q_x + \cos(\theta)\, Q_y \qquad (3)$$

where θ=π/2+φ and φ is the angle of the unitary vector perpendicular to the shoreline pointing landward (at Klaipeda station φ= 90°).

In this work calculations of UI were carried out using observational data from Klaipeda station having a central location over the study region. Time-span of the analysis was limited to the upwelling favourable season from April to September 2000–2015. To calculate daily UI 3-hourly wind data were daily averaged in this study to better fulfil Ekman conditions and later UI values were multiplied by a factor of 10^3 to represent a displacement of volume for each kilometre of the coast ($m^3\ s^{-1}\ km^{-1}$). The start (end) of the upwelling favourable conditions were defined as the date when the daily mean upwelling index becomes positive (starts to decrease). Cumulative upwelling index (CUI), i.e. the sum of daily values before the start of each upwelling event when UI was positive, was also calculated in order to better understand upwelling's response to favourable meteorological conditions.

According to Haapala (1994), it usually takes about 60 hours of mild, permanent direction winds to cause upwelling in the Baltic Sea. Therefore, in this study positive UI values observed for several days in a row and formed under northerly winds were considered as the conditions eligible for upwelling formation.

4

Results

Analysis of satellite SST images allowed identifying 69 distinct coastal upwelling events during the study period from April to September 2000–2015. Below in this section the comparison of the satellite-based upwelling identification with the use of Upwelling Index (UI) calculated from *in situ* measurements (Sub-section 4.1) is presented, followed by the analysis of upwelling-favourable meteorological conditions in Sub-section 4.2. The detailed description of main spatial and temporal parameters of coastal upwelling in the South-Eastern Baltic (SEB) coast, including upwelling-induced modulation of SST, is given in Sub-section 4.3. Sub-section 4.4 describes the major upwelling event recorded in summer 2006. Subsection 4.5 describes the scale of upwelling inflows to the Curonian Lagoon. Sub-sections 4.6 and 4.7 are dedicated for the analysis of upwelling-induced Chl-*a* concentration changes in the SE Baltic Sea and the Curonian Lagoon.

4.1 Satellite observations vs coastal measurements

To evaluate the effectiveness of satellite infrared (IR) SST measurements for upwelling detection in the SE Baltic Sea, the daily water temperature (T_w) records and upwelling index (UI) values calculated from *in situ* wind measurements were analysed and compared with satellite-based upwelling statistics.

It is seen from Figure 6, that during the entire study period the number of cloud-free SST maps was growing from April (around 160 maps) till July (around 450 maps) and then gradually dropping in September. It is also shown, that the biggest discrepancies of upwelling events identified in both, T_w and IR SST data and based on UI values occur in April and September. In turn, evaluation of upwelling index enabled the identification of 96 upwelling events, whereas from IR SST – 69 events and from T_w records only 58 events were identified. This demonstrates that satellite-based results represent about 72% of the total of all possible UI-based events or 87% of upwelling events identified with UI during May-August period, when there is slightly bigger number of cloud-free satellite data available.

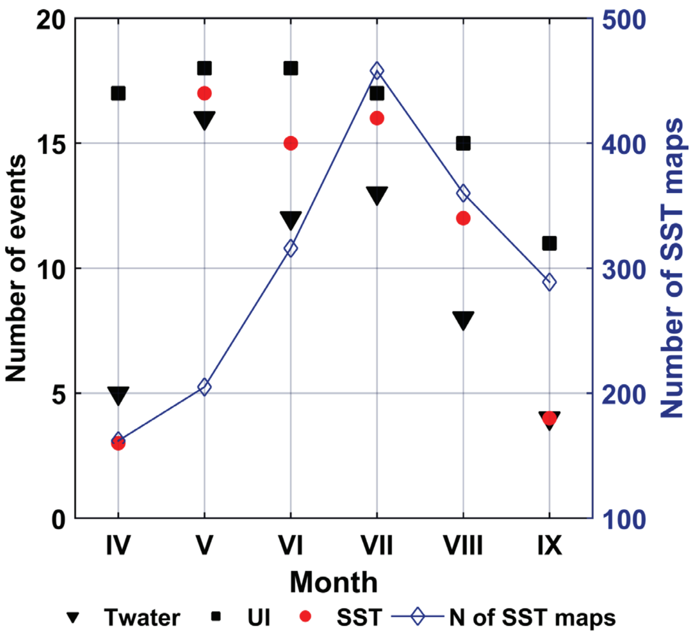


Figure 6. Overall number of upwelling events identified in satellite infrared (IR) imagery (denoted as 'SST, for sea surface temperature'), from water temperature (Tw) measurements at Klaipeda monitoring station and based on upwelling index (UI) in the SE Baltic Sea from April to September 2000–2015. Blue line with diamonds shows the number of satellite images available per month.

6 paveikslas. Bendras apvelingų, identifikuotų palydovinėse IR nuotraukose (pažymėta kaip 'SST'), pagal *in situ* vandens temperatūros duomenis (Tw) iš Klaipėdos priekrantės monitoringo stoties bei remiantis apvelingo indeksu (UI) skaičius PR Baltijos jūroje 2000–2015 m. balandžio rugsėjo mėnesiais. Mėlyna linija su rombais žymi viso laikotarpio palydovinių nuotraukų skaičių kiekvieną mėnesį.

Water temperature (T_w) records from coastal monitoring stations enable to identify only 60% of the total of all possible UI-based events. Moreover, even in cases when upwelling is clearly recorded in direct measurements, upwelling-associated temperature drop will be underestimated anyway, as the cold upwelling core lies at some distance from the coast. This is well exemplified in SST profiles shown in Figure 7, where, depending on the season, the first few pixels near the coast usually have higher SST values and do not represent upwelling core temperatures, especially in locations where the bottom slope is not very steep. For example, near Pape, where the slope is not as steep as it is near Klaipeda and Nida, the cold upwelling core might be as far as 3–8 km from the coast. The largest difference of 2–3 °C between the near-coast and the upwelling-core SST values is observed across all stations in spring and summer, while in autumn this effect is almost negligible.

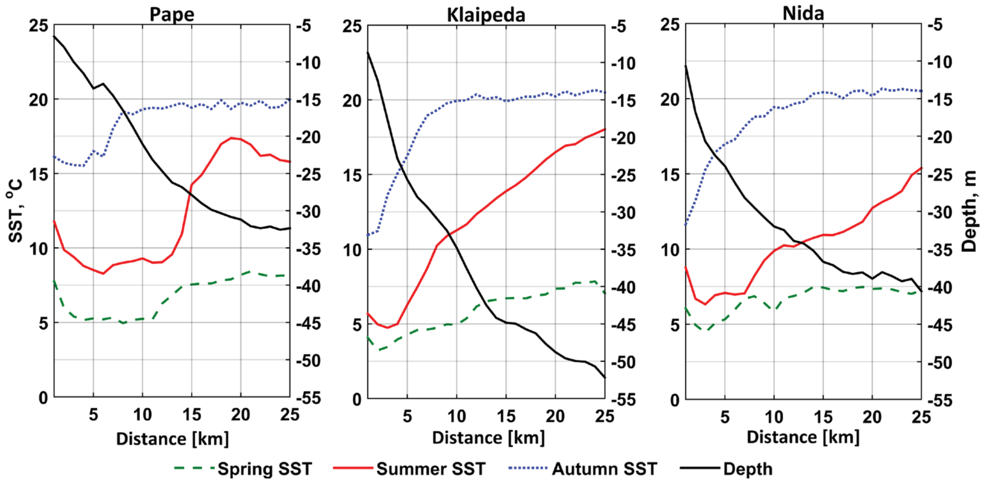


Figure 7. Typical SST and bathymetry profiles in the Baltic Sea near Pape, Klaipeda and Nida. Green-dashed line denotes spring SST, red solid line – summer SST, blue dotted line – autumn SST. Black solid line corresponds to bathymetry profiles (denoted as "Depth").

7 paveikslas. Tipiniai horizontalūs SST ir batimetrijos profiliai Baltijos jūroje ties Pape, Klaipėda ir Nida. Žalia brūkšninė linija žymi pavasario SST, raudona ištisinė linija – vasaros SST, mėlyna punktyrinė linija – rudens SST. Juoda vientisoji linija atitinka batimetrijos profilius (žymima „Depth").

4.2 Meteorological conditions prior to upwelling development

Figure 8 shows monthly wind roses for April–September 2000–2015 built from wind field data taken at Klaipeda station. As can be seen from the Figure 8, westerly winds clearly prevailed during the warm period. In turn, upwelling-favourable northerly winds were more pronounced during spring months, with N-NE winds comprising 21% in April and 18% in May. In June and July, the recurrence of northerly winds decreases to about 15–17%, rising again to about 20% in August and September. In general, upwelling-favourable winds are usually mild not exceeding 9 m s^{-1}, and only in April, a small portion of stronger winds of 9–12 m s^{-1} was observed.

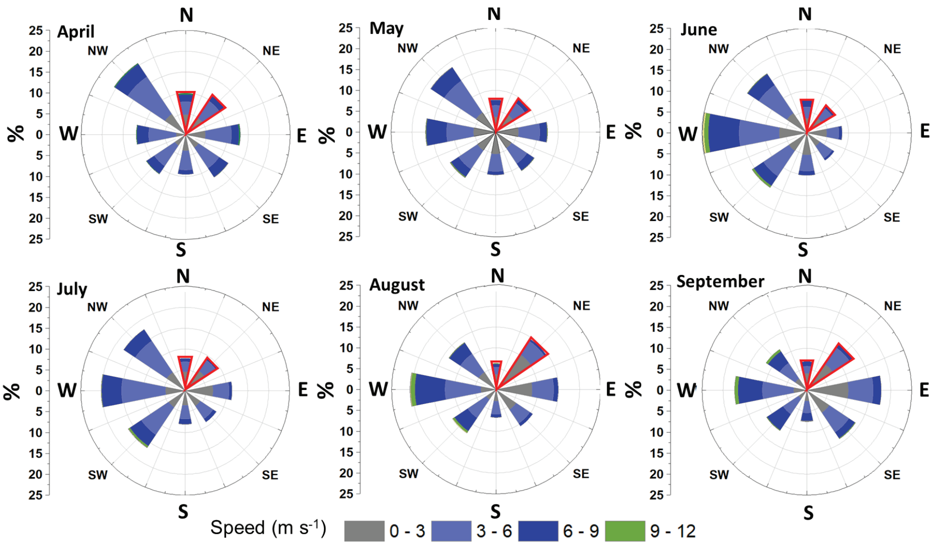


Figure 8. Monthly wind roses for April–September 2000–2015 based on data from Klaipeda coastal meteorological station. Wind directions framed in red indicates upwelling-favourable winds.

8 paveikslas. Vėjų rožės balandžio–rugsėjo mėnesiams. Sudaryta pagal 2000–2015 m. Klaipėdos priekrantės meteorologinės stoties duomenis. Vėjo kryptys, įrėmintos raudonai, žymi apvelingų formavimuisi palankias sąlygas.

Figure 9 a shows that in ~23% of events the upwelling system might respond quite rapidly, and the first surface signatures of cold upwelled waters appear just one day after positive UI values have started to be recorded. Yet, more generally, about 1–3 days of positive UI values are needed for the upwelling front to be manifested in SST data. In about 35% of cases, usually observed in April and September (Figure 9 c), upwelling signatures are manifested only 4 or more days after the favourable wind conditions have been established. As can be seen in Figure 9 b, CUI values prior to upwelling development range from 50 to 900 $m^3\ s^{-1}\ km^{-1}$. More than half (63%) have values up to 200 $m^3\ s^{-1}\ km^{-1}$, and only 9% are much larger, in the range of 600–900 $m^3\ s^{-1}\ km^{-1}$.

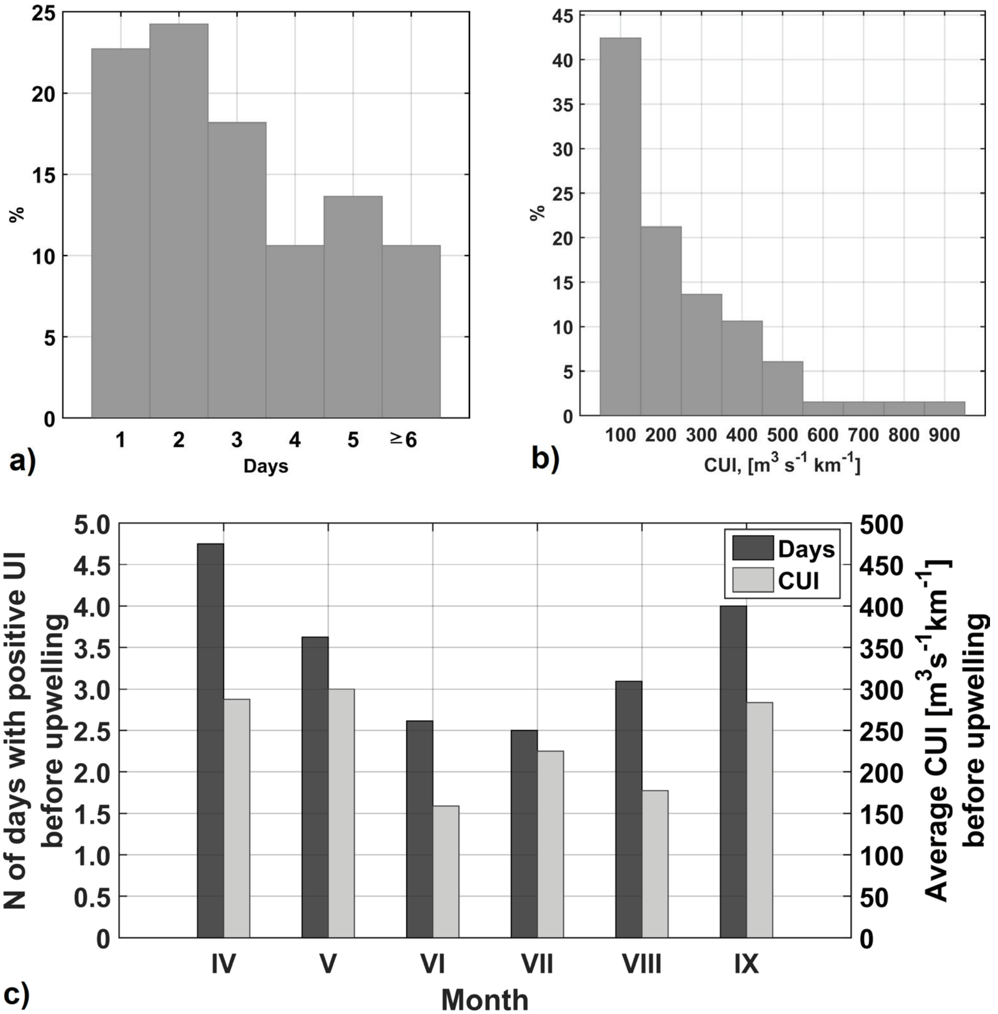


Figure 9. Meteorological conditions prior to coastal upwelling development in the SE Baltic Sea: **(a)** number of days with positive UI values before the first manifestation of coastal upwelling in satellite data; **(b)** cumulative upwelling index (CUI) for all coastal upwelling events identified in satellite data; **(c)** seasonal distribution of a and b.

9 paveikslas. Meteorologinės situacija iki apvelingų formavimosi PR Baltijos jūroje: **(a)** dienų su teigiamu UI skaičius iki apvelingo užfiksavimo palydoviniuose duomenyse; **(b)** kaupiamasis apvelingo indeksas visiems apvelingams, identifikuotiems palydoviniuose duomenyse; **(c)** sezoniniai a ir b pasiskirstymai.

Figure 9 c shows intra-seasonal variation of CUI and the number of days with positive UI before upwelling manifestation in the satellite data. Both parameters have a clear seasonal pattern: according to CUI and UI values, milder upwelling-favourable winds with shorter duration are required to generate an upwelling event during summer months when the seasonal thermocline is shallow and the vertical stratification of the water column is strongest and longer and stronger wind impulse is needed in spring and early autumn. Study results also indicate, that it takes only about 2.5 days with an average CUI of 150–220 $m^3\ s^{-1}\ km^{-1}$ to cause the upwelling in June and July, and more persistent yet weaker winds in August (Figure 9 c). In late spring and early autumn, the positive UI values should last 1–2 days longer (3.5–4.5 days) with the CUI values near 300 $m^3\ s^{-1}\ km^{-1}$.

4.3 Statistical parameters of coastal upwelling in the SE Baltic Sea

4.3.1 Upwelling season, frequency and duration

Figure 10 a shows a monthly distribution of the total number of upwelling events and number of days with upwelling identified over the entire study period. In general, upwelling events were detected during the thermally stratified season between April and September, with the earliest registered on April 14 (2010) and the latest on September 23 (2008). About 90% of events were observed between May and August, with a clear peak in July, when 18 events were registered. July is also characterized by the maximum number of upwelling days (124 days) during 2000–2015, equal to 8 upwelling days per month on average. For the high upwelling season (from May to August), the monthly averaged value is about seven upwelling days per month, or 20–25% of the month.

Figure 10 b shows a histogram distribution of the upwelling duration. The short-lived upwelling events of 2–6 days clearly dominated (57% of the total number), while about 27% of events persisted for 7–10 days. Yet, in cases of consecutive upwelling events the signatures of upwelling may last up to 23 days, as observed in summer 2006 and 2008.

The frequency of coastal upwelling ranged from one (in 2007) to several events per thermally stratified period, occurring about four times per season on average (Figure 10 c). The highest number of upwelling events was recorded in 2014 (eight events), but these events were rather short covering only about 20% of the warm period. The longest upwelling seasons were recorded in 2002, 2006, and 2008, with six upwelling events each year lasting for 52, 51, and 57 days, respectively, covering about 30% of the warm period. The season mean number of upwelling days accounts for about 16% of the warm season (~30 days).

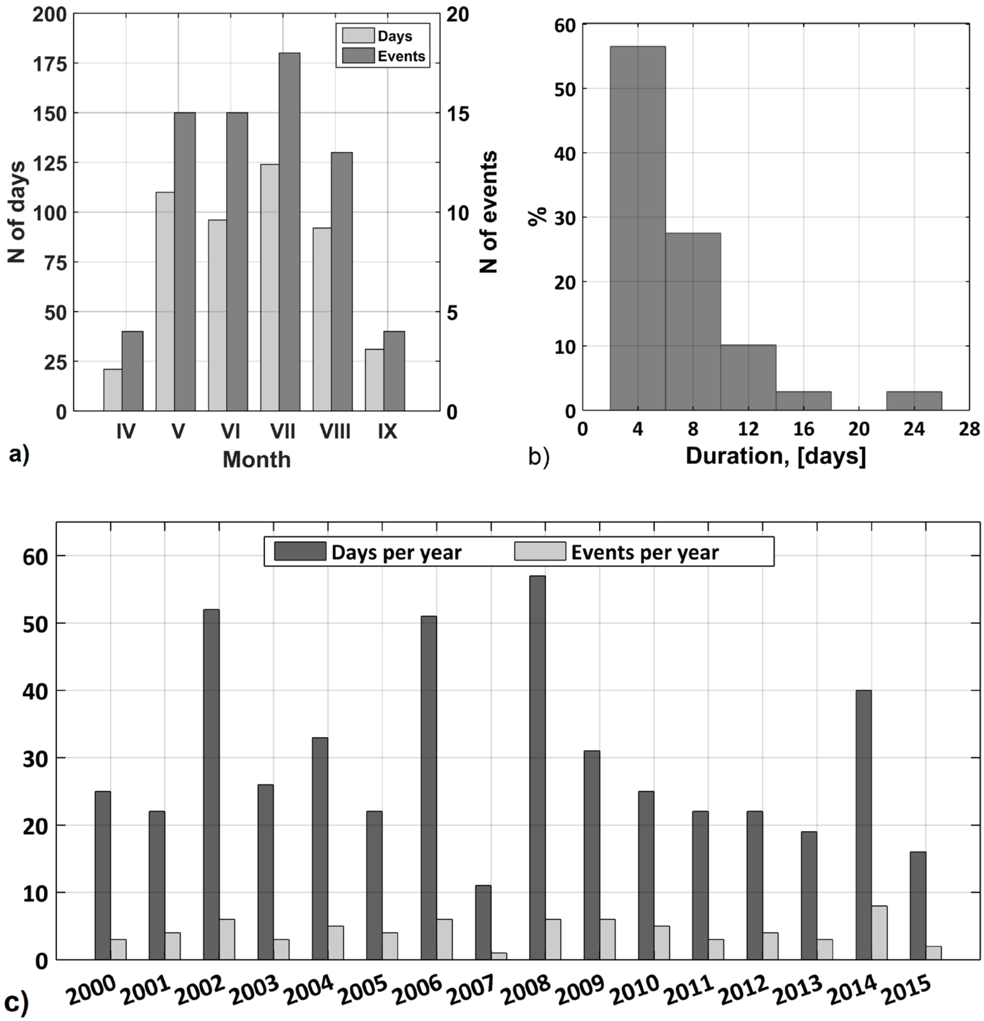


Figure 10. Upwelling season and duration in the SE Baltic Sea in 2000–2015: **(a)** total number of upwelling events/days with upwelling per single month; **(b)** histogram of upwelling duration; **(c)** interannual changes of upwelling duration and frequency.

10 paveikslas. Apvelingo sezoniškumas ir trukmė PR Baltijos jūroje 2000–2015: **(a)** bendras apvelingų/apvelingo dienų skaičius per mėnesį; **(b)** apvelingų trukmės histograma; **(c)** **a**pvelingo trukmės ir dažnumo pokyčiai skirtingais metais.

4.3.2 Modulation of sea surface temperature

The typical range of ΔT values observed in the SST records is about 2–6 °C, nonetheless the maximal values can even reach up to 10–14 °C (Figure 11 a). As Figure 11 b shows, there are no significant latitudinal differences in ΔT values along the SEB coast, with maximum and median values of about 12 °C and 4 °C, respectively. At the same time, one can clearly see a distinct seasonal variability of ΔT, shown in Figures 11 c, d. For instance, the average value of SST drop is around 3.5 °C in spring, while in summer and autumn it is ~5.3 °C (Figure 11 c). The number of ΔT values of 5–10 °C gradually rise from spring to autumn, while the highest SST drop values (>10 °C) are more frequently observed in summer than in autumn (Figure 11 d).

Typical values of SST gradient across the upwelling front range between 0.2 and 0.5 °C km^{-1} (Figure 12 a). In 25% of cases they are larger than 0.6 °C km^{-1} with the maximum recorded values of about 1.6 °C km^{-1}. Considerable spatial variations of SST gradient are evident (Figure 12 b). As can be seen in Figure 12 b, the strength of the local SST gradient changes and depends on the width of the upwelling zone over a particular location, however, the upwelling-associated SST drop is nearly similar along the SEB coast (Figure 11 b). Higher values of SST gradient are observed across relatively narrow parts of the upwelling front near Ventspils, Palanga and Klaipeda, where maximum (median) values of SST gradient are about 1.5 °C km^{-1} (0.5 °C km^{-1}). Moderate SST gradients were observed near Pape, Nida and Kaliningrad, while the lowest values were found near Jurkalne and Liepaja, where the upwelling zone is the widest (see Figures 13 and 14).

Seasonal variations of SST gradients are also visible (Figure 12 c, d). In spring, weak (<0.25 °C km^{-1}) SST gradients are dominant (in about 52% of the cases), while in summer and autumn SST gradients higher than 0.25 °C km^{-1} clearly prevail (58% in summer, 63% in autumn). The highest values (>0.75 °C km^{-1}) are observed more frequently in summer than in spring or autumn. Accordingly, the lowest monthly mean SST gradients are recorded in April (0.21°C km^{-1}) and gradually become higher throughout the warm season, with a clear peak in July (0.43 °C km^{-1}). Starting from August, a decreasing tendency is observed towards autumn, with the monthly mean SST gradient of 0.36 °C km^{-1} observed in September.

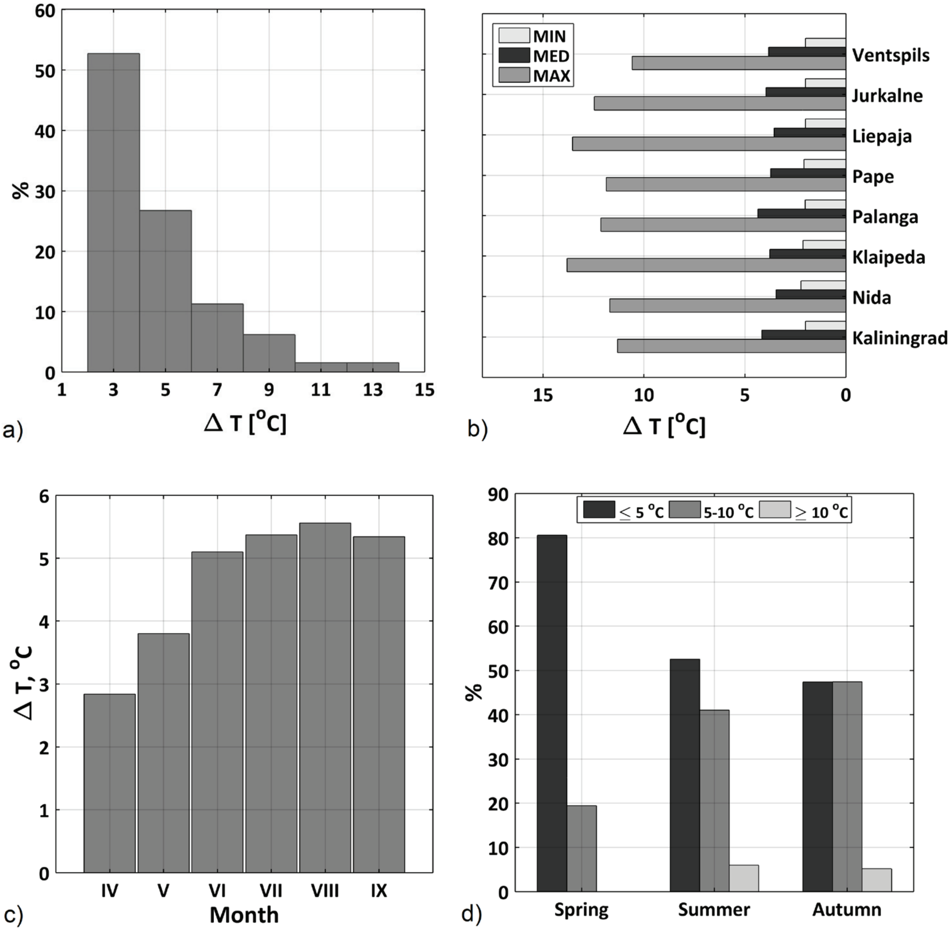


Figure 11. Upwelling induced SST modulations for the period 2000–2015: **(a)** upwelling induced ΔT; **(b)** spatial distribution of ΔT along the SEB coast; **(c)** mean monthly ΔT; **(d)** seasonal changes of ΔT.

11 paveikslas. Apvelingo sukelti SST svyravimai 2000–2015: **(a)** apvelingo sukelti ΔT; **(b)** erdvinis ΔT pasiskirstymas PR Baltijos jūros priekrantėje; **(c)** vidutiniai mėnesio ΔT; **(d)** sezoniniai ΔT pokyčiai.

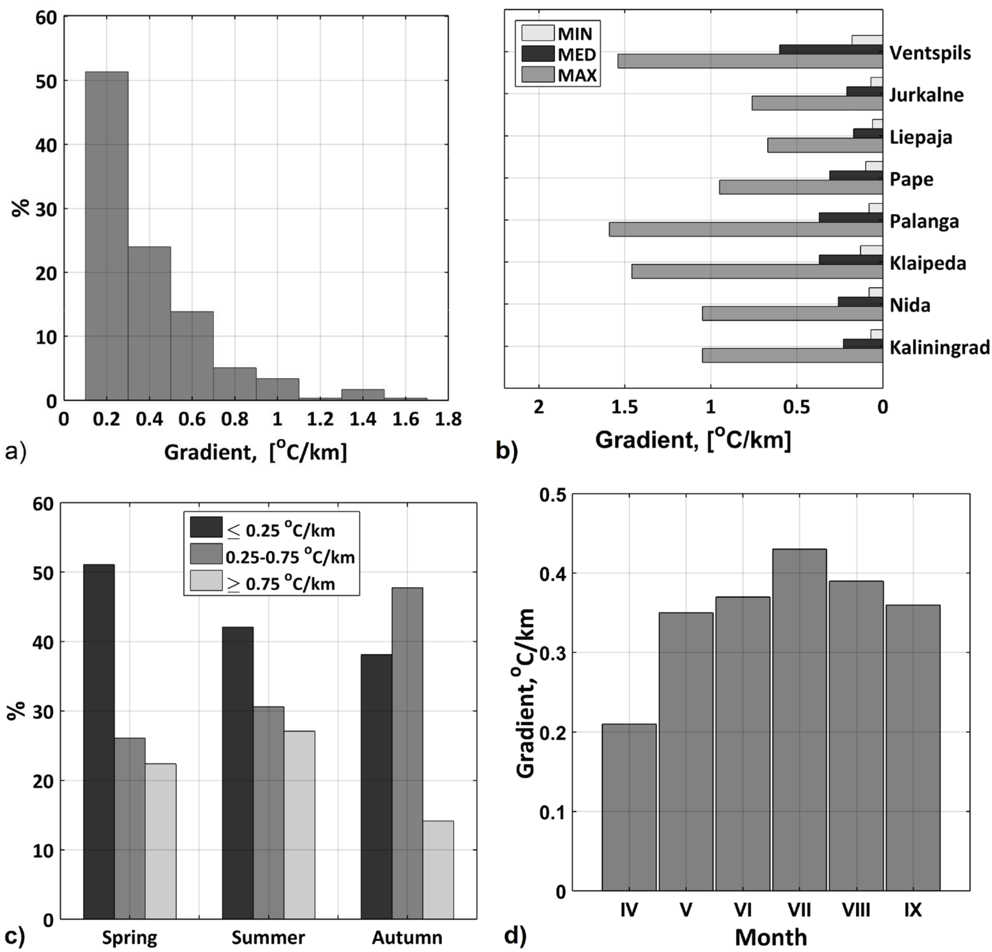


Figure 12. Upwelling-induced SST gradients for the period 2000–2015: **(a)** histogram of horizontal SST gradients; **(b)** spatial distribution of SST gradients along the SEB coast; **(c)** seasonal changes of SST gradients; **(d)** mean monthly SST gradients.

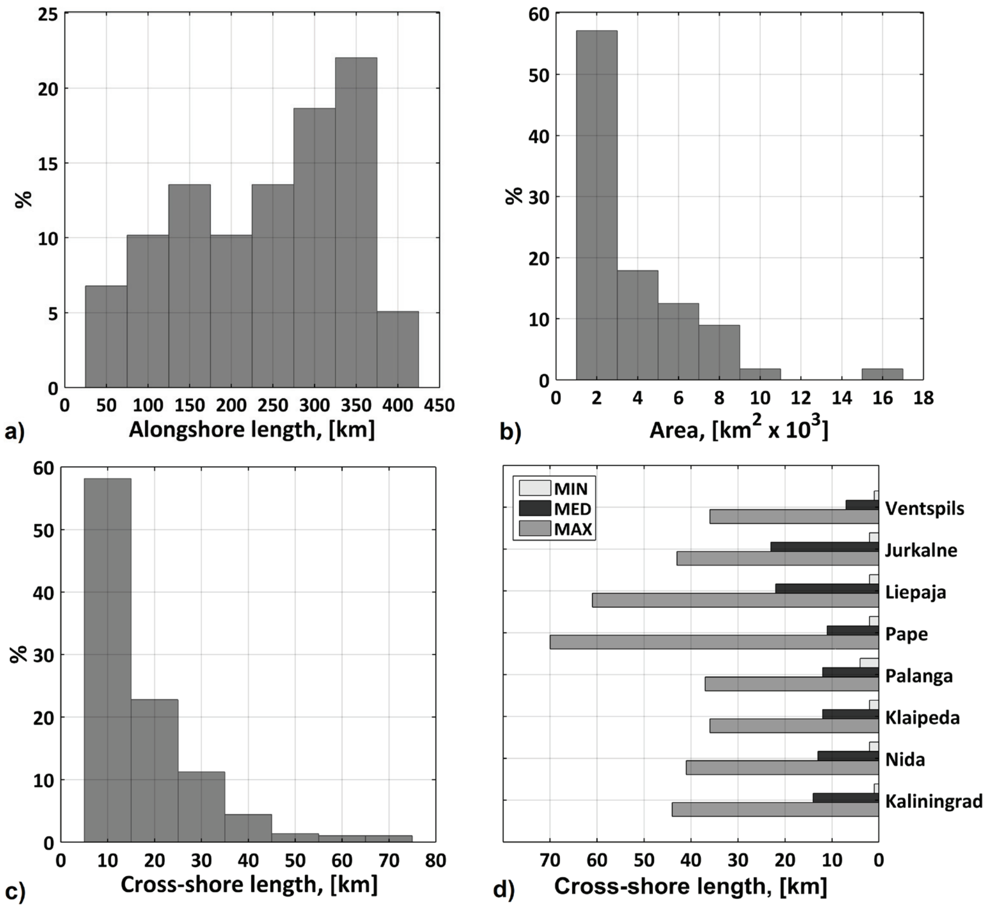
12 paveikslas. Apvelingo sukelti SST gradientai 2000–2015 m. laikotarpiu: **(a)** horizontalių SST gradientų histograma; **(b)** erdvinis SST gradientų pasiskirstymas PR Baltijos jūros priekrantėje; **(c)** sezoniniai SST gradientų pokyčiai; **(d)** vidutiniai mėnesio SST gradientai.

4.3.3 Spatial properties of the upwelling front

As Figure 13 a shows, the observed along-shore length of the upwelling front ranges from 50 to 400 km with the most frequent values of about 300–350 km. The area of upwelling-affected waters varies among the events in the range from several hundred up to several thousand square kilometres. In 57% of cases, upwelling extent is up to 3000 km^2, covering mainly Lithuanian and Latvian coastal waters. Yet it may reach up to 16000 km^2 (Figure 13 b) in some extreme cases, extending over a significant part of Gdansk and eastern Gotland Basins (Figure 14).

The cross-shore extent (width) of the upwelling front in the SE Baltic Sea ranges between 5 and 70 km (Figure 13 c, d). The typical mean values are 10–20 km (Figure 13 d), while 5–15 km width is observed most frequently (Figure 13 c). During the intensive long-lasting events the cross-shore width of the upwelling front may exceed 30–40 km everywhere and reach 60–70 km in some locations (Figure 13 d).

Maximum values of cross-shore extent were recorded along the Latvian coast near Pape (70 km) and Liepaja (61 km). They were about 37 km near Lithuanian coast with slightly larger values observed next to Nida (41 km). Similar values were recorded near Kaliningrad, Jurkalne and Ventspils.



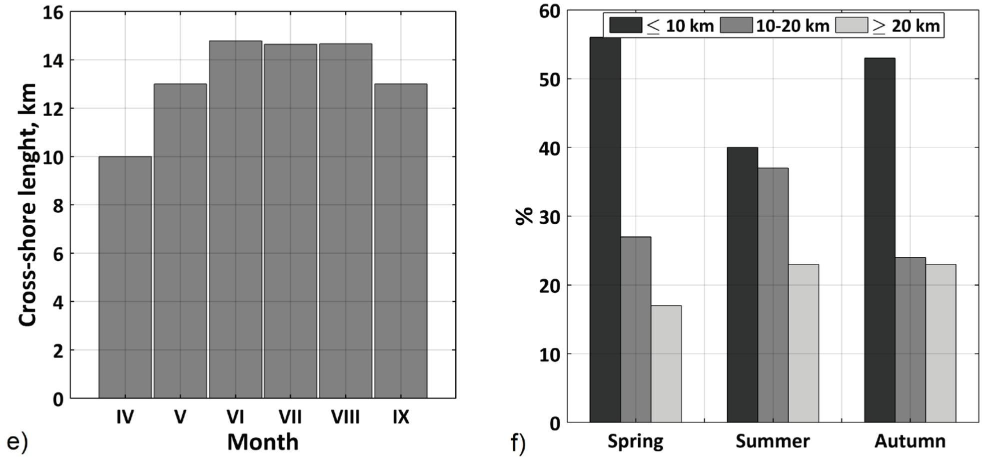


Figure 13. Spatial properties of coastal upwelling front in the SE Baltic Sea. Histogram distributions of **(a)** along-shore length; **(b)** upwelling area; **(c)** cross-shore length; **(d)** spatial distribution of cross-shore length; **(e)** monthly-mean cross-shore length, and **(f)** seasonal variation of cross-shore length.

13 paveikslas. Erdvinės apvelingų PR Baltijos jūroje savybės. Pasiskirstymų histogramos: **(a)** ilgis palei pakrantę; **(b)** apvelingo plotas; **(c)** apvelingo išplitimo atstumas nuo kranto; **(d)** atstumo nuo kranto erdviniai skirtumai; **(e)** mėnesio vidutinis apvelingo išplitimo atstumas nuo kranto ir **(f)** sezoniniai apvelingo išplitimo svyravimai.

Similar to other upwelling properties, the monthly mean upwelling cross-shore extent also has some seasonal variation, rising from 10 km in April up to 15 km during summer months (Figure 13 e). The portion of narrow upwelling fronts (<10 km wide) clearly dominates in spring and autumn months, and wider upwelling fronts (>10–20 km) are observed in summer (Figure 13 f).

Figure 14 shows a map of coastal upwelling frequency in the SE Baltic Sea derived from space-borne SST measurements taken between 2000 and 2015. The frequency map was calculated as a ratio between the sum of upwelling-affected pixels recorded at every 1 km × 1 km grid cell for every single upwelling event at the time of its maximal spatial development and the total number of upwelling events.

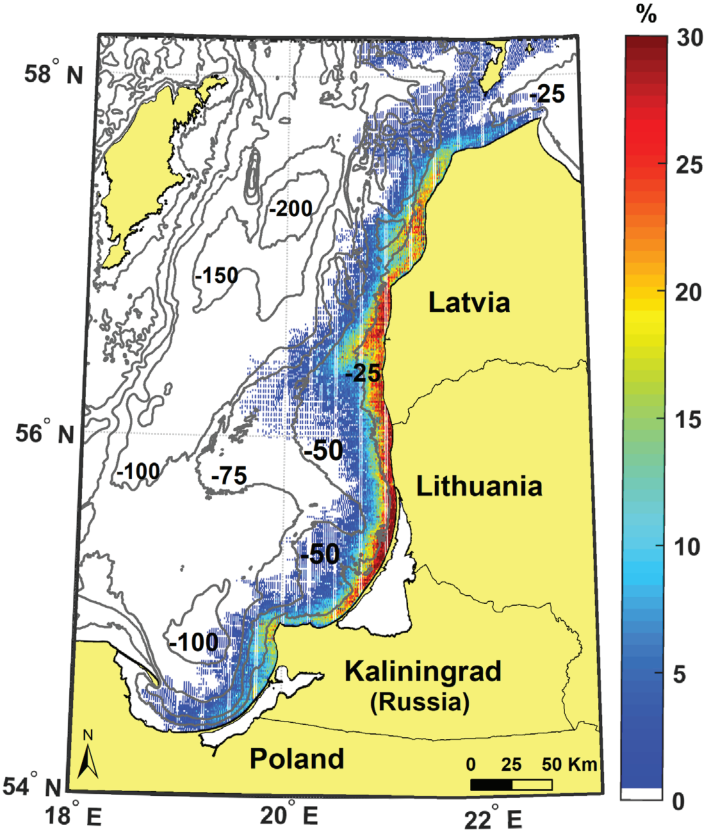


Figure 14. Spatial frequency of coastal upwelling along the SE Baltic Sea coast.

14 paveikslas. Apvelingų erdvinis pasikartojimo dažnumas PR Baltijos jūros priekrantėje.

Coastal upwelling developing under northerly winds has a typical width of the frontal zone of around 10–20 km, and covers the entire Lithuanian and Latvian coasts in 30% of cases. It is also rather frequent near Kaliningrad, but not so pronounced along the Polish and northern Latvian coasts having different geographic orientations. The frontal zone has numerous filamentary features located between 20° and 21°E, spreading up to 50–70 km offshore along isobaths (see Figure 15 for more details). For any upwelling of moderate intensity one would observe similar characteristics: it starts just in the vicinity of the coast and then spreads towards the open sea following the bathymetry contours. More details of upwelling front development and evolution are presented below, considering the major coastal upwelling event that took place in summer 2006.

4.4 Major upwelling event in summer 2006

The analysis of 16-year satellite observations clearly shows that the largest upwelling event in the SE Baltic Sea over the entire observation period took place in the summer of 2006 (Figure 15). The development of this upwelling event is illustrated in Figures 15–17. The available satellite data enabled the upwelling development to be captured both during the active phase, when persistent northerly winds brought cold deep waters to the surface, and during relaxation when the wind direction changed, but strong temperature/density gradients persisted for about two weeks.

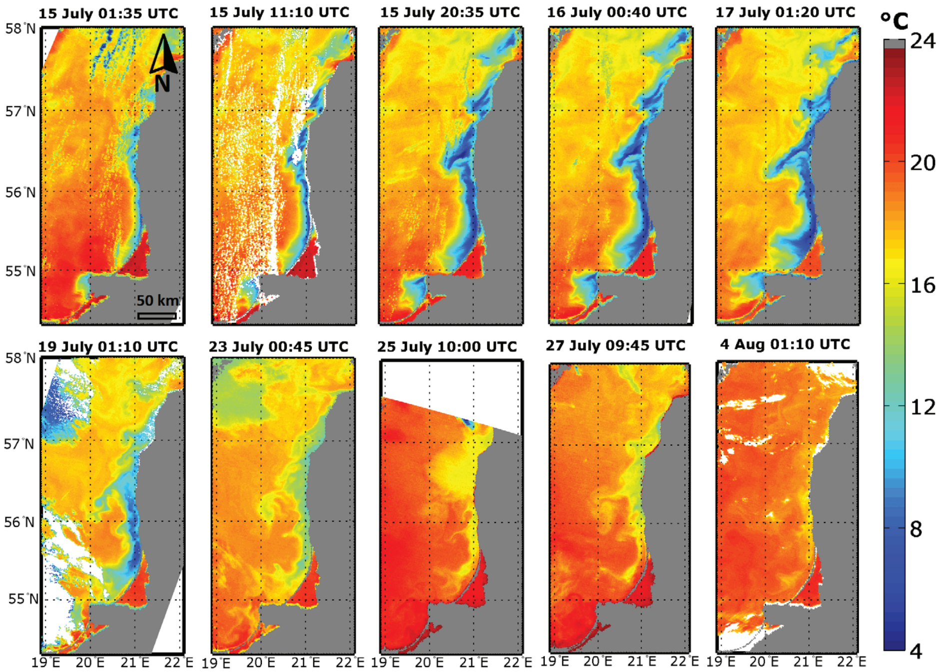


Figure 15. Development of a major coastal upwelling event in SE Baltic Sea in summer 2006.

15 paveikslas. Didžiausio apvelingo PR Baltijos jūroje formavimasis 2006 m. vasarą .

The satellite data show the first signatures of coastal upwelling on 13 July 2006, after the northerly winds started to dominate over the study region during 10–12 July 2006 (Figure 16).

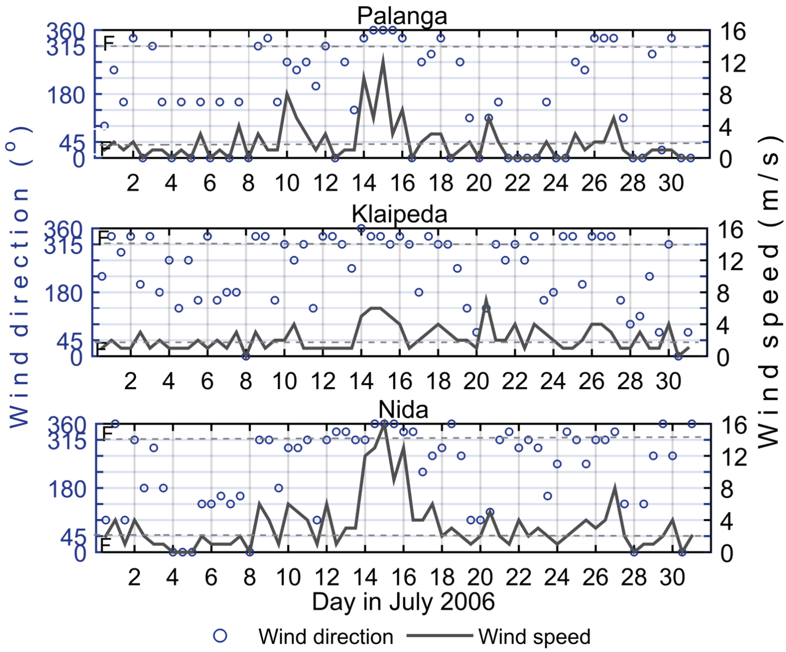


Figure 16. Wind speed and direction recorded in July 2006 at Palanga, Klaipeda and Nida coastal stations. 'F' in the left corners of each panel indicates upwelling-favourable northerly winds.

16 paveikslas. Vėjo greitis ir kryptis 2006 liepos mėn. pagal Palangos, Klaipėdos ir Nidos priekrantės meteorologinių stočių duomenis. 'F' žymėjimas kairiajame kiekvieno skydelio kampe nurodo vėjo kryptis, palankias apvelingų formavimuisi.

The beginning of upwelling is also well seen in water salinity (S) and air temperature (T_a) records made at Nida and Palanga coastal stations (Figure 17). An increase in salinity comes with a rapid drop of water temperature (T_w), marking the beginning of the upwelling event. An adjustment of the marine atmosphere boundary layer to the presence of the cold upwelling front is also clearly seen in T_a profiles (Figure 17) nicely following a sudden drop of water temperature at both stations, in turn, showing that cooling of surface waters is responsible for the air temperature drop down to 10 °C.

An intensive rise of cold deep waters to the sea surface was observed on July 15–17, 2006. During this period, the temperature of the cold upwelling core at the surface was as low as 5–7 °C, while the associated SST difference between the ambient and upwelling waters was up to 14 °C (Figure 15). The largest increase of salinity was observed at both coastal stations on July 14–21 and coincided with the maximal drop of T_w. However, these salinity changes were relatively small, $\Delta S \leq 0.5$ ‰, suggesting that surface salinity changes during upwelling events in the Baltic Sea usually does not exceed 0.5 ‰.

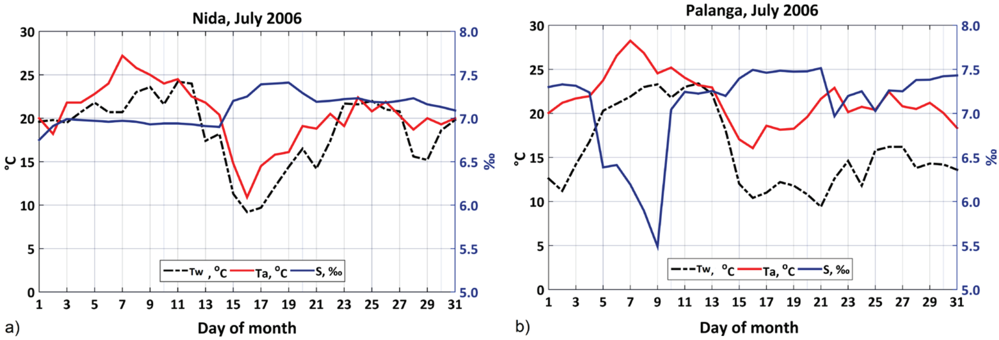


Figure 17. Sea water temperature (T_w), air temperature (T_a) and salinity (S) changes recorded at **(a)** Nida and **(b)** Palanga coastal stations in July 2006.

17 paveikslas. Vandens temperatūros (T_w), oro temperatūros (T_a) ir druskingumo (S) pokyčiai užfiksuoti **(a)** Nidos ir **(b)** Palangos priekrantės stotyse jūroje 2006 liepos mėn.

The movement of cold upwelling core can be traced based on the horizontal SST profiles (Figure 18). In particular, the movement of the cold core is very clearly seen near Nida, where filamentation patterns during the upwelling relaxation phase are not so clearly defined (Figure 15).

At the beginning of the upwelling development, i.e. on 15 July, the cold upwelling core of around 5°C appears near the coast of the Curonian Spit and is found approx. 5 km off the coast. At this stage, the observed seaward movement of the core reaches about 3 cm s^{-1} (Figure 18). On July 17–18, the wind direction changes (Figure 16), and the upwelling enters the relaxation phase, accompanied by gradual SST increase and further widening of the upwelling front. And due to the development of elongated transverse filaments at the frontal boundary, upwelling waters even spread up for about 70 km seaward in certain locations, e.g. near Latvian coast, nicely following regional bathymetric features.

During the relaxation phase, the horizontal velocity of the upwelling core slightly decreases to about 1 cm s^{-1} and keeps nearly constant while it continues moving further offshore. The filamentary jets become unstable, start meandering and evolve into cyclonic eddies that detach from the main upwelling front on July 23 (see Figure 15). Thus, on 27 July the cold upwelling core is already found at about 12.5 km from the coast with the total travel distance of about 8 km within 12 days. At the end of the upwelling relaxation phase, the salinity gradually begins to settle and at the end of July reaches values similar to those prior to the upwelling event. Air temperature is also slightly increasing, even though, as satellite data show in Figure 15, the cold upwelling waters were observed for further two weeks.

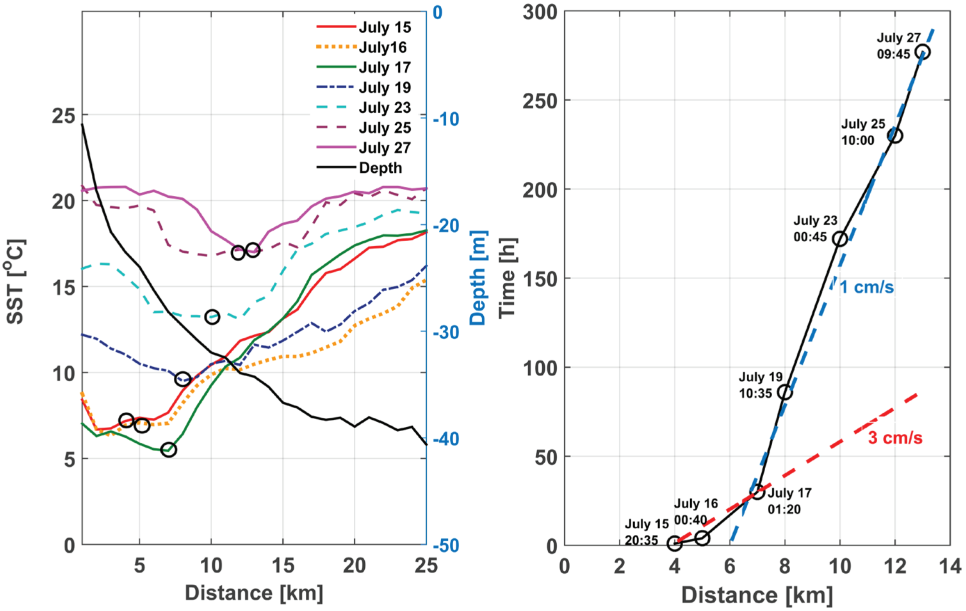


Figure 18. Horizontal SST profiles in 2006 July 15 20:35 GMT, July 16 00:40 GMT, July 17 01:20 GMT, July 19 10:35 GMT, July 23 00:45 GMT, July 25 10:00 GMT and July 27 09:45 GMT (left panel) and the movement of upwelling core (the right panel).

17 paveikslas. Horizontalūs SST profiliai 2006 liepos 15 20:35 GMT, liepos 16 00:40 GMT, liepos 17 01:20 GMT, liepos 19 10:35 GMT, liepos 23 00:45 GMT, liepos 25 10:00 GMT ir liepos 27 09:45 GMT (kairėje) ir apvelingo "šerdies" judėjimas (dešinėje).

4.5 Upwelling influence on the Curonian Lagoon SST

The analysis of available MODIS SST maps has revealed that out of 69 upwelling events recorded in the study, 18 events influenced the hydrological regime of the Curonian Lagoon quite significantly when the inflow of relatively cold and saline upwelling waters from the SE Baltic took place (Table 2).

Such upwelling inflows are averagely observed slightly more than once per season, but in some years there might be more cases when the Baltic Sea water entrainment to the lagoon coincided with an upwelling event. Normally, these inflows of the Baltic Sea waters were recorded to last for 1–3 days. However, then the inflow-favourable hydro-meteorological conditions coincided with the most intensive upwelling event in July 2006, the upwelling waters persisted at the northern part of the lagoon for more than one week changing the environmental conditions from the lagoon-inherent to the marine ones.

Table 2. **SST modulations in Curonian Lagoon during upwellings inflows.**

2 lentelė. **SST pokyčiai Kuršių mariose apvelingo vandenų įtekėjimo metu.**

Date	SST grad., °C km^{-1}	ΔT, °C	Date	SST grad., °C km^{-1}	ΔT, °C
2000.05.12-13	0.81	9.71	2005.06.19	0.37	4.20
2001.07.27-28	0.28	5.21	2006.07.13-20 / 23-31	0.71	16.46
2001.08.25	0.53	5.16	2009.05.13	0.16	2.90
2002.06.02-03	0.44	9.99	2009.07.05	0.52	6.48
2002.09.11	0.26	2.19	2011.08.03	0.63	3.07
2002.09.19	0.30	5.08	2012.05.24-25	0.52	5.67
2003.08.05-06	0.33	5.13	2014.05.03	0.19	4.64
2004.05.13-14	0.37	6.87	2014.06.16	0.30	5.50
2005.05.13-14	0.33	7.52	2015.07.02	0.31	3.41

It can be seen that ΔT between the upwelling affected and ambient lagoon waters was slightly higher than in the SEB coast, i.e. about 5–7 °C on average. During the most intensive inflow, it even reached 16 °C making it very uncharacteristic water temperatures for the Curonian Lagoon. The same pattern is seen with the horizontal temperature gradients. They are also somewhat higher compared to the Baltic Sea (0.1–0.3 °C km^{-1}), averagely around 0.3–0.5 °C km^{-1} and reaching up to 0.8 °C km^{-1}.

The map in Figure 19 a (obtained the same way as the Figure 14 in section 4.3.3) demonstrates the upwelling inflow frequency to the Curonian Lagoon indicating, that usually only Northern part (down from Klaipeda Strait to 55.5 °N) is affected by the inflows.

Figure 19 b shows the typical upwelling intrusion distances down the lagoon being of about 10–25 km with a total affected area of 40–100 km^2. Yet, as it is shown, in some cases the inflow of the upwelling waters reached even the middle part of the lagoon covering about 200 km^2 of the lagoon waters with the inflow distances of up to 40 km. As can be seen from Figure 19 c, demonstrating average wind speed and direction during upwelling inflow events, the winds of northerly directions (most frequently between N and NW) are prevailing when the intrusion of the upwelling waters is observed.

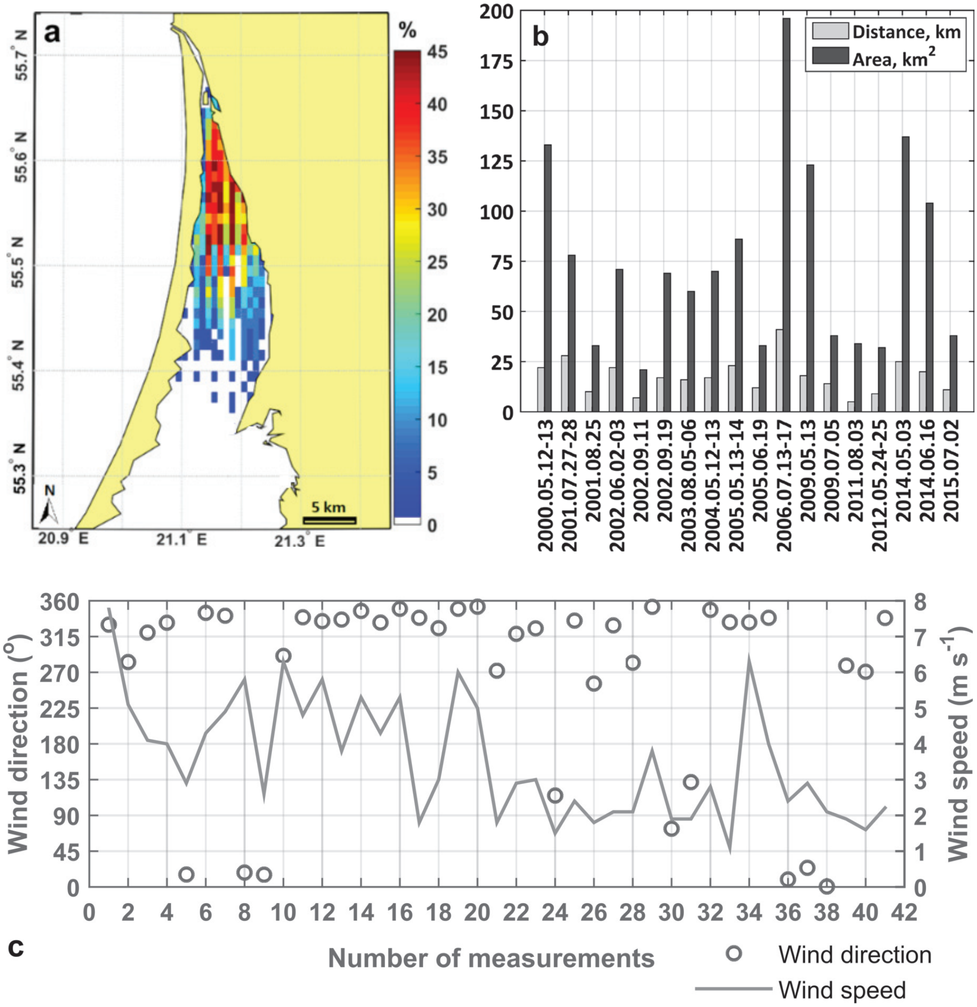


Figure 19. Upwelling influence on the Curonian Lagoon SST: **(a)** Spatial frequency of upwelling inflow; **(b)** inflow distance from the Klaipeda Strait down the Lagoon and affected area of the Lagoon and **(c)** average wind speed and direction at Klaipeda station during the inflow events.

19 paveikslas. Apvelingo poveikis Kuršių marių vandens temperatūrai: **(a)** Erdvinis pasikartojimo dažnumas; **(b)** apvelingo vandenų įtekėjimo atstumas nuo Klaipėdos sąsiaurio į marias ir paveiktas marių plotas bei **(c)** vidutinis vėjo greitis ir kryptis Klaipėdos stotyje apvelingo vandenų įtekėjimo metu.

The most intensive upwelling event during the study period took place in July 2006. As the sea level differences between the lagoon itself and the Baltic Sea lead to an intrusion of upwelling waters down the lagoon (Figures 20–21) it resulted not only in significant changes of SST in the SE Baltic Sea, but was responsible for drastic changes of the water temperatures in the Curonian Lagoon as well. As Figure 20 a shows, the water level at the entrance of the lagoon (Klaipeda Strait) was relatively low compared to the water level in the central parts (Nida). From approximately July 13 the situation became the opposite, i.e. water level in Klaipeda Strait increased and the inflow to the Curonian Lagoon followed. Variable hydrometeorological conditions resulted in the fluctuations of the inflow scale and even though there are satellite data gaps on July 21 and 24, it is obvious, that during the prevalence of stronger northerly winds, the influxes of cold and salty marine waters are stronger (up to 40 km from Klaipeda Strait). With the changes of wind direction, the affected area of the Curonian Lagoon decreases. For instance, on July 25 no signatures of the upwelling inflow are observed, while again, from July 26 to 31 the entrainment of marine waters to the lagoon is clearly visible, thus not as strong as before, with the distance down the lagoon of up to 15 km from Klaipeda Strait.

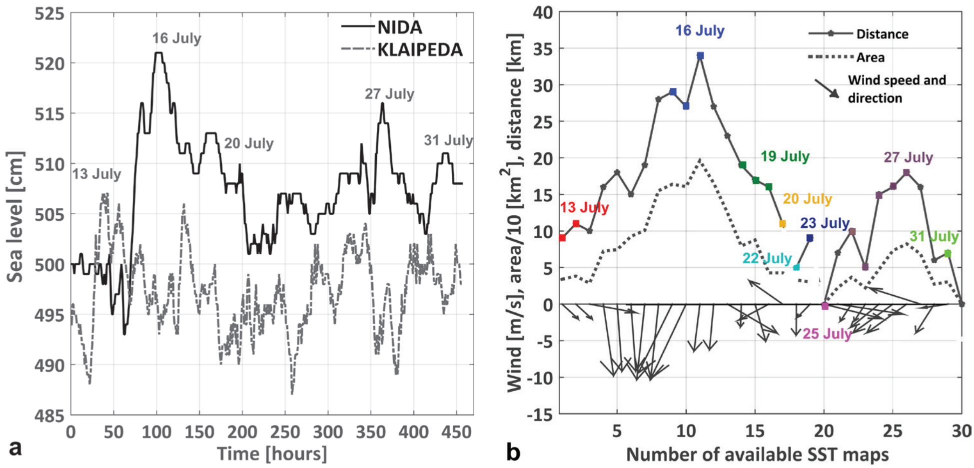


Figure 20 a-b. Wind and water level influence on the marine inflows to the Curonian Lagoon: **(a)** Sea level differences between Nida (Curonian Lagoon) and Klaipeda Strait; **(b)** upwelling inflow distance and area with corresponding wind vectors.

20 a-b paveikslas. Vėjo ir vandens lygio įtaka jūrinio vandens įtekėjimui į marias apvelingų metu: **(a)** vandens lygio skirtumas tarp Nidos (Kuršių mariose) ir Klaipėdos sąsiaurio; **(b)** apvelingo vandenų įtekėjimo atstumas ir plotas su atitinkamais vėjo vektoriais.

In Figure 21, demonstrating the spatial extent of upwelling inflow and changes in the SST during the major upwelling event in July 2006 it is clearly seen that this event also had a major impact on the Curonian Lagoon waters. Here the most vigorous inflow during the entire study period is captured in SST maps, showing, that the inflow leads to a drastic temperature drop (ΔT up to 16 °C) in the Lagoon. From the sequence of the SST maps one can also see that such inflow events might be very rapid with horizontal velocities reaching up to 0.16 m s^{-1} (0.13 m s^{-1} on average), this, again, means, that the Lagoon's ecosystem has to adapt to a very fast changing hydrological conditions so the pressure to the environment is high.

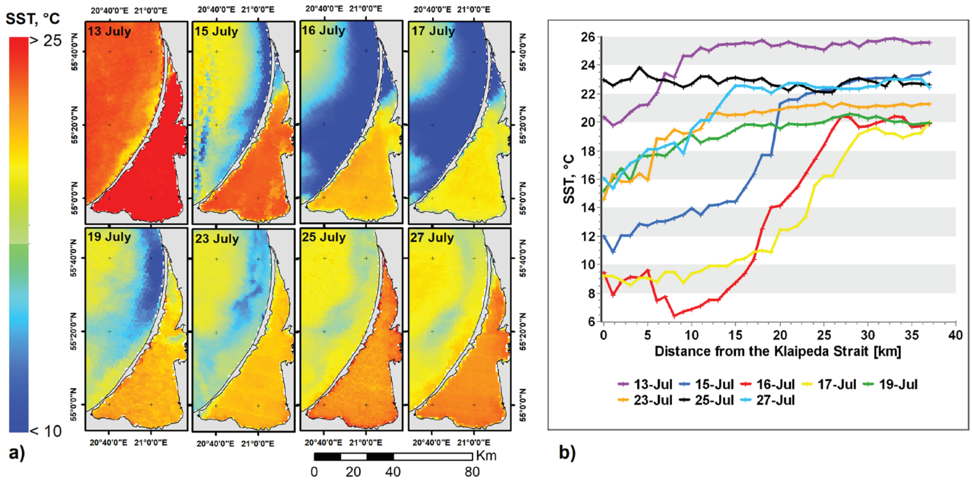


Figure 21. Upwelling inflow to the Curonian Lagoon in July 2006: **(a)** sequence of SST maps; **(b)** horizontal SST profiles going from Klaipeda Strait down the lagoon.

21 paveikslas. Apvelingo vandenų įtekėjimas į Kuršių marias 2006 liepos mėn.: **(a)** SST nuotraukų seka; **(b)** horizontalūs SST profiliai einant nuo Klaipėdos sąsiaurio į marias.

4.6 Upwelling-induced Chl-*a* changes in the coastal zone of the SE Baltic Sea

While there is very little *in situ* data available to study the changes of Chl-*a* concentration at the upwelling sites, these changes are clearly visible in the ocean color imagery. 27 upwelling days in total from 11 distinct upwelling events had concurrent cloud-free SST and Chl-*a* maps. The phytoplankton response to the upwelling events in the SE Baltic Sea coast was analyzed in terms of Chl-*a* variability. Chl-*a* concentrations in relation to SST changes were examined both in the upwelling affected and in reference zones. The main statistical parameters are presented in Table 3.

Table 3. Results of statistical comparison (Welch *t*–test) of two mean concentrations (mean±standard deviation, mg m^{-3}) of Chl-a in the upwelling zone and reference areas (*statistically insignificant differences are indicated with asterisks).

***3 lentelė.* Vidutinių Chl-a koncentracijų (vidurkis±standartinis nuokrypis, mg m^{-3}) apvelingo zonoje ir aplinkiniuose vandenyse statistinio palyginimo rezultatai (Welch *t*–test) (*statistiškai nereikšmingi skirtumai pažymėti žvaigždute).**

Upwelling duration	Date	Up-welling	Refer-ence zone	Upwelling		Reference zone		t value	Df
yy mm dd	mm dd	SST, °C	SST, °C	Chl-*a*, mg m^{-3}		Chl-*a*, mg m^{-3}			
2004 05 12–17	05 13	4.85	9.68	2.51	±0.96	3.93	±1.09	11.21	38.97
	05 14	4.16	9.35	0.69	±0.66	1.26	±0.40	6.86	35.79
	05 16	5.56	9.34	1.66	±0.79	2.50	±0.73	11.05	55.57
	05 17	7.98	13.13	1.12	±0.76	2.00	±2.44	3.65	51.23
2005 06 09–10	06 09	8.59	13.36	3.26	±1.59	4.08	±1.35	3.95	52.07
2005 06 18–21	06 19	11.10	15.82	2.62	±0.88	4.64	±2.74	3.14	47.65
2006 05 07–11	05 08	6.56	8.46	1.98	±0.59	2.70	±1.00	5.06	31.55
2006 06 14–17	06 16	11.52	15.37	1.88	±0.42	2.03	±0.46	0.15	54.60*
2006 07 01–03	07 01	17.40	20.94	2.08	±0.57	3.61	±0.58	15.80	49.53
	07 02	17.01	21.04	2.52	±0.83	4.05	±1.12	8.99	49.13
2007 06 07–17	06 07	14.96	18.70	1.90	±0.94	2.17	±0.62	4.03	52.08
	06 11	14.83	20.03	2.39	±0.76	2.76	±1.29	1.91	41.40*
	06 16	12.41	18.04	1.15	±0.50	1.50	±0.44	3.30	47.30
2008 05 19 / 2008 06 10	06 03	10.66	14.86	2.25	±0.83	3.88	±1.32	6.32	42.00
	06 04	9.26	14.23	2.41	±0.82	3.60	±1.41	4.83	40.06
	06 05	9.71	14.77	1.86	±1.04	2.62	±1.22	2.46	42.13
	06 06	11.91	18.68	1.26	±0.43	2.29	±0.58	6.25	45.96
	06 07	12.26	17.16	1.82	±0.67	3.16	±0.97	6.16	52.92
2008 07 25 / 2008 08 03	07 24	18.64	19.93	7.09	±3.07	10.28	±3.17	14.41	39.13
	07 25	18.70	20.19	4.10	±1.79	10.51	±3.33	15.44	32.07
	07 26	18.85	20.40	5.01	±3.71	10.25	±5.56	9.44	30.32
	07 27	18.55	20.48	3.04	±1.4	5.46	±1.24	9.09	56.61
	07 28	17.72	20.45	3.08	±0.70	5.54	±1.27	8.16	42.07
	07 29	17.06	20.29	2.78	±1.95	4.31	±1.56	5.49	50.54
	07 31	17.84	20.44	3.66	±0.98	3.82	±1.19	1.51	42.25*
2008 09 23–26	09 24	10.32	15.78	1.03	±0.36	0.94	±0.34	1.05	56.59*
2010 06 22–29	06 26	12.27	14.99	1.95	±0.68	3.51	±1.54	3.65	40.67

The analysis of SST during these upwelling events showed that the temperature drop in the upwelling zone compared to the ambient waters varied from 2 to 9 °C (median 5.43 °C) altering the abiotic conditions over the study area (Table 3). Yet, during some upwelling events, it might drop to as low as 3–4 °C, as it was observed during an upwelling event in May 2004 when SST in the upwelling zone was more typical for March than May. Moreover, the upwelling-induced SST drop even during summer months may easily drop below 10 °C, e.g. in June.

The analysis showed that upwelling zones are characterised by significant changes of Chl-*a* concentrations (Figure 22) with a clear decline of the latter in the upwelling affected zones compared to the ambient waters.

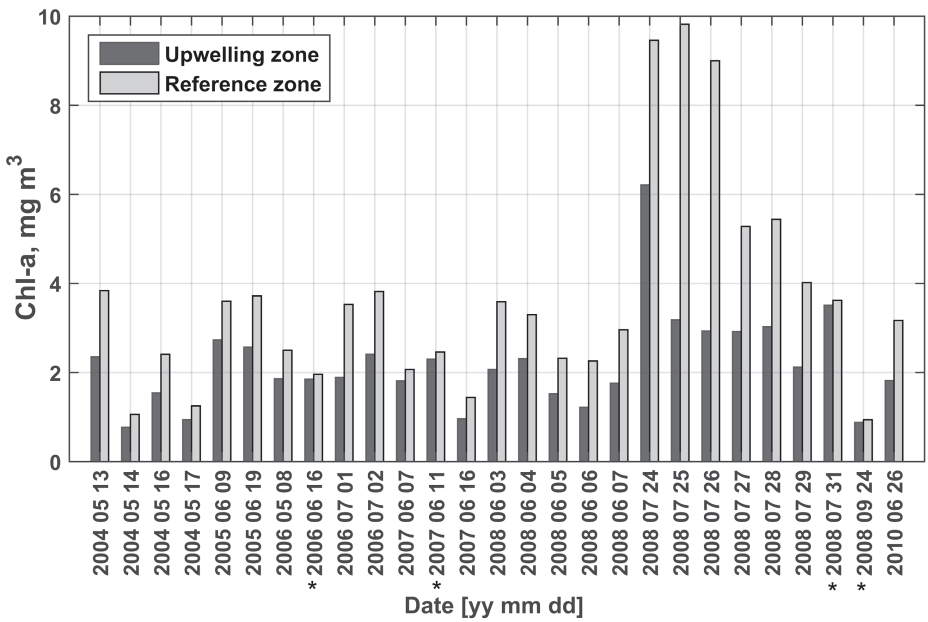


Figure 22. Median of Chl-*a* concentration in the upwelling and reference zones (*statistically insignificant differences are indicated with asterisks).

22 paveikslas. Medianinė Chl-*a* koncentracija apvelingo zonoje ir aplinkiniuose vandenyse (*statistiškai nereikšmingi skirtumai pažymėti žvaigždute).

The statistical comparison of mean Chl-*a* concentrations reveal that in most cases (89%) the difference of Chl-*a* concentrations between upwelling and reference zones was significant, i.e., Chl-*a* concentrations in the upwelling zone were 40–50% smaller compared to those in the ambient waters. Further, the application of GAM to obtain a stressor-response model for the median values of Chl-*a* concentrations showed that the combination of 5 environmental variables (upwelling SST, Nemunas discharge, solar radiation, wind speed, and direction) explained the Chl-*a* deviance of 77.5% with upwelling SST being the most influential variable followed by the solar radiation and wind speed (Table 4).

Table 4. **Relative importance (F value) of the explanatory variables for the changes of Chl-*a* concentration (median value) in the upwelling zone (*significant factors are marked with asterisks)**

4 lentelė. **Aiškinamųjų kintamųjų santykinis svarbumas (F vertė) Chl-*a* koncentracijos (medianinių verčių) pokyčiams apvelingo zonoje (*statistiškai reikšmingi skirtumai pažymėti žvaigždute).**

Environmental variable	F value
n	22
Upwelling SST	3.45*
Solar radiation	2.83*
Wind speed	1.92*
Wind direction	0.36
Nemunas discharge	0.23
Deviance explained	**77.50%**

The upwelling induced SST drop in June 2008 reached more than 7 °C while in July maximum ΔT was smaller, up to 5 °C. In the meantime, up to six times bigger drop of Chl-*a* concentration in the upwelling area was recorded in the July event compared to the one in June. The Chl-*a* decrease in July 2008 was the biggest within all analysed cases, therefore special attention will be given for a detailed analysis of this particular upwelling event in order to better illustrate the complexity of Chl-*a* variability in the SE Baltic Sea waters, as the aforementioned results have shown.

The case that occurred in July–August 2008 was chosen having sequential satellite-derived images of SST and Chl-*a* concentration. Using satellite data, the cold, low-chlorophyll surface waters determined along the coast in summer can be clearly distinguished from the warm, high chlorophyll offshore waters. Evolution of this upwelling event showing significantly lower than normal seawater temperatures resulting from coastal upwelling along the SEB coast together with corresponding changes in Chl-*a* concentration is illustrated in Figures 23 and Figure 25. The meteorological situation at the time of the upwelling development is presented in Figure 24.

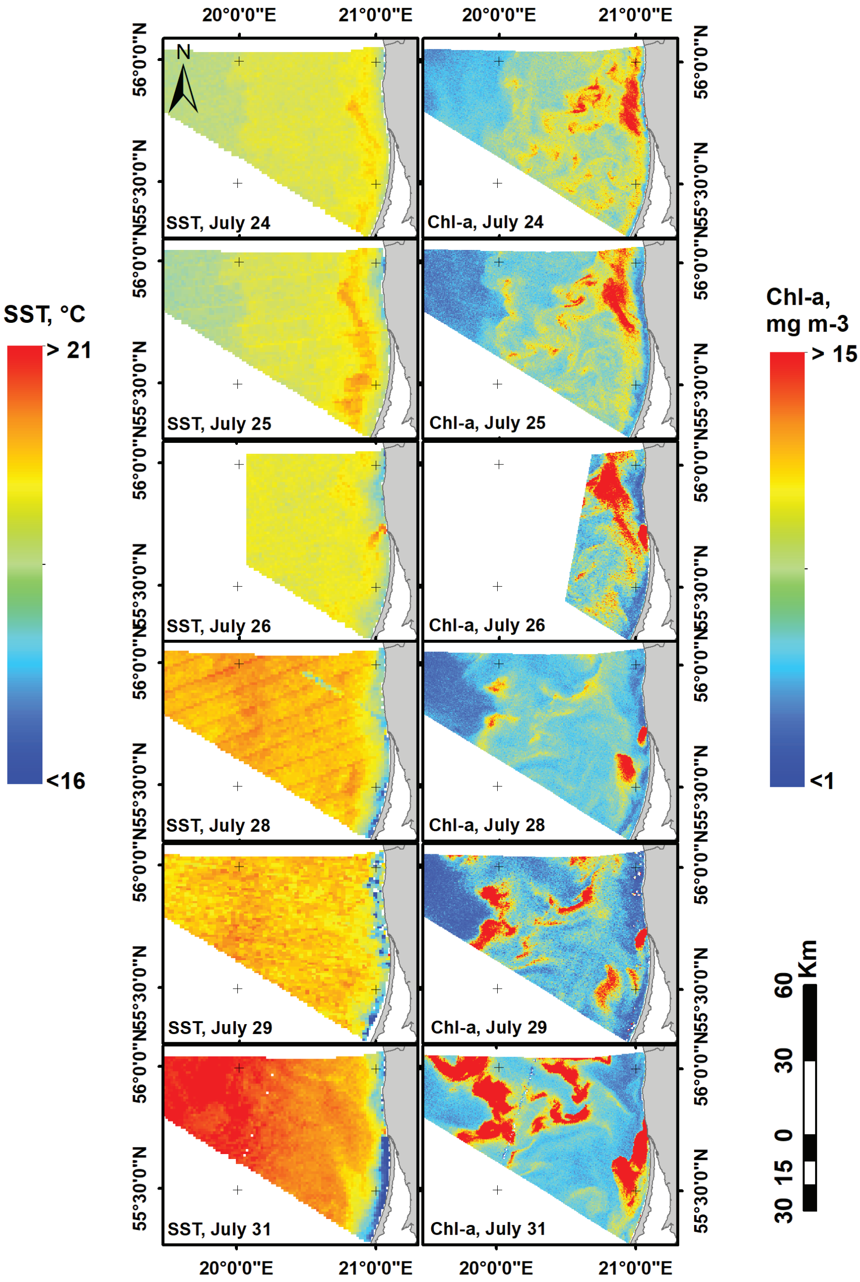


Figure 23. SST and Chl-*a* maps during upwelling in July 2008.

23 paveikslas. SST ir Chl-*a* žemėlapiai 2008 liepos mėn. apvelingo metu.

Wind measurements from Klaipeda station show that variable wind conditions prevailed in the end of July–beginning of August. From the wind speed and direction records the upwelling development phases can be distinguished (Figure 24) The upwelling was apparently triggered by the persistent upwelling-favourable northerly winds with an average speed of about 3 m s^{-1}. The pre-upwelling phase was relatively short then an active phase, with the steady winds blowing parallel to the coast and inducing an offshore Ekman transport of surface waters was observed from July 24–25, then followed by the upwelling relaxation from July 31 with the upwelling front at the sea surface spreading offshore till about August 03.

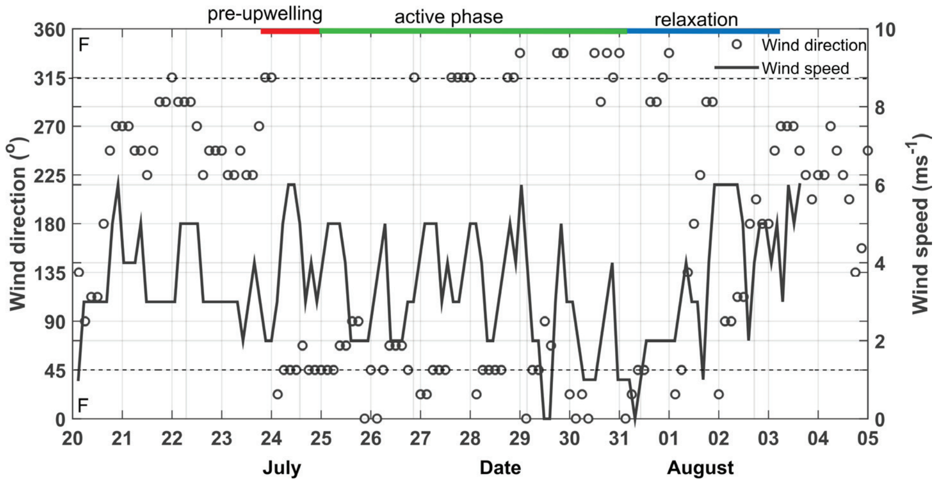


Figure 24. Wind speed and direction in Klaipeda. 'F' symbol in the left corners indicates upwelling-favourable northerly winds. Red bar indicates the time interval of pre-upwelling phase, green bar – upwelling active phase and the blue bar represents upwelling relaxation.

24 paveikslas. Vėjo greitis ir kryptis Klaipėdoje. „F" simbolis kairiajame kampe nurodo apvelingų formavimuisi palankius šiaurės krypčių vėjus. Raudona linija rodo prieš-apvelingo stadiją, žalia linija – apvelingo aktyvią stadiją ir mėlynos spalvos linija – apvelingo relaksacijos periodą.

Satellite maps (Figure 23) and SST profiles (Figure 25) of July 24 show that the water masses near the coast are becoming slightly colder than the open sea (ΔT=1.67 °C). Nevertheless, the temperature difference is yet too small to clearly define an upwelling event in the SST records as 2 °C threshold is usually used to identify CU in the satellite images (e.g. Myrberg and Andrejev 2003; Gidhagen, 1987).

In the Chl-*a* records of the same day (July 24) the signatures of upwelling are very well explicit therefore one can observe more productive coastal waters being pushed away further offshore, marking the beginning of coastal upwelling in Chl-*a* records (Figures 23 and 25). So even though SST records indicate the beginning of the upwelling event in July 25, Ekman offshore drift depicted in Chl-*a* records implies that the pre-upwelling phase lasted till about July 24. This, again, demonstrates that during well-stratified summer conditions the upwelling system might respond very rapidly to the presence of favourable winds. This is very clearly shown in Chl-*a* profile at Palanga as the sharp difference between Chl-*a* concentrations in the first 2 km from the coast compared to the ambient waters is observed in July 24 (Figure 25).

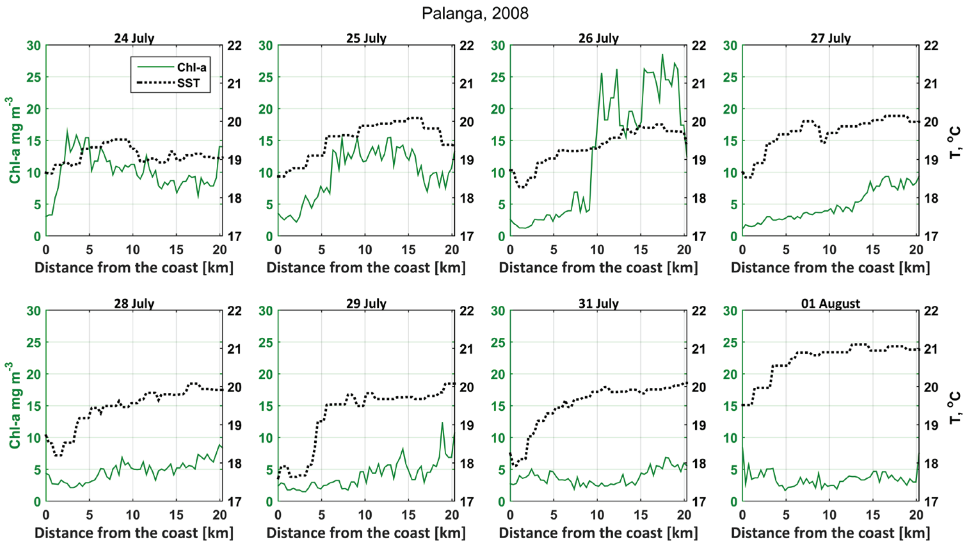


Figure 25. Horizontal Chl-*a* and SST profiles at Palanga.

25 paveikslas. Horizontalūs Chl-*a* ir SST profiliai ties Palanga.

In July 25 northerly winds were still prevailing making the upwelling more distinguishable from the surrounding waters with ΔT of around 2°C while Chl-*a* concentration maps indicate explicitly upwelling zone as a wide (>5 km) band of less productive waters along the coast (Figure 25). As retrieved from satellite images, a clear decline of the Chl-*a* concentration is observed in the coastal zone (~4 mg m^{-3}) relative to the upwelling unaffected ambient waters (up to 15 mg m^{-3}).

Water level records (Figure 26) at the Nida coastal station in the lagoon and Klaipeda Strait show that the favourable hydrological situation for the formation of plume occurred at the time the upwelling was present with a tendentious sea-level fall at the SEB coast. Both, SST and Chl-*a* maps indicate that on July 26 the hydro-biological situation in the coastal zone near the entrance of the Lagoon became more complex.

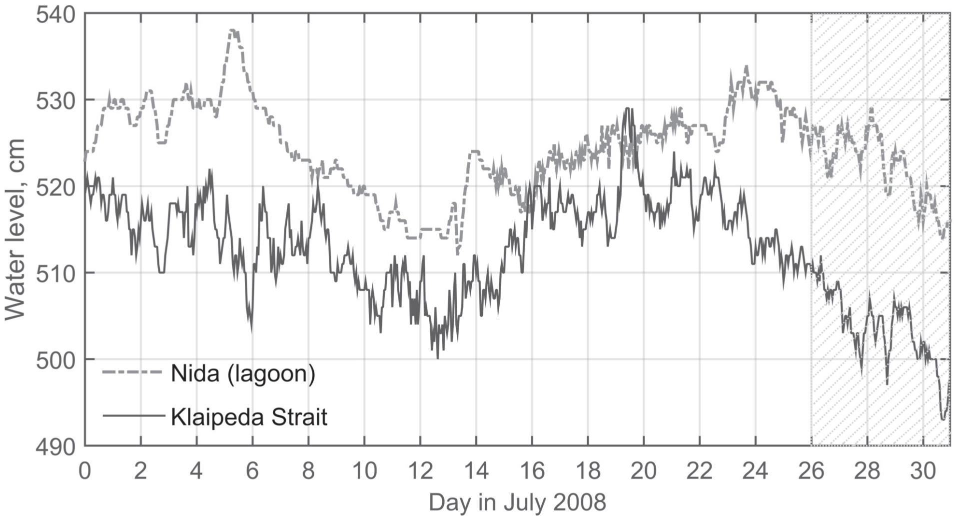


Figure 26. Water level in Nida (Curonian Lagoon) and Klaipeda hydrometeorological stations. The pattern filled area represent the time interval when the plume was present in the SE Baltic Sea coast.

26 paveikslas. Vandens lygis Nidos (Kuršių marios) ir Klaipėdos hidrometeorologinėse stotyse. Užpildytas plotas žymi laiko intervalą, kuomet Baltijos jūros pakrantėje buvo stebimas pliumas.

The outflow of the fresh, warm and highly productive waters from Curonian Lagoon directed southwards can be very well seen from July 26 both in SST and in Chl-*a* satellite images, dividing the upwelling zone into the northern and southern parts (Figure 23). Even though plume areas were excluded, the Chl-*a* concentrations given for the whole upwelling area (see Table 3) might still have been influenced to some extent by the plume at the southern part of the upwelling zone. In turn, Palanga profiles on July 26 showed more extreme changes in Chl-*a* as the coastal area of about 10 km wide had a Chl-*a* concentration of about 2–5 mg m^{-3}, i.e. up to five times or even more smaller compared to the concentrations of ambient waters (20–25 mg m^{-3}).

On July 27–31 upwelling favourable wind conditions continued and the upwelling became more distinct in the temperature records (ΔT up to 5 °C), and the more persistent upwelling became, the more Chl-*a* concentration in the coastal waters decreased with the lowest values (~3 mg m^{-3}) observed on July 27–29. At the same time plume from the lagoon became very intense (Figure 23). The upwelling-favourable winds still prevailed and in SST records of July 31, a clear trail of warmer waters steering to the south is evident. The upwelling itself was also more pronounced to the south from Klaipeda Strait than in the northern part, as can be seen in SST maps, separating highly productive plume waters from the coast.

From the active phase of the upwelling to the onset of relaxation between July 24–31 the mean values of Chl-*a* concentration decreased steadily from around 7 mg m^{-3} to less than 3 mg m^{-3} and only when upwelling entered the relaxation phase Chl-*a* values started to increase slightly, as horizontal Chl-*a* profile of August 01 indicated (Figure 25).

4.7 Upwelling influence on the Curonian Lagoon Chl-*a* concentration

It was mentioned earlier that upwellings are quite often accompanied by the plume from the Curonian Lagoon, but there also were cases, when the opposite situation occurred and the inflows of marine waters were recorded to influence the northern part of the lagoon. The analysis of space-born SST and Chl-*a* maps came in handy analysing the upwelling influence to the Curonian Lagoon environment. For the analysis, again, the cases with concurrent SST and Chl-*a* maps were taken to illustrate the scale of upwelling inflow together with its impact on Chl-*a* concentration (Figure 27).

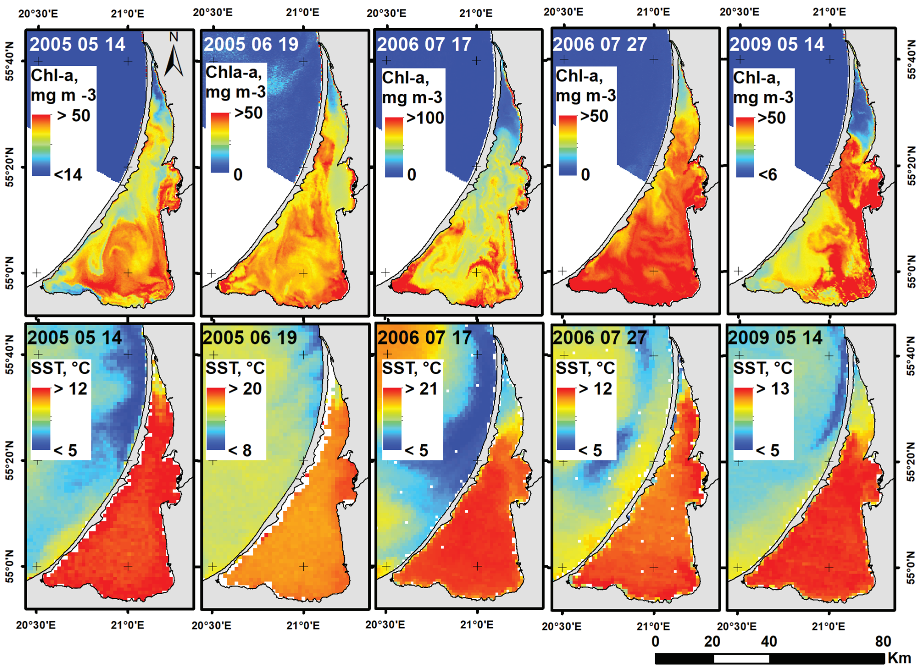


Figure 27. SST and Chl-*a* maps.

27 paveikslas. SST ir Chl-*a* žemėlapiai.

As retrieved from satellite images, the inflows of upwelling waters to the lagoon have a significant effect to the SST and Chl-*a* variability as the areas with lowest Chl-*a* concentrations in the northern part of the Lagoon coincide with the areas of lower water temperatures. From Figure 27, demonstrating the spatial extent of upwelling inflow through the SST and Chl-*a* concentration changes it is seen that during some cases, e.g. the upwelling in July 2006 or May 2009 the inflow waters nearly reached the middle part of the lagoon with the distances of up to 30 km. When cold and less productive sea waters push away and dilute highly productive waters of the lagoon, the average Chl-*a* concentrations become markedly lower in the inflow zone with cold water temperatures compared to the ones in ambient waters (Figure 28).

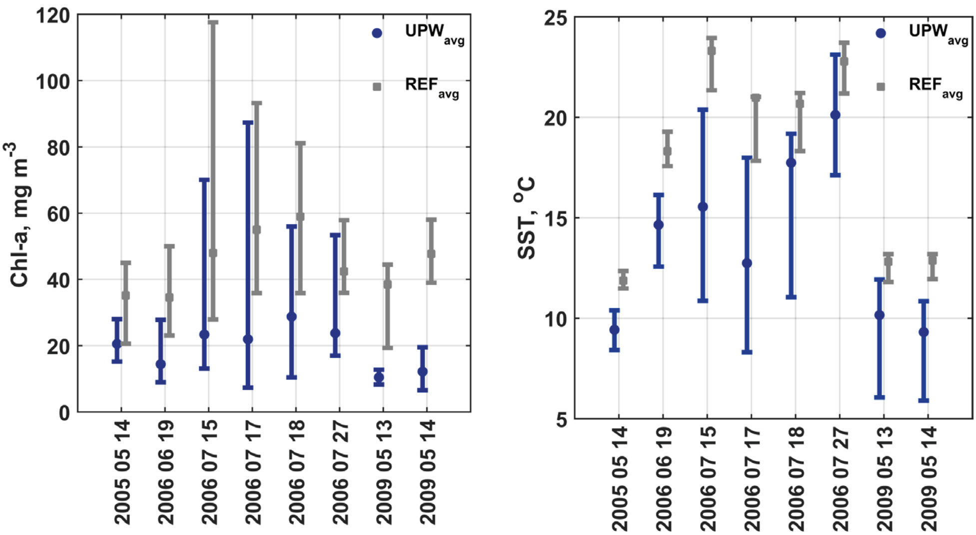


Figure 28. Satellite-derived Chl-*a* concentration and SST in the Curonian Lagoon: Chl-*a* concentration/SST in the upwelling inflow area is denoted as UPW_{avg} and as REF_{avg} in the reference area.

28 paveikslas. Palydovais išmatuota Chl-*a* koncentracija ir SST Kuršių mariose: Chl-*a* koncentracija/SST apvelingo zonoje pažymėta kaip UPW_{avg} ir kaip REF_{avg} aplinkiniuose vandenyse.

Despite the season, the changes in Chl-*a* concentrations vary within different events. For example, Chl-*a* concentration of the study area was strongly influenced during summer inflows in July 2006 that coincided with the major upwelling event in the SEB coast. Here, a sharp drop in SST resulted in the Chl-*a* concentrations decrease to as low as several mg m^{-3} while in the reference area Chl-*a* concentrations reached more than 100 mg m^{-3}. An inflow event in 2009 May 13–14 demonstrates that even a slight temperature drop can result in significant Chl-*a* changes. In this case the upwelling inflow-related temperature drop was only 2–4°C, but the average Chl-*a* concentration in the inflow zone (10–12 mg m^{-3}) was nearly 4 times lower than in the ambient waters (40–50 mg m^{-3}).

5

Discussion

5.1 Upwelling identification: advantages and limitations of satellite observations and coastal measurements

The oldest measurements of water temperature in the Baltic Sea recorded in scientific literature dates back to the second half of the 18th century and within the connection to the increasing trend of establishing seaside resorts on the German coast, the interest in water temperature (and salinity) increased. In turn, the first scientific observation of coastal upwelling in the Baltic Sea was carried out in 1834 by Alexander von Humboldt (Matthaus, 2010); however, upwelling, as a process itself, remained poorly understood for a long while, as the *in situ* measurements were random in character (Leppäranta and Myrberg, 2009) and, to be accurate, still are rare in space and time.

In the frame of the Lithuanian National Baltic Sea monitoring plan (see *www.gamta.lt* for more details), the sampling from a ship in the coastal waters of the Baltic Sea is generally carried out once per season, i.e. 4 times per year in several stations. One should mention that monitoring of the coastal zone from ships could be useful providing information on upwelling properties during cloudy conditions and on a vertical scale. However, the conventional point sampling from ships, performed typically once per season is not able to capture all upwelling events and is not able to identify upwelling associated spatial or temporal variations in the water quality that is vital for comprehensive assessment and management of water bodies (Gholizadeh et al., 2016). Additionally, daily measurements of water temperature are available from three coastal monitoring stations at Nida, Klaipeda Strait, and Palanga. As the study results have shown, the upwelling identification in water temperature measurements from coastal monitoring stations results in missing a significant number of upwelling events. Analysis of *in situ* T_w measurements from coastal monitoring stations enabled Jurkin and Kelpsaite (2012) to identify only 20 upwelling events along the Lithuanian coast during summer periods of 1993–2011, i.e., significantly fewer than in this study during a shorter time period. The primary reason why some coastal upwelling events might be missing from coastal *in situ* records is that the water near the coast, where observers usually take the samples, is still warmer than SST values measured from satellites. Satellite measurements correspond to the SSTs within the first 1–2 km off the coast. Another reason behind such a small number of upwelling detections in coastal T_w records might be a possible location of upwelling front at some distance from the coast, thus, spatial properties of coastal upwelling cannot be evaluated from the point-based *in situ* monitoring.

The results of this study showed that coastal upwelling is rather frequently observed in the SE Baltic Sea coast, however, due to the lack of high spatial frequency and large temporal coverage data the number of coastal upwelling events and their parameters were underestimated in this region, as shown in the previously existing studies (e.g. Jurkin and Kelpsaite, 2012). The upwelled waters are characterized by significantly lower water temperatures compared to the ambient waters, so an upwelling-related surface temperature drop in the upwelling region can be detected by remote sensing. In turn, data gaps arising due to the limitations of *in situ* point monitoring can be supplemented additionally from the spaceborne measurements.

In this study, a combination of both remote sensing data and *in situ* observations is used to systematically investigate the development of coastal upwelling allowing the assessment of its spatial and temporal characteristics and implications for the coastal environment. The application of MODIS IR data allowed identifying 69 upwelling events during a warm period (April–September) of 2000–2015. As it is shown in Figure 6, the use of water temperature measurements from coastal stations allowed the identification of only 58 upwelling events, which is 40% less than the number of theoretical events and about 15% less than those detected in satellite data.

The number of upwelling events identified based on the theoretical Upwelling Index is higher (96 upwellings) than one from satellite observations. As Figure 6 shows the largest discrepancies between upwelling events identified in satellite-based SSTs and based on Upwelling Index are found in April and September. In April, this might be attributed to the fact that background water temperature is relatively low during this month, °C (see, e.g., Figure 4 in Kozlov et al. (2014)) and, hence, SST contrast between ambient and upwelled waters is not well pronounced in satellite data. A possible reason of missing some upwelling events in September might be the deepening of the mixed layer due to the thermal convection and turbulent mixing during autumn (Myrberg and Lehmann, 2013) making it difficult to distinguish low-intensity upwelling events in IR SST data. However, the most important reason for missing upwelling events in satellite data is the cloud cover. As it is shown inFigure 6, there is a relatively small number of cloud-free satellite data during April and September compared to the period from May to August.

Even with the limitation of no retrievals under cloudy conditions and restraints of measuring the deeper layers of the ocean, high-resolution infrared data add information in the critical coastal areas (Vazquez-Cuervo et al., 2017). In turn, one may conclude that satellite data are indeed an efficient tool for observing and quantifying upwelling parameters, as coastal T_w records might miss some upwelling events or underestimate the upwelling-associated water temperature drop. Even though conventional measurements and theoretical calculations are effective under cloud cover, they are not able to provide any information on the spatial properties of the upwelling. In addition, one of the major advantages of remote sensing is its cost-effective capability to collect a long time series of SST data covering large geographic areas, thus, enabling to analyse spatial and temporal properties of coastal upwelling. The validation of satellite IR SST maps against buoy records in the SE Baltic and *in situ* observations at several coastal stations in the Curonian Lagoon performed by Kozlov et al. (2014) showed a very good correspondence between space-borne and conventional SST measurements, suggesting that satellite IR imagery is a rather effective tool for SST studies in the Baltic Sea region under relatively cloud-free summer conditions, therefore, can be used further to analyse the SST development during upwelling events in the study region.

5.2 Coastal upwelling in the SE Baltic Sea: regional features and scales of variability

Development. In contrast to the major upwelling systems of the Global Ocean generated by persistent winds blowing alongshore towards the equator or seasonal wind-driven coastal upwelling systems (Kampf and Chapman, 2016) upwelling events are rather episodic in the Baltic Sea (Karstensen et al., 2014), varying in accordance with local winds and coastline configuration. In general, wind conditions in the Baltic Sea region are dominated by westerlies (Leppäranta and Myrberg, 2009) with south-westerly (SW), northerly (N) and north-easterly (NE) winds occurring most frequently over the entire Baltic Sea basin (Soomere and Keevallik, 2003) and there are no clearly defined seasonally reversing wind patterns in the Baltic Sea. Accordingly, coastal upwelling can occur with a sustained wind over the Baltic Sea in almost any direction (Sproson and Sahlee, 2014) throughout the year.

Nonetheless, some monthly patterns of upwelling-favourable winds in the study region might be seen in coastal records (Figure 8), providing useful information on the phenology of coastal upwelling phenomena over the study site. It is known, that N and NE winds are known to trigger coastal upwelling in the SE Baltic Sea, and only in the northernmost part of Latvia and along the Polish coast it is favoured by winds from easterly directions (Gurova et al., 2013). For the analysis of upwelling response to meteorological conditions, upwelling index (UI) and cumulative upwelling index (CUI) were used to assess upwelling favourable winds. The results of this study show that generally, about 1–3 days of positive UI values are needed for the upwelling front to be manifested in SST data, and it is in agreement with the findings by Haapala (1994). Although, a seasonal pattern of wind strength and duration needed to induce an upwelling event in the SE Baltic Sea region is observed. The milder upwelling-favourable winds (average CUI of 150–220 $m^3 s^{-1} km^{-1}$) with shorter duration (about 2.5 days) are required to generate an upwelling event during summer months when the seasonal thermocline is shallow and the vertical stratification of the water column is at its strongest. In late spring and early autumn the positive UI values should last 1–2 days longer (3.5–4.5 days) with the CUI values near 300 $m^3 s^{-1} km^{-1}$, implying that more wind energy is needed to trigger upwelling over the less stratified water column (Haapala, 1994).

Frequency and duration. In general, coastal upwellings in the study region are detected in satellite SST maps from April to September, when the water masses are already well-stratified whereas in the northern parts of the Baltic Sea upwelling is typically observed only from June, as there is usually no pronounced temperature stratification in April or May (Lehmann et al., 2012). However, although N and NE winds and associated Ekman transport in the SE Baltic Sea were rather strong, the number of identified upwelling events is relatively low during early spring or autumn, perhaps related to the weak vertical stratification in April. Besides, upwelling favourable winds acting over a shallow thermocline are more efficient in generating an upwelling front, and this front can be progressively displaced offshore by Ekman transport (Letelier et al., 2009), thus wind-induced deepening of the mixed layer in September also results in a smaller number of upwelling events.

Lehmann et al. (2012) analysed upwelling frequencies for different Baltic Sea regions based on visual analysis of satellite SST data from May to September 1990–2009. They found the highest upwelling frequencies (up to 25%) along the Swedish coast in the western Gotland Basin and in Bornholm Basin. Frequencies of 10–15% were found along the western Finish and Estonian coast, while the SE Baltic coast had a range of frequency of 5–12%. In this study, the season mean number of upwelling days accounts for about 16% of the warm season (~30 days), i.e., somewhat longer than reported in Lehmann et al. (2012) and in Golenko and Golenko (2012), which recorded 27 upwelling days from the reanalysis data for 1970–2010 in this part of the Baltic Sea. Moreover, the cases when upwelling events covered even 30% of the warm season were also observed. The results of this study show that coastal upwelling in the SE Baltic Sea is more frequent than, e.g., along the nearby Polish coast with 23 upwelling days (13% of the warm period from April to September), as recorded in Bednorz et al. (2013).

The study findings suggest that short-lived (2–6 days) upwellings are dominant, yet the chains of consecutive upwelling events might also be observed when the first upwelling event contributes to the formation of the initial stratification setup for the next one, and in such case even relatively weak winds can lead to upwelling (Myrberg et al., 2010). While not so frequent, such long-lasting events might be of great importance for the whole region influencing both the natural (e.g. weather, ecosystems) and socio-economic (e.g., tourism) environment of the coastal area.

Modulations of SST. One of the key changes induced by coastal upwelling in the marine environment is a rapid drop of sea surface temperature that might strongly influence coastal ecosystems through the direct effects of temperature on species performance and indirectly through species interactions (Iles et al., 2012). Previous studies of Lehmann and Myrberg (2008) have shown that the temperature drop during upwelling events near Lithuanian and Latvian coasts is about 4–8 °C and is in agreement with the results of this study. Nevertheless, the maximal ΔTs observed in this study are significantly higher than it was hitherto recorded. As Figure 15 shows, the upwelling related SST drop might even reach up to 14 °C in the SE Baltic Sea coast, so depending on the initial seawater temperatures, an upwelling event can result in SSTs atypical for the hydrological norms for the given months. For example, monthly mean May SST in SEB coast is around 10 °C (see, e.g., Figure 4 in the literature Kozlov et al., 2014) though during upwelling events it might drop to as low as 3–4 °C, as it was observed during upwelling event in May 2004, i.e. temperatures in the upwelling zone were more typical for March, than May. Moreover, the temperature of the cold upwelling core at the surface was as low as 5–7 °C during major upwelling event, i.e. up to three times smaller than the ambient waters.

Typical values of SST gradient across the upwelling front range between 0.2 and 0.5 °C km^{-1} (Figure 12 a), but considerable spatial variations of SST gradient are evident (Figure 12 b), as the strength of the local SST gradient changes depending on the width of the upwelling zone over a particular location, being highest across relatively narrow parts of the upwelling and lower where the upwelling zone is the widest. It is interesting to note, that SST gradients observed in the major upwelling systems are relatively smaller than those observed in the SE Baltic Sea region, e.g. in the upwelling front off central Chile the seasonal means are found to be ~0.01 °C km^{-1}, whereas weekly SST gradients can be one order of magnitude higher, ~0.1–0.25 °C km^{-1} (Letelier et al., 2009). The results of this study show that in 25% of cases horizontal SST gradients are larger than 0.6 °C km^{-1} with the maximum recorded values of about 1.6 °C km^{-1}. Although these values are somewhat lower than the ones given in Lehmann and Myrberg (2008), they agree with the results presented in Bychkova and Victorov (1987) or Esiukova et al. (2017).

Spatial properties. Satellite-derived SST data the most commonly show an upwelling plume extending about 300–350 km along the coast, presumably governed by the direction of upwelling-favourable winds and local configuration of the coast. Thus, an upwelling covers almost the entire coastal zone of the SE Baltic Sea. The alongshore extent estimated in this study is somewhat longer than previously reported (Lehmann et al. 2012; Bychkova and Viktorov, 1987; Gidhagen, 1987). In the SE Baltic coast upwelling occurs chiefly in the narrow band adjacent to the coastline, with the typical cross-shore extent of about 10–20 km (Figure 13 d), while 5–15 km width is observed most frequently (Figure 13 c) being very close to the internal Rossby radius of 2–10 km for the Baltic Sea (Leppäranta and Myrberg, 2009). Spatially, the dynamics of upwelling systems are modulated due to the effects of varying coastline orientation and topographic features (Walter et al., 2018). In turn, some distinct latitudinal differences of upwelling cross-shore extent related to the changing bathymetry of the study site are clearly seen in Figure 14 d. The similar results were also reported in Gidhagen (1987), Lehmann & Myrberg (2008), Lehmann et al. (2012). During the intensive long-lasting events the cross-shore width of the upwelling front may exceed 30–40 km everywhere. The formation of such a wide frontal zone is presumably linked to the evolution of an upwelling front over topography and the generation of elongated transverse filaments extending far offshore as shown in Figure 15. The analysis of 16-year satellite observations clearly show that a major upwelling event in the SE Baltic Sea took place in summer 2006, similar to what was detected, e.g., along the southern coast of the Gulf of Finland (Suursaar and Aps, 2007; Uiboupin and Laanemets, 2009). In cases as such, the cross-shore width of the upwelling plume might even reach 60–70 km in some locations (Figure 13 d), when the mesoscale structures (meanders, filaments) of an alongshore upwelling jet develop, thus, strongly exceeding the maximum values of internal Rossby radius observed in summer (Fennel et al., 1991). The development of upwelling filaments is of a particularly high interest, as these elongated cold-water structures represent an intense mechanism for transport of upwelled water to the great distances from the coast. The formation of such a wide frontal zone is very important for enhancing the exchange of biological properties between coastal and open sea waters, and is presumably linked to the evolution of an upwelling front over the topography which leads to the generation of elongated transverse filaments (Zhurbas et al., 2006). The generation of such cold water jets and transverse filaments was reported earlier (Kozlov et al., 2012; Bychkova and Viktorov, 1987; Zhurbas et al., 2006), but the length reported was twice as short as the one recorded here. The overall pattern shown in Figure 14 is somewhat similar to the one drawn in Bychkova and Viktorov (1988).

5.3 The role of coastal upwelling: implications for the environment

A wind-driven upwelling in the Baltic Sea may occur at any time of the year, although the thermal effects may not be noticeable when the sea waters are not thermally stratified (Bednorz et al., 2013), and an upwelling event may have no significant impact to biotic and abiotic environment. Abiotic factors of the study region such as air temperature, water transparency, SST, salinity, and nutrient availability are subjected to high variability due to coastal upwelling, in turn, upwelling events taking place during the warm season are of great importance as more warm-limited species are abundant. Upwellings are also recognized as efficient contributors to the exchange processes between the coastal and offshore waters (Levy, 2008), redistributing heat and salt (Laanemets et al., 2011) and are also known to change the nutrient conditions in the Baltic Sea (Vahtera et al., 2005).

Influence on the species composition. The studies performed in other parts of the Baltic Sea indicate that coastal upwelling induced nutrient supply, advection, replacement/mixing of water masses and changes in water temperature might affect not only single phytoplankton species but could result in changes of the entire phytoplankton community (e.g. Lips and Lips, 2010; Laanemets et al., 2004). For example, cyanobacteria have relatively high-temperature optima (Kanoshina et al., 2003), thus, a clear fold decrease of the filamentous cyanobacteria biomass during an upwelling event in comparison with that before development of the upwelling is observed (Lips and Lips, 2010). This implies that if the temperature conditions are not favourable, then even the high nutrient concentrations in the upwelling areas cannot facilitate the cyanobacterial growth (Kanoshina et al., 2003). Observations by Vahtera (2007) show that when upwelling of cold and phosphate enriched water from the thermocline commences, the displacement of diazotroph (capable of nitrogen fixation) populations takes place; also, surface dwelling (from the surface down to 5 m) populations such as *Nodularia spumigena (N. spumigena)* are transported offshore, therefore the upwelling waters are almost entirely free of *N. spumigena* while populations, residing in the deeper depths (10–15 m), such as *Aphanizomenom* sp. can be displaced to the surface along with the upwelling waters. In the study of Kononen et al. (2003) it was concluded that upwelling can also result in changing of migratory behavior of *Heterocapsa triquetra (H. triquetra).* In addition, the advection of coastal water offshore during upwelling can also have important implications for the local population dynamics of broadcast spawning organisms (Reddin et al., 2015). Eggs and larvae of anchovy and horse-mackerel were scarcely found in the upwelling areas in the Black Sea, suggesting that sudden temperature drop might also influence the abundance of thermophilic species (Niermann et al., 1994). On the other hand, upwelling areas might be favourable for cold-adapted fish species. Before this study, relatively little attention has been given to the physical and biological characteristics of upwelled water masses and their effect to the SE Baltic Sea coastal environment, thus, further field studies are required to explore the upwelling impact on species composition and abundance during such events in the SE Baltic Sea and during upwelling inflows to the Curonian Lagoon.

Modification of Chl-a distribution patterns. The results of this study reveal a clear role of upwelling on Chl-*a* concentrations, although typically there is a temporal and spatial shift between the thermal and biological effects of upwelling (Kowalewski, 2005). It was shown that in the SE Baltic Sea the upwelling zones with thermal differences are characterized by the significant changes of Chl-*a* concentration (Table 3) and a clear decline of the latter in the zones affected by the upwelling compared to the areas where the upwelling is not observed. However, Chl-*a* values are highly variable due to strong event-scale variability. During some events the Chl-*a* concentration changes might be more pronounced than in other cases in relation to the seasonality, initial concentrations and the intensity of an upwelling event. Respectively, the changes in Chl-*a* concentration during the upwelling events were recorded along the Polish coast of the Baltic Sea. The results based on a time series of synoptic SeaWiFS images likewise revealed significantly higher Chl-*a* concentrations during non-upwelling periods than during upwelling events in Hel, Łeba and Kołobrezeg regions (Krężel et al., 2005).

SST, in general, is the primary indicator of upwelling during the warm season in the Baltic Sea although a detailed study of the upwelling in July 2008 demonstrated that an upwelling can be identified in the Chl-*a* maps even before the thermal signatures in the surface layer appear, as normally it is not possible to recognize the beginning of an upwelling from SST maps when cooler water has been uplifted but has not surfaced yet (Delpeche-Ellmann et al., 2017). In turn, an upwelling can first be seen in Chl-*a* maps as highly productive waters are pushed away further offshore, causing a significant increase in water transparency (Nowacki et al., 2009) and at the same time marking the beginning of the coastal upwelling in Chl-*a* records. The aforementioned suggests that the primary decline of Chl-*a* concentration during upwelling events is related to the displacement of water masses as the peak of production is physically removed from the main upwelling region due to cross-frontal advection (Franks, 1992) and only later, the temperature changes step in. Again, studies imply that the environmental effect of the upwelling is generally restricted to the areas of cooler water in the Baltic Sea (Vahtera et al., 2005).

The statistical analyses of Chl-*a* concentrations in the SE Baltic Sea show that the Chl-*a* concentrations in the upwelling zones significantly differ from those observed in the ambient waters and are 40–50% smaller. Besides, even though upwelling SST was found to be the most influential variable to Chl-*a* concentrations, it is interesting to note, that the upwelling events characterised with the highest drop in SST do not always result in the biggest drop of Chl-*a*, as, for example, in the upwelling cases during summer of 2008 (Table 3). Again, implying that other environmental factors affected by the upwelling e.g., vertical nutrient flux, should be taken into account when evaluating the impact of the upwelling event on the coastal ecosystem functioning.

It is also interesting to note that the initial effect of coastal upwelling to Chl-*a* concentrations in the Baltic Sea is the opposite to what is observed in the upwelling systems of the Global Ocean. In general, the nutrient enrichment and exposure of the upwelled phytoplankters to the surface radiation are expected to enhance the growth of phytoplankton (Ishizaka et al., 1983). On the contrary, the upwellings in the Baltic Sea are often associated with the decline in Chl-*a* concentration (Uiboupin et al., 2012) as a consequence of the dilution and transport of productive coastal waters further offshore and decrease in water temperature (Kratzer et al., 2011).

Upwelling influence on the abiotic environment. The results obtained here likewise provide the initial evidence of the upwelling influence to the abiotic environment of the SE Baltic Sea region. For example, it is shown that the presence of cold upwelling front might significantly alter the stratification of the marine atmosphere boundary layer (MABL) and result in a significant drop of air temperature, altering local weather. The analysis of the major upwelling event in July 2006 showed that the cooling of the surface waters is responsible for the air temperature drop down to 10 °C (Figure 17). In turn, during the summer-time holiday season a coastal upwelling might also have a negative impact on particular tourist areas due to the rapid drop of water and air temperatures nearshore (Lehmann et al., 2012).

Upwelling is also prone to affect the formation and frequency of sea fog (Leeparanta and Myrberg, 2009; Dietze and Loptien, 2016) that might have implications for, e.g., Klaipeda Port activities in terms of reduction of visibility, hampering and restricting navigational possibilities in the port. And it is also known to have an influence to the near-surface winds in the coastal zone as the cold upwelling front alters the stratification in the MABL, which becomes more stable, and subsequently lowers the near-surface wind speed and surface stress (Kozlov et al., 2012; Kudryavtsev et al., 1996; Kudryavtsev et al., 2014). This, in turn, should be taken into account when planning the near-shore wind farming in this area in the near future.

Moreover, a coastal upwelling might be responsible for transporting sub-halocline water towards the surface one and irreversibly mixing them into less saline surface water due to the differential advection (Reissmann et al., 2009). As the results of this study show, the upwelling-related salinity changes in the SE Baltic Sea are small ($\Delta S \leq 0.5$ ‰) and in agreement with Haapala (1994), suggesting that surface salinity changes during upwelling events in the Baltic Sea usually does not exceed 0.5 ‰.

Upwelling influence on the Curonian Lagoon waters. As the Ekman transport during upwellings produces a sea-level fall at the coast (Leppäranta and Myrberg, 2009) the discharge of fresh water from the Curonian Lagoon forms a buoyant plume (Gelfenbaum and Stumpf, 1993) that is frequently observed during upwelling events. However, the marine inflows to the lagoon might also take place in the study region.

In total, 18 upwelling events during the study period were recorded to influence the hydrological regime of the Curonian Lagoon when the inflow from the SE Baltic Sea to the lagoon took place. Such marine intrusions, as described in Zemlys et al. (2013), are mainly determined by barotropic inflows driven by the sea–lagoon water level difference and indicate that generally, northerly winds lead to an intrusion of marine water into the lagoon. These short-term water level differences are mainly dependent on the wind forcing, so, when the intense wind events coincide with the low river discharge, intrusions of salt water can even reach the central parts of the lagoon. Moreover, the Curonian Lagoon is considerably smaller and shallower water body compared to the Baltic Sea with the higher water temperature during summer months, thus when marine water entrainment coincides with upwelling events, the environmental effect becomes even more significant here. The inflows of upwelling waters can supply large amounts of dissolved nutrients to the Curonian Lagoon and change its biotic and abiotic conditions, thus having a significant effect on the chlorophyll/primary production changes.

The investigation of cloud-free MERIS/Envisat images of the entire period evidently reveals a temporal impact of the upwelling on the Chl-*a* concentration in the Curonian Lagoon, when cold and less productive sea waters entering the lagoon push away and dilute the highly productive waters. Such inflow events might be very rapid, as horizontal velocities show. This, again, means, that the ecosystem has to adapt to a very fast changing hydrological conditions and the pressure to the environment might be high, as both phytoplankton and zooplankton are dominated by the freshwater species (Gasiunaite et al., 2005). Upwelling inflows from the Baltic Sea might temporarily affect even the composition of species in the Curonian Lagoon, as the marine species enter the lagoon only during seawater intrusions (Gasiunaite et al., 2008; Zemlys et al., 2008). For example, the presence of marine toxic cyanobacteria species *N. spumigena* was observed in the northern part of the Curonian Lagoon, following the intrusion of brackish water from the Baltic Sea (Paldaviciene et al., 2009).

Upwelling inflows to the lagoon significantly change the established environmental conditions in the inflow zone. In turn, the areas having the lowest Chl-*a* concentration in the northern part of the Lagoon coincide with the areas of lower water temperatures. The initial concentrations of Chl-*a* are much higher in the lagoon and may reach the concentrations of hundred mg m^{-3}, whereas in the Baltic Sea the Chl-*a* concentration is of several mg m^{-3}. Thus the upwelling in the lagoon has even larger environmental effect, especially in the large entrainment cases when the inflow of upwelling waters nearly reach the middle part of the lagoon, covering about 200 km^2 of the lagoon waters with the inflow distances of up to 35 km (Figure 19). On the western coast, where the influence of Nemunas river discharge is weaker, marine waters can go even further and reach the southern part of the Curonian Lagoon (Zemlys et al., 2013). This is quite significant considering the total length of the lagoon is about 93 km (Žaromskis, 1996). A similar pattern to changes in the Chl-*a* was observed in the changes of the biomass and the intensity of production processes in the northern part of the lagoon, as described in Sulijiene, (1990) (cited in Krevs et al., 2007) showing that depending on the degree of the marine water intrusion, the upwelling inflow to the lagoon results in the primary production changes of a much bigger scale compared to those in the Baltic Sea.

5.4 Effects of upwelling on water quality

Global to regional monitoring of the surface ocean, coastal waters, estuaries, lakes and other water bodies, relevant to the water quality managers is believed to be an essential element for the sustainability of the ocean resources (Pitarch et al., 2016). The Baltic Sea physics has several specific features and one of them is spatially and temporally frequent upwelling, causing "random noise" to time series, thus it is a challenge for monitoring programmes with temporally limited sampling (Myrberg et al., 2019). Monitoring is a crucial part of the implementation of the Marine Strategy Framework Directive (MSFD), also the EU Water Framework Directive 2000/60/EC (WFD). However, National monitoring programs are not able to cover all water bodies, thus both the EU's directives and HELCOM recommend a higher implementation of remote sensing data for monitoring and assessment activities (Harvey et al., 2018) as it can provide frequent data with large spatial coverage for studies of water quality parameters such as chlorophyll-*a* (Bresciani et al 2011).

WFD is widely accepted as the most substantial and ambitious piece of European environmental legislation to date for water management with the purpose to establish a framework for the protection of European waters in order to reach "good status" objectives for water bodies throughout the EU (Voulvoulis et al., 2017). The analysis of the satellite Chl-*a* and SST images of the SE Baltic Sea region show that through the reduced chlorophyll-*a* concentrations the effect of upwelling can be linked to a better water quality in the coastal zone compared to the waters further offshore. Several examples showing WFD water quality classes based on Chl-*a* concentration values in the SE Baltic Sea coast and Curonian Lagoon are presented in Figure 29, demonstrating that the upwelling-affected waters can be distinguished from the ambient ones as having a better quality based on WFD water quality classes.

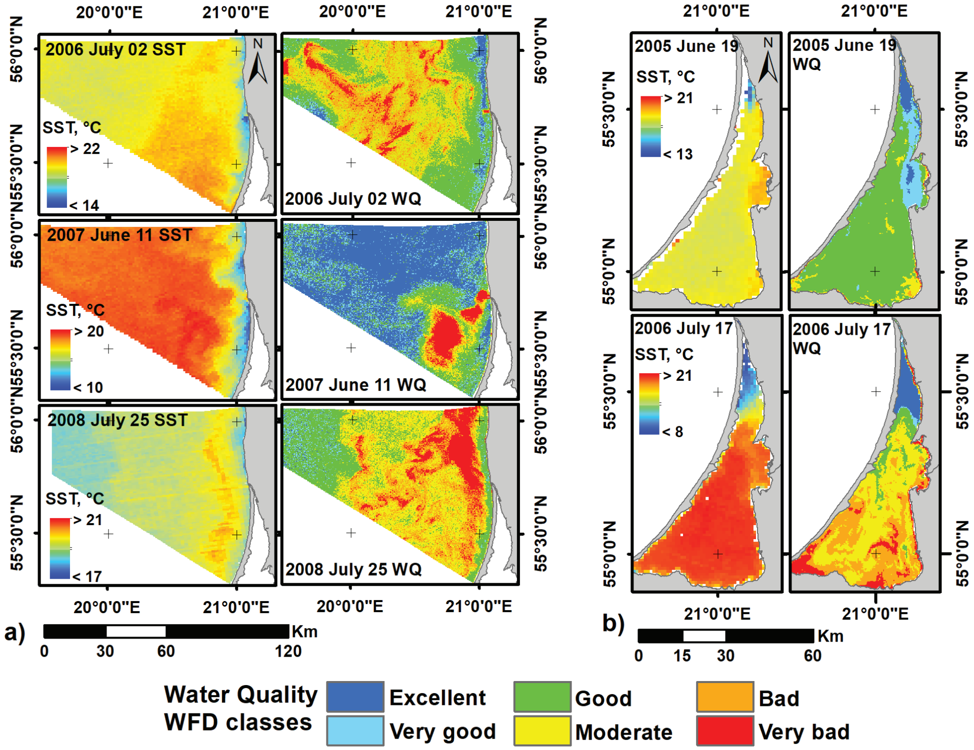


Figure 29. Upwelling-associated water quality changes in **(a)** the SE Baltic Sea coast and **(b)** Curonian Lagoon.

29 paveikslas. Apvelingo sukelti vandens kokybės pokyčiai **(a)** PR Baltijos jūroje ir **(b)** Kuršių mariose.

This is very well exemplified in the upwelling cases of 02 July 2006 or 25 July 2008. Here the "excellent" to "good" quality waters along the coast are clearly distinguished compared to the areas further offshore with accumulations of high concentrations of Chl-*a*. In turn, the ambient waters are characterized as having "bad" to "very bad" water status according to the water quality WFD classes. However, as the upwelling case on 11 June 2007 shows, the entire region is classified as "excellent" to "good" and the upwelling cannot be so clearly distinguished from the water quality values, especially in the northern part of the coast. On the other hand, to the south from Klaipeda strait the upwelling induced offshore transport directs the flow of the plume from the Curonian Lagoon to the open waters and a band of "excellent" quality waters indicates the presence of the upwelling at the coast of the Curonian Spit. It is interesting to note that the Baltic Sea upwelling might have an opposite effect than the oceanic one – a temporary increase of water quality while the oceanic water during the upwelling periods often has water quality conditions failing to meet the water quality standards (Brown and Nelson, 2015)

It is also worth mentioning, that the Curonian Lagoon is considered to be an important element for touristic development in the region. Although, this development is hampered by eutrophication and, in turn, poor water quality, insufficient for bathing (Schernewski et al., 2017), summer algae blooms and low transparency, which negatively influence the socio-economic dynamics of the area (Inacio et al., 2018). Therefore, as shown in Figure 29 b, another important aspect of the upwelling water entrainment events is the water quality improvement in the hyper-eutrophic Curonian Lagoon. Here, the areas with cold temperatures are characterised by an "excellent" water quality according to the water quality WFD classes whereas ambient waters, depending on the initial Chl-*a* concentration can be characterised even as "very bad". Even though water quality improvement is a short-term event, it can contribute indirectly to the environment, which is more attractive for tourism activities through the increased transparency/reduced algal blooms. Besides, such events should be taken into account when evaluating the overall state of the environment as the measurements of water quality indicators during upwelling events might represent very different conditions from the typical ones.

6

Conclusions

1. In general, it takes about 1–3 days of northerly winds for the coastal upwelling to be manifested in the sea surface temperature maps of the south-eastern Baltic Sea, with milder winds of a shorter duration during summer months, and longer and stronger winds in spring and autumn.
2. The coastal upwelling is most reliably identified in satellite infrared data of the SE Baltic Sea from May to August, when up to 87% of all theoretical upwelling events can be detected owing to well pronounced upwelling-induced SST changes and relatively cloudless weather conditions.
3. About 90% of all upwelling events recorded during April–September in 2000–2015 were observed between May and August peaking in July. Short-lived (2–6 days long) upwelling events clearly dominate in the record, occurring about four times per season and covering about 16 % of the warm (April–September) period.
4. Considerable spatial variations of the upwelling-induced SST gradient are observed within a typical range of 0.2–0.5 °C km^{-1}. In summer and autumn prevailing SST gradients are higher than in spring, with the highest values (> 0.75 °C km^{-1}) most frequently observed in summer.
5. Typically, the upwelling area covers mainly Lithuanian and Latvian coastal waters, while during extreme events it can extend over a significant part of

Gdansk and eastern Gotland Basins. The cross-shore extent of the upwelling front in the SE Baltic Sea ranges between 5 km and 70 km, and clearly depends on the changing bathymetry.

6. The pronounced intrusions of the relatively cold and saline upwelling water into the Curonian Lagoon are observed 1–2 times per season with an average duration of 1–3 days. Such inflows form under northerly winds when the water level drops down in the northern part of the Lagoon. During such events, the water temperature difference between the upwelling and the ambient water in the Lagoon is somewhat higher than the average values observed in the SE Baltic Sea.
7. As observed, the northern part of the Lagoon is mostly affected by the upwelling inflows extending to about 10–25 km southward from Klaipeda Strait. In some rare cases, the inflows propagate up to 40 km southward till the central part of the Lagoon covering about 200 km^2 of its surface area.
8. In most cases, a significant decrease of 40–50 % in Chl-*a* concentration is observed in the upwelling zone. Upwelling-induced SST changes and offshore water transport appear to be the most influential factors affecting Chl-*a* concentrations in the coastal zone.
9. During upwelling inflows, Chl-*a* concentration drops down by an order of magnitude in the Curonian Lagoon, which has a much stronger effect compared to the coastal waters of the SE Baltic Sea.

7

References

1. Aceves-Medina, G., Palomares-García, R., Gómez-Gutiérrez, J., Robinson, C.J., Saldierna-Martínez, R.J., 2009. Multivariate characterization of spawning and larval environments of small pelagic fishes in the Gulf of California. J Plankton Res 31, 1283–1297. https://doi.org/10.1093/plankt/fbp056
2. Aguirre, C., García-Loyola, S., Testa, G., Silva, D., Farias, L., 2018. Insight into anthropogenic forcing on coastal upwelling off south-central Chile. Elem Sci Anth 6, 59. DOI: http://doi.org/10.1525/elementa.314
3. Alenius, P., Myrberg, K., Nekrasov, A., 1998. The physical oceanography of the Gulf of Finland: a review. Boreal Env. Res. 3, 97–125.
4. Al-Tahir, R., Richardson, T., Mahabir, R., 2009. Advancing the Use of Earth Observation Systems for the Assessment of Sustainable Development. The Journal of the Association of Professional Engineers of Trinidad and Tobago Vol.38, No.1, pp.6-15, ISSN 1000 7924
5. Austin, R.W., 1993. Optical Remote Sensing of the Oceans: BC (Before CZCS) and AC (After CZCS). Ocean Colour: Theory and Applications in a Decade of CZCS Experience 1–15. https://doi.org/10.1007/978-94-011-1791-3_1
6. Azis Ismail, M.F., Ribbe, J., Karstensen, J., Rossi, V., 2019. Remote sensing of upwelling off Australia's north-east coast. Ocean Sci. Discuss. 1–31. https://doi.org/10.5194/os-2018-142

7. Bakun, A. 1973. Coastal upwelling indices, west coast of North America, 1946-71. U.S.Dep. Commer., NOAA Tech. Rep., NMFS SSRF-671, 103 p.
8. Bakun, A., 1990. Global climate change and intensification of coastal ocean upwelling. Science 247, 198–201. https://doi.org/10.1126/science.247.4939.198
9. Bakun, A., Agostini, V.N., 2001. Seasonal patterns of wind-induced upwelling/downwelling in the Mediterranean Sea. https://doi.org/10.3989/scimar.2001.65n3243
10. Bakun, A., Field, D.B., Redondo-Rodriguez, A., Weeks, S.J., 2010. Greenhouse gas, upwelling-favorable winds, and the future of coastal ocean upwelling ecosystems. Global Change Biology 16, 1213–1228. https://doi.org/10.1111/j.1365-2486.2009.02094.x
11. Barua D.K., 2005. Coastal Upwelling and Downwelling. In: Schwartz M.L. (eds) Encyclopedia of Coastal Science. Encyclopedia of Earth Science Series. Springer, Dordrecht
12. Barzandeh, A., Eshghi, N., Hosseinibalam, F. and Hassanzadeh, S., 2018. Wind-driven Coastal Upwelling along the Northern Shoreline of the Persian Gulf,. BGTA. https://doi.org/10.4430/bgta0235
13. Bednorz, E., Półrolniczak, M., Czernecki, B., 2013. Synoptic conditions governing upwelling along the Polish Baltic coast. Oceanologia 55 (4), 767–785. https://doi.org/10.5697/oc.55-4.767
14. Bednorz, E., Półrolniczak, M., Czernecki, B., Tomczyk, A.M., 2019. Atmospheric Forcing of Coastal Upwelling in the Southern Baltic Sea Basin. Atmosphere 10, 327. https://doi.org/10.3390/atmos10060327
15. Benoit-Bird, K. J., Waluk, C. M., & Ryan, J. P. (2019). Forage species swarm in response to coastal upwelling. Geophysical Research Letters, 46, 1537–1546. https://doi.org/10.1029/2018GL081603
16. Bettencourt, J.H., Rossi, V., Hernández-García, E., Marta-Almeida, M., López, C., 2017. Characterization of the structure and cross-shore transport properties of a coastal upwelling filament using three-dimensional finite-size Lyapunov exponents. Journal of Geophysical Research: Oceans 122, 7433–7448. https://doi.org/10.1002/2017JC012700
17. Bonekamp, H., Montagner, F., Santacesaria, V., Nogueira Loddo, C., Wannop, S., Tomazic, I., O'Carroll, A., Kwiatkowska, E., Scharroo, R., Wilson, H., 2016. Core operational Sentinel-3 marine data product services as part of the Copernicus Space Component. Ocean Sci. 12, 787–795. https://doi.org/10.5194/os-12-787-2016
18. Bograd, S.J., Schroeder, I., Sarkar, N., Qiu, X., Sydeman, W.J., Schwing, F. B., 2009. Phenology of coastal upwelling in the California Current. Geophys Res Lett. 36. https://doi.org/doi:10.1029/2008GL035933

19. Boyer, K.E., Kertesz, J.S., Bruno, J.F., 2009. Biodiversity effects on productivity and stability of marine macroalgal communities: the role of environmental context. Oikos 118, 1062–1072. https://doi.org/10.1111/j.1600-0706.2009.17252.x
20. Bresciani, M., Stroppiana, D., Odermatt, D., Morabito, G., Giardino, C., 2011. Assessing remotely sensed chlorophyll-a for the implementation of the Water Framework Directive in European perialpine lakes. Science of The Total Environment 409, 3083–3091. https://doi.org/10.1016/j.scitotenv.2011.05.001
21. Bresciani, M., Giardino, C., Stroppiana, D., Pilkaitytė, R., Zilius, M., Bartoli, M., Razinkovas, A., 2012. Retrospective analysis of spatial and temporal variability of chlorophyll-a in the Curonian Lagoon. J. Coastal Conserv. 16 (4), 511–519.
22. Brink, K.H., 1983. The near-surface dynamics of coastal upwelling. Progress in Oceanography 12, 223–257. https://doi.org/10.1016/0079-6611(83)90009-5
23. Brown, O.B.; Minnett, P.J., 1999. MODIS Infrared Sea Surface Temperature Algorithm; Tech. Report ATBD25, FL 33149–1098; University of Miami: Coral Gables, FL, USA
24. Brown, C. and Nelson W., 2015. A Method to Identify Estuarine Water Quality Exceedances Associated with Ocean Conditions. ENVIRONMENTAL MONITORING AND ASSESSMENT. Springer, New York, NY, 187(133):14
25. Bryhn, A.C., Sessa, C., Hakanson, L., 2010. Costs, ecosystem benefits and policy implications of remedial measures to combat coastal eutrophication – a framework for analyses and a practical example related to the gulf of Ryga. In: Eutrophication: Ecological Effects, Sources, Prevention and Reversal. pp. 103-134
26. Bychkova, I.; Viktorov, S., 1987 Use of satellite data for identification and classification of upwelling in the Baltic Sea. Oceanology, 27, 158–162.
27. Bychkova, I.; Viktorov, S.; Shumakher, D.A. A relationship between the large-scale atmospheric circulation and the origin of coastal upwelling in the Baltic Sea. Meteorol. Gidrol. 1988, 10, 91–98.
28. Capone, D.G., Hutchins, D.A., 2013. Microbial biogeochemistry of coastal upwelling regimes in a changing ocean. Nature Geoscience 6, 711–717. https://doi.org/10.1038/ngeo1916
29. Carr, M.-E., Kearns, E.J., 2003. Production regimes in four Eastern Boundary Current systems. Deep Sea Research Part II: Topical Studies in Oceanography, The US JGOFS Synthesis and Modeling Project: Phase II 50, 3199–3221. https://doi.org/10.1016/j.dsr2.2003.07.015
30. Casabella, N., Lorenzo, M.N., Taboada, J.J., 2014. Trends of the Galician upwelling in the context of climate change. Journal of Sea Research 93, 23–27. https://doi.org/10.1016/j.seares.2014.01.013

31. Chen, W., Zhang, T., Guan, L., 2017. "Radiation Transfer in the Ocean and Ocean Color" in Liang, Shunlin (ed.), *Comprehensive Remote Sensing*, (43-78) Elsevier
32. Chenillat, F., Riviere, P., Capet, X., Di Lorenzo, E., Blanke, E., 2012. North Pacific Gyre Oscillation modulates seasonal timing and ecosystem functioning in the California Current upwelling system. Geophys Res Lett. 39 (1). https://doi.org/10.1029/2011GL049966
33. Croll, D. A., Marinovic, B., Benson, S., Chavez, F. P., Black, N., Ternullo, R., & Tershy, B. R., 2005. From wind to whales: Trophic links in a coastal upwelling system. Marine Ecology Progress Series, 289, 117–130. https://doi.org/10.3354/meps289117
34. Cropper, T.E., Hanna, E., Bigg, G.R., 2014. Spatial and temporal seasonal trends in coastal upwelling off Northwest Africa, 1981–2012. Deep-Sea Research I 86, 94–111.
35. Dabuleviciene, T.; Kozlov, I.E.; Vaiciute, D.; Dailidiene, I., 2018. Remote Sensing of Coastal Upwelling in the South-Eastern Baltic Sea: Statistical Properties and Implications for the Coastal Environment. Remote Sens., 10(11), 1752; https://doi.org/10.3390/rs10111752
36. Dailidienė, I., Davulienė, L., 2008. Salinity trend and variation in the Baltic Sea near the Lithuanian coast and in the Curonian Lagoon in 1984–2005. Journal of Marine Systems, Baltic Sea Science Congress 2007 74, S20–S29. https://doi.org/10.1016/j.jmarsys.2008.01.014
37. Davenport, R., Neuer, S., Hernandez-Guerra, A., Rueda, M.J., Llinas, O., Fischer, G., Wefer, G., 1999. Seasonal and interannual pigment concentration in the Canary Islands region from CZCS data and comparison with observations from the ESTOC. International Journal of Remote Sensing 20, 1419–1433. https://doi.org/10.1080/014311699212803
38. Delpeche-Ellmann, N., Mingelaitė, T., Soomere, T., 2017. Examining Lagrangian surface transport during a coastal upwelling in the Gulf of Finland, Baltic Sea. Journal of Marine Systems 171, 21–30. https://doi.org/10.1016/j.jmarsys.2016.10.007
39. Delpeche-Ellmann, N., Soomere, T., Kudryavtseva, N., 2018. The role of nearshore slope on cross-shore surface transport during a coastal upwelling event in Gulf of Finland, Baltic Sea. Estuarine, Coastal and Shelf Science 209, 123–135. https://doi.org/10.1016/j.ecss.2018.03.018
40. Dierssen, H.M., and Randolph, K., 2013. Remote Sensing of Ocean Color. Encyclopedia of Sustainability Science and Technology. Springer-Verlag Berlin Heidelberg. 25 pp.

41. Dietze, H., Loptien, U., 2016. Effects of surface current–wind interaction in an eddy-rich general ocean circulation simulation of the Baltic Sea. Ocean Sci 12, 977–986. https://doi.org/10.5194/os-12-977-2016
42. Diffenbaugh, N.S., Snyder, M.A., Sloan, L.C., 2004. Could CO2-induced land-cover feedbacks alter near-shore upwelling regimes? PNAS 101, 27–32. https://doi.org/10.1073/pnas.0305746101
43. Ekman, V., 1905. On the influence of the earth‘s rotation on ocean currents. Arkiv for Matematik, Astronomi och Fysik, 2(11), 1-52
44. Emery, W.J., Castro, S., Wick, G.A., Schluessel, P., Donlon, C., 2001. Estimating Sea Surface Temperature from Infrared Satellite and In Situ Temperature Data. Bulletin of the American Meteorological Society 82, 2773–2785. https://doi.org/10.1175/1520-0477(2001)082<2773:ESSTFI>2.3.CO;2
45. Esiukova, E.E., Chubarenko, I.P., Stont, Z.I., 2017. Upwelling or Differential Cooling? Analysis of Satellite SST Images of the Southeastern Baltic Sea. Water Resour 44 (1), 69–77. https://doi.org/10.1134/S0097807817010043
46. Fennel, W., Seifert, T., Kayser, B., 1991. Rossby radii and phase speeds in the Baltic Sea. Cont. Shelf Res. 11 (1), 23–36. https://doi.org/10.1016/0278-4343(91)90032-2
47. Fennel, W., Lass, H.U., 2007. On the impact of wind curls on coastal currents. Journal of Marine Systems 68, 128–142. https://doi.org/10.1016/j.jmarsys.2006.11.004
48. Fisher, J.I., Mustard, J.F., 2004. High spatial resolution sea surface climatology from Landsat thermal infrared data. Remote Sensing of Environment 3, 293–307. https://doi.org/10.1016/j.rse.2004.01.008
49. Fomferra, N. and Brockmann, C., "The BEAM project web page," Brockmann Consult, Hamburg, Germany, available from: http://www.brockmann-consult.de/beam/ (17 January 2006).
50. Franks, P., 1992. Sink or swim, accumulation of biomass at fronts. Mar. Ecol. Prog. Ser. 82, 1–12. https://doi.org/10.3354/meps082001
51. Fuchs, R., Pinazo, C., Douillet, P., Fraysse, M., Grenz, C., Mangin, A., Dupouy, C., 2013. Modelling ocean–lagoon interaction during upwelling processes in the South West of New Caledonia. Estuar Coast Shelf Sci 135, 5–17. https://doi.org/10.1016/j.ecss.2013.03.009
52. Garrison, T., 2006. *Essentials of Oceanography*. Thomson Learning Inc., ISBN 0-495-01175-4
53. Gasiūnaitė, Z.R., Cardoso, A.C., Heiskanen, A.-S., Henriksen, P., Kauppila, P., Olenina, I., Pilkaitytė, R., Purina, I., Razinkovas, A., Sagert, S., Schubert, H., Wasmund, N., 2005. Seasonality of coastal phytoplankton in the Baltic Sea: Influence of salinity and eutrophication. Estuarine, Coastal and Shelf Science 65, 239–252. https://doi.org/10.1016/j.ecss.2005.05.018

54. Gasiūnaitė Z.R., Daunys D., Olenin S., Razinkovas A., 2008. The Curonian Lagoon. In: Schiewer U. (eds) Ecology of Baltic Coastal Waters. Ecological Studies (Analysis and Synthesis), vol 197. Springer, Berlin, Heidelberg https://doi.org/10.1007/978-3-540-73524-3_9
55. Garcon, V.C., Bell, T.G., Wallace, D., Arnold, S.R., Baker A.et al., 2014. Perspectives and Integration in SOLAS Science in Peter S. Liss, Martin T. Johnson (eds) *Ocean-Atmosphere Interactions of Gases and Particles*, DOI 10.1007/978-3-642-25643-1_5, (247-306), Springer
56. Giardino, C., Bresciani, M., Pilkaitytė, R., Bartoli, M., Razinkovas, A., 2010. In situ measurements and satellite remote sensing of case 2 waters: first results from the Curonian Lagoon. OCEANOLOGIA 52, 197–210. https://doi.org/10.5697/oc.52-2.197
57. Gidhagen, L., 1987. Coastal upwelling in the Baltic Sea—Satellite and in situ measurements of sea-surface temperatures indicating coastal upwelling. Estuar Coast Shelf Sci 24 (4), 449–462. https://doi.org/10.1016/0272-7714(87)90127-2
58. Gelfenbaum, G., Stumpf, R.P., 1993. Observations of Currents and Density Structure across a Buoyant Plume Front. Estuaries 16, 40–52. https://doi.org/10.2307/1352762
59. Geller, G.N., Halpin, P.N., Helmuth, B., Hestir, E.L., Skidmore, A., Abrams, M.J., Aguirre, N., Blair, M., Botha, E., Colloff, M., Dawson, T., Franklin, J., Horning, N., James, C., Magnusson, W., Santos, M.J., Schill, S.R., Williams, K., 2017. Remote Sensing for Biodiversity. The GEO Handbook on Biodiversity Observation Networks 187–210. https://doi.org/10.1007/978-3-319-27288-7_8
60. Gholizadeh, M.H., Melesse, A.M., Reddi, L., 2016. A Comprehensive Review on Water Quality Parameters Estimation Using Remote Sensing Techniques. Sensors (Basel) 16. https://doi.org/10.3390/s16081298
61. Golenko, M.N., Golenko, N.N., 2012. Structure of dynamic fields in the Southeastern Baltic during wind forcings that cause upwelling and downwelling. Oceanology 52, 604–616. https://doi.org/10.1134/S0001437012050086
62. Gomez-Gesteira, M., Moreira, C., Alvarez, I., deCastro, M., 2006. Ekman transport along the Galician coast (northwest Spain) calculated from forecasted winds. J. Geophys. Res. 111. https://doi.org/doi:10.1029/2005JC003331
63. González-Rodríguez, E., Trasviña-Castro, A., Gaxiola-Castro, G., Zamudio, L., Cervantes-Duarte, R., 2012. Net primary productivity, upwelling and coastal currents in the Gulf of Ulloa, Baja California, México. Ocean Sci. 8, 703–711. https://doi.org/10.5194/os-8-703-2012
64. Grant, K.T., Estes, G.B., 2009. Darwin in Galápagos: Footsteps to a New World. Princeton University Press. 376 p.
65. Gurova, E., Lehmann, A., Ivanov, A., 2013. Upwelling dynamics in the Baltic Sea studied by a combined SAR/infrared satellite data and circulation mod-

el analysis. Oceanologia 55, 687–707. https://doi.org/ttps://doi.org/10.5697/oc.55-3.687

66. Haapala, J., 1994. Upwelling and its Influence on Nutrient Concentration in the Coastal Area of the Hanko Peninsula, Entrance of the Gulf of Finland. Estuar Coast Shelf Sci 38, 507–521. https://doi.org/10.1006/ecss.1994.1035
67. Haffner, G.D., Yallop, M.L., Hebert, P.D.N., Griffiths, M., 1984. Ecological Significance of Upwelling Events in Lake Ontario. Journal of Great Lakes Research 10, 28–37. https://doi.org/10.1016/S0380-1330(84)71804-1
68. Harvey E.T., Krause-Jensen D., Stæhr P.A., Groom G.B. & Hansen, L.B., 2018. Literature review of remote sensing technologies for coastal chlorophyll-a observations and vegetation coverage. Part of ReSTEK (Brug af Remote Sensing teknologier til opgørelse af klorofylkoncentrationer og vegetationsudbredelse i danske kystvande) and DCE Remote sensing in coastal area projects. Aarhus University, DCE – Danish Centre for Environment and Energy, 47 pp. - Technical Report from DCE – Danish Centre for Environment and Energy No. 112. http://dce2.au.dk/pub/TR112.pdf
69. HELCOM, 1998. The third Baltic Sea pollution load compilation; Baltic Sea Environment, Proceedings, 70, 133 pp.
70. Hu, J., Wang, X.H., 2016. Progress on upwelling studies in the China seas. Reviews of Geophysics 54, 653–673. https://doi.org/10.1002/2015RG000505
71. Ibe, A.C, and Ajayi, T.O., 1985. *Possible Upwelling Phenomenon off the Nigerian Coast.* Technical Paper No25, Nigerian Institute for Oceanography and Marine Research, ISBN 978-2345-0022
72. Iles, A.C., Gouhier, T.C., Menge, B.A., Stewart, J.S., Haupt, A.J., Lynch, M.C., 2012. Climate-driven trends and ecological implications of event-scale upwelling in the California Current System. Global Change Biology 18, 783–796. https://doi.org/10.1111/j.1365-2486.2011.02567.x
73. Inácio, M., Schernewski, G., Nazemtseva, Y., Baltranaitė, E., Friedland, R., Benz, J., 2018. Ecosystem services provision today and in the past: a comparative study in two Baltic lagoons. Ecol Res 33, 1255–1274. https://doi.org/10.1007/s11284-018-1643-8
74. INFORM Prototype/Algorithm Validation Report Update. 2016. D5.15. p. 140. Available online: http://inform.vgt.vito.be/files/documents/INFORM_D5.15_v1.0.pdf (accessed on 05 November 2018).
75. Ishizaka, J., Takahashi, M., Ichimura, S., 1983. Evaluation of coastal upwelling effects on phytoplankton growth by simulated culture experiments. Marine Biology 76, 271–278. https://doi.org/10.1007/BF00393028
76. Jacox, M.G., Edwards, C.A., Hazen, E.L., Bograd, S.J., 2018. Coastal Upwelling Revisited: Ekman, Bakun, and Improved Upwelling Indices for the U.S.

West Coast. Journal of Geophysical Research: Oceans 123, 7332–7350. https://doi.org/10.1029/2018JC014187

77. Jakimavičius, D., Kriaučiūnienė, J., Šarauskienė, D., 2018. Impact of climate change on the Curonian Lagoon water balance components, salinity and water temperature in the 21st century. Oceanologia 60, 378–389. https://doi.org/10.1016/j.oceano.2018.02.003
78. Johns, B., Marsaleix, P., Estournel, C., Véhil, R., 1992. On the wind-driven coastal upwelling in the Gulf of Lions. Journal of Marine Systems 3, 309–320. https://doi.org/10.1016/0924-7963(92)90008-V
79. Jiang, L., Breaker, L.C., Yan, X.-H., 2010. A model for estimating cross-shore surface transport with application to the New Jersey Shelf. J. Geophys. Res. 115. https://doi.org/10.1029/2009JC005998
80. Jurkin, V., Kelpsaite, L., 2012. Upwelling by the Lithuanian coast: Numerical prediction using GIS methods. IEEE/OES Baltic International Symposium (BALTIC). https://doi.org/DOI: 10.1109/BALTIC.2012.6249197
81. Kahru, M., Hakansson, B., Rud, O., 1995. Distributions of the sea-surface temperature fronts in the Baltic Sea as derived from satellite imagery. Cont. Shelf Res., 6 15, 663–679. https://doi.org/10.1016/0278-4343(94)E0030-P
82. Kämpf, J., 2015. Interference of wind-driven and pressure gradient-driven flows in shallow homogeneous water bodies. Ocean Dynamics 65, 1399–1410. https://doi.org/10.1007/s10236-015-0882-2
83. Kämpf, J. and Chapman, P., 2016: *Upwelling systems of the world*. Springer International Publishing, Switzerland, 433pp., doi:10.1007/978-3-319-42524-5.
84. Kämpf, J., 2017. Wind-Driven Overturning, Mixing and Upwelling in Shallow Water: A Nonhydrostatic Modeling Study. Journal of Marine Science and Engineering 5, 47. https://doi.org/10.3390/jmse5040047
85. Kanoshina, I., Lips, U., Leppänen, J.-M., 2003. The influence of weather conditions (temperature and wind) on cyanobacterial bloom development in the Gulf of Finland (Baltic Sea). Harmful Algae 2, 29–41. https://doi.org/10.1016/S1568-9883(02)00085-9
86. Karstensen, J., Liblik, T., Fisher, J., Bumke, K., Krahmann, G., 2014. Summer upwelling at the Boknis Eck time-series station (1982 to 2012) – a combined glider and wind data analysis. Biogeosciences 11, 3603–3617. https://doi.org/doi:10.5194/bg-11-3603-2014
87. Keister, J.E., Cowles, T.J., Peterson, W.T., Morgan, C.A., 2009. Do upwelling filaments result in predictable biological distributions in coastal upwelling ecosystems? Progress in Oceanography, Eastern Boundary Upwelling Ecosystems: Integrative and Comparative Approaches 83, 303–313. https://doi.org/10.1016/j.pocean.2009.07.042

88. Klemas, V., 2011. Remote Sensing Techniques for Studying Coastal Ecosystems: An Overview. coas 27, 2–17. https://doi.org/10.2112/JCOASTRES-D-10-00103.1
89. Kononen, K., Huttunen, M., Hällfors, S., Gentien, P., Lunven, M., Huttula, T., Laanemets, J., Lilover, M., Pavelson, J., Stips, A., 2003. Development of a deep chlorophyll maximum of Heterocapsa triquetra Ehrenb. at the entrance to the Gulf of Finland. Limnology and Oceanography 48, 594–607. https://doi.org/10.4319/lo.2003.48.2.0594
90. Kortum,G.,Lehmann,A.,1997.A.v.Humboldts Forschnungsfahrtaufder Ostsee in Sommer 1834. Schriften des Naturwissenschaftlichen Vereins für Schleswig-Holstein 67, 45–58.
91. Kowalewski, M., 2005. The influence of the Hel upwelling (Baltic Sea) on nutrient concentrations and primary production - the results of an ecohydrodynamic model. Oceanologia, 4 47, 567–590.
92. Kozlov, I.E., Kudryavtsev, V.N., Johannessen, J.A., Chapron, B., Dailidiene, I., Myasoedov, A.G., 2012. ASAR imaging for coastal upwelling in the Baltic Sea. Adv Space Res., 8 50, 1125–1137. https://doi.org/10.1016/j.asr.2011.08.017
93. Kozlov,I., Dailidiene, I., Korosov, A., Klemas, V., Mingelaite, T., 2014. MODIS-based sea surface temperature of the Baltic Sea Curonian Lagoon. J Marine Syst 129, 157–165. https://doi.org/10.1016/j.jmarsys.2012.05.011
94. Kratzer, S., Ebert, K., Sørensen, K., 2011. Monitoring the Bio-optical State of the Baltic Sea Ecosystem with Remote Sensing and Autonomous In Situ Techniques. In: Harff J., Björck S., Hoth P. (eds) *The Baltic Sea Basin. Central and Eastern European Development Studies (CEEDES)*. Springer, Berlin, Heidelberg, https://doi.org/10.1007/978-3-642-17220-5_20
95. Kratzer, S., Kowalczuk, P. and Sagan, S., 2017. "Bio-optical water quality assessment" in Pauline Snoeijs-Leijonmalm, Hendrik Schubert, Teresa Radziejewska (eds.), *Biological Oceanography of the Baltic Sea*, p. 527-545, Springer, DOI 10.1007/978-94-007-0668-2_15
96. Krauss, G.-J., Nies, D.H., 2015. Ecological Biochemistry: Environmental and Interspecies Interactions. John Wiley & Sons.
97. Krevs, A., Koreiviene, J., Paskauskas, R., Sulijiene, R., 2007. Phytoplankton production and community respiration in different zones of the Curonian lagoon during the midsummer vegetation period. Transitional Waters Bulletin TWB, Transit. Waters Bull. 1(2007), 17-26 ISSN 1825-229X, DOI 10.1285/i1825229Xv1n1p17
98. Krężel, A., Szymanek, L., Kozłowski, Ł., Szymelfenig, M., 2005. Influence of coastal upwelling on chlorophyll a concentration in the surface water along the Polish coast of the Baltic Sea. Oceanologia 47, 433–452.

99. Kudryavtsev, V.N., Grodsky, S.A., Dulov, V.A., Malinovsky, V.V., 1996. Observations of atmospheric boundary layer evolution above the Gulf Stream frontal zone. Boundary-Layer Meteorol 79, 51–82. https://doi.org/10.1007/BF00120075
100. Kudryavtsev, V., Kozlov, I., Chapron, B., Johannessen, J.A., 2014. Quad-polarization SAR features of ocean currents. J. Geophys. Res. 119, 6046–6065. https://doi.org/10.1002/2014JC010173
101. Kuliński, K., Pempkowiak, J., 2011. The carbon budget of the Baltic Sea. Biogeosciences 8, 3219–3230. https://doi.org/10.5194/bg-8-3219-2011
102. Kuvaldina, N., Lips, I., Lips, U., Liblik, T., 2010. The influence of a coastal upwelling event on chlorophyll *a* and nutrient dynamics in the surface layer of the Gulf of Finland, Baltic Sea, Hydrobiologia, 639:221–230DOI 10.1007/s10750-009-0022-4
103. Laanemets, J., Kononen, K., Pavelson, J., Poutanen, E.-L., 2004. Vertical location of seasonal nutriclines in the western Gulf of Finland. Journal of Marine Systems 52, 1–13. https://doi.org/10.1016/j.jmarsys.2004.03.003
104. Laanemets, J., Zhurbas, V., Elken, J. and Vahtera, E., 2009. Dependence of upwelling-mediated nutrient transport on wind forcing, bottom topography and stratification in the Gulf of Finland: Model experiments. Boreal Environment Research 14(1):213-225
105. Laanemets, J.,Vali, G., Zhurbas, V., Elken, J., Lips, I., Lips, U., 2011. Simulation of mesoscale structures and nutrient transport during summer upwelling events in the Gulf of Finland in 2006. Boreal Environment Research 16 (suppl.A):15-26, ISSN 1797-2469
106. Landeira, J.M., Lozano-Soldevilla, F., Barton, E.D., 2012. Mesoscale advection of Upogebia pusilla larvae through an upwelling filament in the Canaries Coastal Transition Zone (CTZ). Helgol Mar Res 66, 537–544. https://doi.org/10.1007/s10152-011-0289-5
107. Lehmann, A., Myrberg, K., 2008. Upwelling in the Baltic Sea — A review. J Marine Syst 74, S3–S12. https://doi.org/10.1016/j.jmarsys.2008.02.010
108. Lehmann, A., Myrberg, K., Hoflich, K., 2012. A statistical approach to coastal upwelling in the Baltic Sea based on the analysis of satellite data for 1990–2009. Oceanologia, 3 54, 369–393. https://doi.org/10.5697/oc.54-3.369
109. Leppäranta, M., Myrberg, K., 2009. *Physical Oceanography of the Baltic Sea*. Springer-Praxis, Heidelberg, Germany. ISBN 978-3-540-79702-9.
110. Letelier, J., Pizarro, O. and Nunez, S., 2009. Seasonal variability of coastal upwelling and the upwelling front off central Chile. Journal of Geophysical Research, VOL. 114, C12009, doi:10.1029/2008JC005171
111. Lévy, M., 2008. The Modulation of Biological Production by Oceanic Mesoscale Turbulence. In: Weiss J.B., Provenzale A. (eds) Transport and Mixing in

Geophysical Flows. Lecture Notes in Physics, vol 744. Springer, Berlin, Heidelberg 219–261. https://doi.org/10.1007/978-3-540-75215-8_9

112. Lips, I., Lips, U., 2010. Phytoplankton dynamics affected by the coastal upwelling events in the Gulf of Finland in July-August 2006. Journal of Plankton Research 32, 1269–1282. https://doi.org/10.1093/plankt/fbq049

113. Lips, U., Lips, I., Liblik, T., Kikas, V., Altoja, K., Buhhalko, N., Rünk, N., 2011. Vertical dynamics of summer phytoplankton in a stratified estuary (Gulf of Finland, Baltic Sea). Ocean Dynamics 61, 903–915. https://doi.org/10.1007/s10236-011-0421-8

114. Liu, Y., Fu, W., 2018. Assimilating high-resolution sea surface temperature data improves the ocean forecast potential in the Baltic Sea. Ocean Science 14, 525–541. https://doi.org/10.5194/os-14-525-2018

115. Llewellyn-Jones, D.T., Minnett, P.J., Saunders, R.W., Zavody, A.M., 1984. Satellite multichannel infrared measurements of sea surface temperature of the N.E. Atlantic Ocean using AVHRR/2. Quarterly Journal of the Royal Meteorological Society 110, 613–631. https://doi.org/10.1002/qj.49711046504

116. Mamoutos, I., Zervakis, V., Tragou, E., Karydis, M., Frangoulis, C., Kolovoyiannis, V., Georgopoulos, D., Psarra, S., 2017. The role of wind-forced coastal upwelling on the thermohaline functioning of the North Aegean Sea. Continental Shelf Research, Investigating fertilizing mechanisms and ecosystem functioning in an E. Mediterranean productivity "hotspot": The case of the oligotrophic NE Aegean Sea 149, 52–68. https://doi.org/10.1016/j.csr.2017.05.009

117. Matthaus, W., 2010. Germany and the investigation of the Baltic Sea hydrography during the 19th and early 20th century. Meereswiss. Ber., Warnemünde 83

118. Mazzini, P.L.F., Barth, J.A., 2013. A comparison of mechanisms generating vertical transport in the Brazilian coastal upwelling regions. Journal of Geophysical Research: Oceans 118, 5977–5993. https://doi.org/10.1002/2013JC008924

119. Mcgregor, H., Mulitza, S., 2007. Rapid 20th-century increase in coastal upwelling off northwest Africa revealed by high-resolution marine sediment cores. https://doi.org/10.22498/pages.15.2.28

120. Minnett, P.J., (2001) "Satellite Remote Sensing of Sea Surface Temperatures" in John H. Steele, Steve A. Thorpe, Karl K. (eds) *Elements of Physical Oceanography: A Derivative of the Encyclopedia of Ocean Sciences*, p. 291-304, Elsevier Science ISBN: 9780123757258.

121. Mikhailova, E.N., Ivanov, V.A., Kosnyrev, V.R., 1997. Upwelling in the northwestern Black Sea during the period of summer-time warming. Phys. Oceanogr. 8, 243–251. https://doi.org/10.1007/BF02523664

122. Morel, A., Prieur, L., 1977. Analysis of variations in ocean color1. Limnology and Oceanography 22, 709–722. https://doi.org/10.4319/lo.1977.22.4.0709

123. Morgan, S.G., 2014. Behaviorally Mediated Larval Transport in Upwelling Systems. Advances in Oceanography. https://doi.org/10.1155/2014/364214
124. Myrberg, K., Andrejev, O., 2003. Main upwelling regions in the Baltic Sea - a statistical analysis based on three-dimensional modelling. Boreal Env. Res. 8, 97–112.
125. Myrberg, K., Andrejev, O., Lehmann, A., 2010. Dynamic features of successive upwelling events in the Baltic Sea - a numerical case study. Oceanologia 52, 77–99.
126. Myrberg, K.; Lehmann, A. Topography, Hydrography, Circulation and Modelling of the Baltic Sea. In Soomere, T., Quak, E., (Eds.) *Preventive Methods for Coastal Protection: Towards the Use of Ocean Dynamics for Pollution Control*; Springer: Berlin, Germany, 2013; pp. 31–64.
127. Myrberg, K., Korpinen S., Uusitaloc, L., 2019. Physical oceanography sets the scene for the Marine Strategy Framework Directive implementation in the Baltic Sea. Marine Policy, https://doi.org/10.1016/j.marpol.2019.103591
128. Navarro-Pérez, E., Barton, E.D., 1998. The physical structure of an upwelling filament off the North-West African coast during August 1993. South African Journal of Marine Science 19, 61–73. https://doi.org/10.2989/025776198784126827
129. Niermann, U., Bingel, F., Gorbun, A., Gordina, A.D., Gucu, A.C., Kideys, A.E., Konsulov, A., Radu, G., Subbotin, A.A. and Zaika, V.E. (1994) Distribution of Anchovy eggs and larvae (*Engraulis encasicolus* Cuv.) in the Black Sea in 1991-1992. *ICES J. Mar. Sci. 51, 395-406*
130. Njoku, E.G., 1990. Satellite Remote Sensing of Sea Surface Temperature. Surface Waves and Fluxes 311–338. https://doi.org/10.1007/978-94-009-0627-3_8
131. Nommann, S., Sildam, J., Noges, T., Kahru, M., 1991. Plankton distribution during a coastal upwelling event off Hiiumaa, Baltic Sea: impact of short-term flow field variability. Continental Shelf Research 11, 95–108. https://doi.org/10.1016/0278-4343(91)90037-7
132. Norman, M., Parampil, S.R., Rutgersson, A., Sahlée, E., 2013. Influence of coastal upwelling on the air–sea gas exchange of CO2 in a Baltic Sea Basin. Tellus B: Chemical and Physical Meteorology 65, 21831. https://doi.org/10.3402/tellusb.v65i0.21831
133. Nowacki, J., Matciak, M., Szymelfenig, M., Kowalewski, M., 2009. Upwelling characteristics in the Puck Bay (the Baltic Sea). OCEANOL HYDROBIOL ST XXXVIII, 3–16. https://doi.org/DOI 10.2478/v10009-009-0014-8
134. Olenina I., Olenin S., 2002. Environmental Problems of the South-Eastern Baltic Coast and the Curonian Lagoon. In: Schernewski G., Schiewer U. (eds) *Baltic Coastal Ecosystems*. Central and Eastern European Development Studies. Springer, Berlin, Heidelberg

135. Orren, M., 1995. Upwelling Along the West Coast of Ireland: What can we learn from the experience in the Benguela Upwelling System? In Hagen, E. and Jorge da Silva, A. *Dynamics of upwlling in the ICES area.* ICES Coop.Res.Rep. No.206. ISSN 1017-6195
136. Paldavičienė, A., Mazur-Marzec, H., Razinkovas, A., 2009. Toxic cyanobacteria blooms in the Lithuanian part of the Curonian Lagoon. OCEANOLOGIA 51, 203–216. https://doi.org/10.5697/oc.51-2.203
137. Pardo, P., Padín, X., Gilcoto, M., Farina-Busto, L., Pérez, F., 2011. Evolution of upwelling systems coupled to the long-term variability in sea surface temperature and Ekman transport. Climate Research 48, 231–246. https://doi.org/10.3354/cr00989
138. Pegliasco, C., Chaigneau, A., Morrow, R., 2015. Main eddy vertical structures observed in the four major Eastern Boundary Upwelling Systems. Journal of Geophysical Research: Oceans 120, 6008–6033. https://doi.org/10.1002/2015JC010950
139. Pelegrí, J.L., Marrero-Díaz, A., Ratsimandresy, A.W., 2006. Nutrient irrigation of the North Atlantic. Progress in Oceanography, Gabriel T. Csanady: Understanding the Physics of the Ocean 70, 366–406. https://doi.org/10.1016/j.pocean.2006.03.018
140. Pitarch, J., Volpe, G., Colella, S., Krasemann, H., Santoleri, R., 2016. Remote sensing of chlorophyll in the Baltic Sea at basin scale from 1997 to 2012 using merged multi-sensor data. Ocean Sci. 379–389. https://doi.org/10.5194/os-12-379-2016
141. Pitcher, G.C., Figueiras, F.G., Hickey, B.M., Moita, M.T., 2010. The physical oceanography of upwelling systems and the development of harmful algal blooms. Prog Oceanogr 85, 5–32. https://doi.org/10.1016/j.pocean.2010.02.002
142. Plattner, S., Mason, D.M., Leshkevich, G.A., Schwab, D. J., Rutherford, E. S., 2006. Classifying and Forecasting Coastal Upwellings in Lake Michigan Using Satellite Derived Temperature Images and Buoy Data. J. Great Lakes Res. 32, 63–76. https://doi.org/10.3394/0380-1330(2006)32[63:CAFCUI]2.0.CO;2
143. Rao, Y.R., Murthy, C.R., 2001. Coastal Boundary Layer Characteristics during Summer Stratification in Lake Ontario. JOURNAL OF PHYSICAL OCEANOGRAPHY 31, 17.
144. Reddin, C.J., Docmac, F., O'Connor, N.E., Bothwell, J.H., Harrod, C., 2015. Coastal Upwelling Drives Intertidal Assemblage Structure and Trophic Ecology. PLoS One 10. https://doi.org/10.1371/journal.pone.0130789
145. Reissmann, J.H., Burchard, H., Feistel, R., Hagen, E., Lass, H.U., Mohrholz, V., Nausch, G., Umlauf, L., Wieczorek, G., 2009. Vertical mixing in the Baltic Sea and consequences for eutrophication – A review. Progress in Oceanography 82, 47–80. https://doi.org/10.1016/j.pocean.2007.10.004

146. Relvas, P., Monteiro, C., Cravo, A., Cardeira, S., Madureira, M., Rita, F., Sánchez, R., 2014. Cross-shore exchanges imposed by an upwelling filament, in: OCEANS 2014 - TAIPEI. Presented at the OCEANS 2014 - TAIPEI, pp. 1–7. https://doi.org/10.1109/OCEANS-TAIPEI.2014.6964385
147. Robinson, I.S., 2004. *Measuring the oceans from space: the principles and methods of satellite oceanography*. Springer/Praxis Publishing. ISBN: 3540426477
148. Rossi, V., López, C., Hernández-García, E., Sudre, J., Garçon, V., Morel, Y., 2009. Surface mixing and biological activity in the four Eastern Boundary Upwelling Systems. Nonlinear Processes in Geophysics 16, 557–568. https://doi.org/10.5194/npg-16-557-2009
149. Rossi, V., Feng, M., Pattiaratchi, C., Roughan, M., Waite, A.M., 2013. On the factors influencing the development of sporadic upwelling in the Leeuwin Current system: Sporadic Upwelling Off Western Australia. Journal of Geophysical Research: Oceans 118, 3608–3621. https://doi.org/10.1002/jgrc.20242
150. Rossi, V., Schaeffer, A., Wood, J., Galibert, G., Morris, B., Sudre, J., Roughan, M., Waite, A.M., 2014. Seasonality Of Sporadic Physical Processes Driving Temperature And Nutrient High-Frequency Variability In The Coastal Ocean Off Southeast Australia. Journal of Geophysical Research. Oceans 119, 445–460. https://doi.org/10.1002/2013jc009284
151. Saldívar-Lucio, R., Di Lorenzo, E., Nakamura, M., Villalobos, H., Lluch-Cota, D., Del Monte-Luna, P., 2016. Macro-Scale Patterns in Upwelling/Downwelling Activity at North American West Coast. PLoS One 11. https://doi.org/10.1371/journal.pone.0166962
152. Schalles, John F. (2006) „Optical Remote Sensing Techniques to estimate Phytoplankton Chlorophyll *a Concentrations in* coastal waters with varying suspended matter and CDOM concentrations“ in L.L.Richardson and E.F. LeDrew (eds.) *Remote Sensing of Aquatic Coastal Ecosystem Processes*: *Science and Management Applications*, 27-79.
153. Schernewski, G., Behrendt, H., Neumann, T., 2008. An integrated river basin-coast-sea modelling scenario for nitrogen management in coastal waters. J Coast Conserv 12, 53–66. https://doi.org/10.1007/s11852-008-0035-6
154. Schernewski, G., Baltranaitė, E., Kataržytė, M., Balčiūnas, A., Čerkasova, N., Mėžinė, J., 2017. Establishing new bathing sites at the Curonian Lagoon coast: an ecological-social-economic assessment. Journal of Coastal Conservation. https://doi.org/10.1007/s11852-017-0587-4
155. Schroeder, T., Schaale, M., Fischer, J., 2007. Retrieval of atmospheric and oceanic properties from MERIS measurements: A new Case-2 water processor for BEAM. International Journal of Remote Sensing 28, 5627–5632. https://doi.org/10.1080/01431160701601774

156. Schwing, F. B., O'Farrell, M., Steger, J. M. and Baltz, K., 1996. Coastal upwelling indices, West Coast of North America, 1946 – 1995, NOAA Tech. Memo., NOAA-TM-NMFS-SWFSC-231, 144 pp
157. She, J., Høyer, J.L., Larsen, J., 2007. Assessment of sea surface temperature observational networks in the Baltic Sea and North Sea. Journal of Marine Systems 65, 314–335. https://doi.org/10.1016/j.jmarsys.2005.01.004
158. Silvestrova, K.P., Zatsepin, A.G., Myslenkov, S.A., 2017. Coastal upwelling in the Gelendzhik area of the Black Sea: Effect of wind and dynamics. Oceanology 57, 469–477. https://doi.org/10.1134/S0001437017040178
159. Snyder, M.A., Sloan, L.C., Diffenbaugh, N.S., Bell, J.L., 2003. Future climate change and upwelling in the California Current: FUTURE CLIMATE CHANGE AND UPWELLING IN THE CALIFORNIA CURRENT. Geophys. Res. Lett. 30. https://doi.org/10.1029/2003GL017647
160. Sreeush, M.G., Valsala, V., Pentakota, S., Prasad, K.V.S.R., Murtugudde, R., 2018. Biological production in the Indian Ocean upwelling zones –Part 1: refined estimation via the use of a variable compensation depth in ocean carbon models. Biogeosciences 15, 1895–1918. https://doi.org/10.5194/bg-15-1895-2018
161. Soomere, T., Keevallik, S., 2003. Directional and extreme wind properties in the Gulf of Finland. Proc. Estonian Acad. Sci. Eng., 9, 73–90.
162. Sproson, D., Sahlée, E., 2014. Modelling the impact of Baltic Sea upwelling on the atmospheric boundary layer. Tellus A: Dynamic Meteorology and Oceanography, 1 66. https://doi.org/10.3402/tellusa.v66.24041
163. Stanichnaya, R., Davidov, A., Stanichny, S., Soloviev, D., 2004. Coastal upwelling in the Black Sea as derived from satellite remote sensing. Presented at the 35th COSPAR Scientific Assembly, p. 3786.
164. Suursaar, U., Aps, R., 2007. Spatio-temporal variations in hydro-physical and -chemical parameters during a major upwelling event off the southern coast of the Gulf of Finland in summer 2006. Oceanologia 49, 209–228.
165. Sulijiene, R., 1990. Primary production of phytoplankton in water bodies of Lithuania.Vilnius (in Russian).
166. Tapia, F.J., Navarrete, S.A., Castillo, M., Menge, B.A., Castilla, J.C., Largier, J., Wieters, E.A., Broitman, B.L., Barth, J.A., 2009. Thermal indices of upwelling effects on inner-shelf habitats. Progress in Oceanography 83, 278–287. https://doi.org/10.1016/j.pocean.2009.07.035
167. Teodoro, A.C., 2016. Optical Satellite Remote Sensing of the Coastal Zone Environment — An Overview. Environmental Applications of Remote Sensing. https://doi.org/10.5772/61974
168. Thompson, S.A., Sydeman, W.J., Santora, J.A., Black, B.A., Suryan, R.M., Calambokidis, J., Peterson, W.T., Bograd, S.J., 2012. Linking predators to

seasonality of upwelling: Using food web indicators and path analysis to infer trophic connections. Progress in Oceanography 101, 106–120. https://doi.org/10.1016/j.pocean.2012.02.001

169. Tomczak, M., 1981. Coastal upwelling systems and Eastern boundary currents: A review of terminology. Geoforum 12, 179–191. https://doi.org/10.1016/0016-7185(81)90019-1
170. Troupin, C., Mason, E., Beckers, J.-M., Sangrà, P., 2012. Generation of the Cape Ghir upwelling filament: A numerical study. Ocean Modelling 41. https://doi.org/10.1016/j.ocemod.2011.09.001
171. Uiboupin, R., Laanemets, J., 2009. Upwelling characteristics derived from satellite sea surface temperature data in the Gulf of Finland, Baltic Sea. Boreal Env. Res. 14, 297–304.
172. Uiboupin, R., Laanemets, J., Sipelgas, L., Raag, L., Lips, I., Buhhalko, N., 2012. Monitoring the effect of upwelling on the chlorophyll a distribution in the Gulf of Finland (Baltic Sea) using remote sensing and in situ data. Oceanologia 54, 395–419. https://doi.org/10.5697/oc.54-3.395
173. Vaiciute, D., 2012. *Distribution patterns of optically active components and phytoplankton in the estuarine plume in the South Eastern Baltic Sea* (Doctoral dissertation). Klaipeda University, Klaipeda, Lithuania. 128 p.
174. Vahtmäe, E., Kutser, T., Martin, G., Kotta, J., 2006. Feasibility of hyperspectral remote sensing for mapping benthic macroalgal cover in turbid coastal waters—a Baltic Sea case study. Remote Sensing of Environment 101, 342–351. https://doi.org/10.1016/j.rse.2006.01.009
175. Vahtera, E., 2007. *The role of phosphorus as a regulator of bloom-forming diazotrophic cyanobacteria in the Baltic Sea* (Doctoral dissertation). Finish Institute of Marine Research, Helsinki, Finland. ISBN 978-952-10-4193-8
176. 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 Marine Syst 58, 67–82. https://doi.org/10.1016/j.jmarsys.2005.07.001
177. Valipour, R., Rao, Y.R., León, L.F., Depew, D., 2019. Nearshore-offshore exchanges in multi-basin coastal waters: Observations and three-dimensional modeling in Lake Erie. Journal of Great Lakes Research 45, 50–60. https://doi.org/10.1016/j.jglr.2018.10.005
178. Varela, R., Álvarez, I., Santos, F., deCastro, M., Gómez-Gesteira, M., 2015. Has upwelling strengthened along worldwide coasts over 1982-2010? Scientific Reports 5, 10016. https://doi.org/10.1038/srep10016
179. Vazquez-Cuervo, J., Torres, H.S., Menemenlis, D., Chin, T., Armstrong, E.M., 2017. Relationship between SST gradients and upwelling off Peru and Chile:

model/satellite data analysis. International Journal of Remote Sensing 38, 6599–6622. https://doi.org/10.1080/01431161.2017.1362130

180. Vermote EF, Tanrè D, Deizè JL, Herman M, Morcrette JJ (1997) Second Simulation of the Satellite Signal in the Solar Spectrum, 6S: An Overview. IEEE Transaction on Geoscience and Rem Sens 35:675–686
181. Voulvoulis, N., Arpon, K. D. & Giakoumis, T. The EU Water Framework Directive: From great expectations to problems with implementation. Science of The Total Environment 575, 358–366 (2017).
182. Vidal, T., Calado, A.J., Moita, M.T., Cunha, M.R., 2017. Phytoplankton dynamics in relation to seasonal variability and upwelling and relaxation patterns at the mouth of Ria de Aveiro (West Iberian Margin) over a four-year period. PLOS ONE 12, e0177237. https://doi.org/10.1371/journal.pone.0177237
183. Wasmund, N. and Siegel, H., 2008. Phytoplankton. In Feistel, R., Nausch, G., Wasmund, N.(eds) *State and Evolution of the Baltic Sea, 1952-2005: A Detailed 50-Year Survey of Meteorology and Climate, Physics, Chemistry, Biology, and Marine Environment*, DOI:10.1002/9780470283134.ch15
184. Walter, R.K., Armenta, K.J., Shearer, B., Robbins, I., Steinbeck, J., 2018. Coastal upwelling seasonality and variability of temperature and chlorophyll in a small coastal embayment. Continental Shelf Research 154, 9–18. https://doi.org/10.1016/j.csr.2018.01.002
185. Wang, D., Gouhier, T.C., Menge, B.A., Ganguly, A.R., 2015. Intensification and spatial homogenization of coastal upwelling under climate change. Nature 518, 390–394. https://doi.org/10.1038/nature14235
186. Wick, G.A., Bates, J.J., Scott, D.J., 2002. Satellite and Skin-Layer Effects on the Accuracy of Sea Surface Temperature Measurements from the GOES Satellites. J. Atmos. Oceanic Technol. 19, 1834–1848. https://doi.org/10.1175/1520-0426(2002)019<1834:SASLEO>2.0.CO;2
187. Wilson, W.S., Lindstrom E.J. and Apel J.R., 2008. Satellite oceanography, history and introductory concepts, p.65-79 in Steele, J.H., Turekian, K.K. & Thorpe, S.A. (eds) *Encyclopedia of Ocean Sciences (2nd edition)*, Academic Press
188. Xiu, P., Chai, F., Curchitser, E.N., Castruccio, F.S., 2018. Future changes in coastal upwelling ecosystems with global warming: The case of the California Current System. Sci Rep 8. https://doi.org/10.1038/s41598-018-21247-7
189. Zalewski, M., Ameryk, A., Szymelfenig, M., 2005. Primary production and chlorophyll a concentration during upwelling events along the Hel Peninsula (the Baltic Sea). Oceanological and Hydrobiological Studies 34(Suppl.2):97-113
190. Zhurbas, V.M., Stipa, T., Mälkki, P., Paka, V.T., Kuzmina, N.P., Sklyarov, E.V., 2004. Mesoscale variability of the upwelling in the southeastern Baltic Sea: IR images and numerical modelling. Oceanology 44, 619–628.;

191. Zhurbas, V., Oh, I.S., Park, T., 2006. Formation and decay of a longshore baroclinic jet associated with transient coastal upwelling and downwelling: A numerical study with applications to the Baltic Sea. J. Geophys. Res. 111. https://doi.org/10.1029/2005JC003079;
192. Zhurbas, V., Laanemets, J., Vahtera, E., 2008. Modeling of the mesoscale structure of coupled upwelling/downwelling events and the related input of nutrients to the upper mixed layer in the Gulf of Finland, Baltic Sea. J. Geophys. Res., C5 113. https://doi.org/10.1029/2007JC004280
193. Zemlys, P., Ferrarin, C., Umgiesser, G., Gulbinskas, S., Bellafiore, D., 2013. Investigation of saline water intrusions into the Curonian Lagoon (Lithuania) and two-layer flow in the Klaipėda Strait using finite element hydrodynamic model. https://doi.org/10.5194/os-9-573-2013
194. Zemlys, P., Ertürk, A., Razinkovas, A., 2008. 2D finite element ecological model for the Curonian lagoon. Hydrobiologia 611, 167–179. https://doi.org/10.1007/s10750-008-9452-7
195. Žaromskis, R., 1996. Okeanai, jūros, estuarijos. Vilnius, 293 p. (in Lithuanian)

8

Santrauka

ĮVADAS

Temos aktualumas

Vėjo sukeltas priekrantės apvelingas – reiškinys, kurio metu paviršiniai priekrantės vandenys yra nustumiami toliau nuo kranto, o juos pakeičia šalti, maistinėmis medžiagomis prisotinti vandenys, kurie yra pakeliami iš gilesnių sluoksnių į paviršių (Kampf ir Chapman, 2016). Apvelingo reiškinys yra gana dažnai pastebimas dideliuose ežeruose, estuarijose bei vandenynuose (Plattner ir kt., 2006). Abiotinių ir biotinių veiksnių sąveika apvelingų metu turi didelę įtaką visai aplinkai nuo fizinių, biologinių procesų iki socialinių bei ekonominių veiklų (Rossi ir kt., 2009; Saldívar-Lucio ir kt., 2016). Apvelingų regionai, būdami svarbūs žvejybos plotai (Hu ir Wang, 2016), yra gana reikšmingi žvejams, be to, jų vaidmuo atmosferos–vandenyno CO_2 apykaitoje, perdirbant ir pernešant anglį į atvirus vandenis (McGregor ir Mulitza, 2007) yra svarbus mokslininkams, analizuojantiems klimatinius bei biologinius aplinkos pokyčius (Barzandeh ir kt., 2018). Taip pat apvelingai yra svarbūs valdant ir prognozuojant jūros išteklius (Jiang ir kt., 2010, Saldívar-Lucio ir kt., 2016).

Pasauliniame vandenyne apvelingai yra gana dažnas reiškinys, ypač priekrantės regionuose (Myrberg ir Andrejev, 2003). Palei rytines vandenynų pakrantes pusiaujo krypčių vėjų bei Žemės sukimosi sąveika sukelia vertikalų vandens maišymąsi ir atsinaujinimą, viršutinio vandens sluoksnio papildymą maistingomis medžiagomis, kuris skatina mikroskopinio fitoplanktono, sudarančio pagrindą jūros mitybos tinklui, augimą (Jacox ir kt., 2018). Šie regionai pasižymi dideliu biologiniu produktyvumu ir yra intensyviai eksploatuojami žvejybos tikslais, tad yra išskiriami tarp svarbiausių ekosistemų planetoje (Xiu ir kt., 2018).

Priekrantės apvelingas taip pat vaidina svarbų vaidmenį ekologiškai jautriuose pasaulinio vandenyno regionuose, kaip, pavyzdžiui, Baltijos jūra. Dėl specifinio geografinio Baltijos jūros išsidėstymo priekrantės apvelingas čia yra gana dažnas reiškinys (Lehmann ir Myrberg, 2008; Bychkova ir Viktorov, 1987), todėl išsamūs priekrantės apvelingo tyrimai yra svarbūs vertinant vandens ir energijos mainus Baltijos jūros regione (Zhurbas ir kt., 2008), analizuojant vertikalius vandens stratifikacijos pokyčius (Sproson ir Sahlee 2014) bei priekrantės vandenų maišymąsi su atvira jūra (Kahru ir kt., 1995; Levy, 2008). Apvelingai sukelia staigius jūros paviršiaus temperatūros (*ang. Sea Surface Temperature*, SST), druskingumo ir maistinių medžiagų koncentracijos pokyčius, kurie yra labai glaudžiai susiję su jūros priekrantės ekosistemos funkcionavimu (Fisher ir Mustard, 2004; Kowalewski, 2005; Krężel ir kt., 2005). Be to, apvelingai gali itin reikšmingai paspartinti pirminės produkcijos gamybą, kuri, savo ruožtu, skatina mitybos grandinę nuo antrinės produkcijos iki vartotojų, nuo zooplanktono iki žuvų, paukščių bei jūrinių žinduolių (Orren, 1995).

Dėl savo svarbos priekrantės apvelingas buvo nagrinėjamas daugelyje tyrimų, tačiau daugumoje atliktų darbų paprastai buvo analizuojami priekrantės apvelingai bei jų sukelti padariniai visame Baltijos jūros baseine, tuo tarpu apvelingo savybės bei poveikis gamtinei aplinkai PR Baltijos jūros regione buvo gana menkai ištyrinėtas. Taip pat nebuvo analizuotas apvelingo poveikis Kuršių marių vandenims. Tai yra pirmasis išsamus vėjo sukelto priekrantės apvelingo PR Baltijos jūros regione tyrimas, panaudojant palydovinius nuotolinių stebėjimų ir *in situ* monitoringo duomenis 2000–2015 m. laikotarpiu. Šiame darbe pateikiama išsami statistinė informacija apie regionines apvelingų savybes bei poveikį Baltijos jūros pakrantės ir Kuršių marių aplinkai.

Tyrimo tikslas ir pagrindiniai uždaviniai

Šio darbo tikslas – įvertinti vėjo sukelto priekrantės apvelingo savybes ir jo poveikį Pietryčių Baltijos jūros ir Kuršių marių aplinkai.

Pagrindiniai uždaviniai:

1. įvertinti palydovinių duomenų tinkamumą apvelingų PR Baltijos jūroje identifikavimui bei jo savybių vertinimui;

2. išanalizuoti meteorologines sąlygas, lemiančias apvelingų PR Baltijos jūroje formavimąsi;
3. išanalizuoti PR Baltijos jūros apvelingų erdvines savybes bei jų pokyčius laike remiantis integruotu palydovinių stebėjimų ir *in situ* duomenų panaudojimu;
4. įvertinti priekrantės apvelingų poveikį Kuršių marių vandenims;
5. įvertinti apvelingo poveikį chlorofilo-*a* pasiskirstymui PR Baltijos jūros priekrantės vandenyse bei Kuršių mariose.

Darbo naujumas

Šiame darbe pateikiami naujausi priekrantės apvelingo savybių PR Baltijos jūros regione rezultatai bei poveikio priekrantės aplinkai ir Kuršių marių vandenims analizė. Šis tyrimas, iki šiol, yra pirmasis išsamus ilgo laikotarpio priekrantės apvelingo tyrimas PR Baltijos jūros regione panaudojant palydovinių stebėjimų ir *in situ* matavimų duomenis. Be to, siekiant geriau suprasti, koks yra apvelingo reagavimas į palankias meteorologines sąlygas, ir įvertinti palydovinių duomenų taikymo efektyvumą priekrantės apvelingo tyrimams, čia pirmą kartą buvo panaudotas Ekmano teorijos pagrindu sukurtas „Apvelingo Indeksas“. Galiausiai, derinant daugiaspektrinius palydovinius duomenis buvo gauta vertingų įžvalgų apie priekrantės apvelingų ekologinį vaidmenį ir pirmą kartą buvo parodyta, kad apvelingai daro didelę įtaką aplinkos sąlygoms ne tik Baltijos jūros priekrantėje, bet ir sekliose Kuršių mariose.

Rezultatų mokslinė ir praktinė reikšmė

Šis tyrimas yra reikšmingas postūmis siekiant suprasti priekrantės apvelingo regionines savybes, nes daugumoje iki šiol atliktų darbų apvelingai buvo nagrinėjami visame Baltijos jūros baseine, pateikiant ribotą informaciją apie jo dinamines ir erdvines savybes PR Baltijos regione. Savo ruožtu, remiantis daugiaspektriniais palydoviniais duomenimis, suteikiančiais galimybę išanalizuoti fizines ir biologines priekrantės apvelingų savybes plačiu erdviniu ir laiko mastu, šis tyrimas pagilino mokslines žinias apie pagrindines okeanografines apvelingų savybes tyrimų regione, taip pat suteikė vertingų įžvalgų apie jūros ir marių sąveiką. Be to, šio tyrimo rezultatai davė pagrindą apvelingo sukeltų Chl-*a* pokyčių analizei PR Baltijos jūros priekrantėje bei Kuršių marių vandenyse naudojant palydovinius duomenis. Išsami apvelingo reiškinių statistika ir jų savybės gali būti naudojamos vertinant ekosistemos reakciją į staigius biogeofizinius gradientus, kuriuos sukelia priekrantės apvelingo formavimasis.

Rezultatų aprobavimas

Šio darbo rezultatai buvo pristatyti 10 tarptautinių ir 2 nacionalinėse konferencijose:

1. The Baltic Sea Science Congress, 2015, Ryga, Latvija
2. Baltic Earth Doctoral Conference, 2015, Tartu/Vilsandi, Estija
3. Baltic Earth/Gulf of Finland PhD Seminar in connection to the Gulf of Finland Year's Final Scientific Forum, 2015 Talinas, Estija
4. EOS-COST Workshop on the use of new satellite datasets in marine climate applications, 2016, Porto, Portugalija
5. The Baltic Earth conference, 2016, Nida, Lietuva
6. EO4Baltic Workshop 2017, Helsinkis, Suomija
7. The Baltic Sea Science Congress, 2017, Rostokas, Vokietija
8. IEEE 2018, Klaipėda, Lietuva
9. Jūros ir Krantų tyrimai, 2018, Klaipėda, Lietuva
10. Open Readings, 2019, Vilnius, Lietuva
11. Jūros ir Krantų tyrimai, 2019, Klaipėda, Lietuva
12. 2019 Living Planet Symposium, 2019, Milanas, Italija.

Šios disertacijos rezultatai buvo paskelbti 2 mokslinėse publikacijose. Viena publikacijų publikuota mergautine pavarde Mingėlaitė, T.

1. Delpeche-Ellman, N., **Mingelaite, T.**, Soomere, T., 2017. Examining Lagrangian surface transport during a coastal upwelling in the Gulf of Finland, Baltic Sea, Journal of Marine Systems, Vol. 171, p. 21-30, https://doi.org/10.1016/j.jmarsys.2016.10.007
2. **Dabuleviciene, T.**; Kozlov, I.E.; Vaiciute, D.; Dailidiene, I., 2018. Remote Sensing of Coastal Upwelling in the South-Eastern Baltic Sea: Statistical Properties and Implications for the Coastal Environment. Remote Sens. 10(11), 1752; https://doi.org/10.3390/rs10111752

Disertacijos struktūra

Disertaciją sudaro šie skyriai: įvadas, literatūros apžvalga, medžiaga ir metodai, rezultatai, diskusija, išvados ir literatūros sąrašas. Disertacijos apimtis – 81 puslapis, kuriuose yra 29 paveikslai ir 4 lentelės. Disertacijoje panaudotas 195 literatūros šaltiniai. Disertacija parašyta anglų kalba su išplėstine santrauka lietuvių kalba.

PADĖKA

1/3 savo gyvenimo praleidau universitete. Tai yra gana ilgas laikas, todėl esu dėkinga daugybei nuostabių žmonių, kurie per visus šiuos metus buvo su manimi. Už tai, kad suteikė galimybę eiti į priekį, padrąsino, palaikė mane silpnomis akimirkomis ir dalinosi laime džiaugsmingų akimirkų metu.

Pirmiausia noriu padėkoti tėvams, kuriuos labai myliu: Elenai ir Aloyzui. Be jų begalinės meilės ir palaikymo nebūčiau ten, kur esu šiandien. Ir nebūčiau tas žmogus, koks esu šiandien. Niekada negalėsiu pakankamai padėkoti savo mamai už darbo dienas ir naktis, kurias ji atidavė, kad aš galėčiau įgyvendinti savo svajones. Deja, mano tėčio su mumis jau nebėra, bet aš žinau, kad dabar danguje turiu angelą sargą, padedantį įveikti sunkumus. Aš jį vadinu tėčiu.

Taip pat noriu padėkoti savo vadovei prof. dr. Ingai Dailidienei už tai, kad nuo pat bakalauro studijų įtraukė mane į akademinį pasaulį ir taip paskatino domėtis mokslu. Ji visada mane palaikė ir davė laisvę dalyvauti įvairiuose projektuose doktorantūros metu, leisdama augti moksline prasme. Ačiū jums už pasitikėjimą.

Nuoširdžiausią padėką noriu skirti dr. Igor Kozlov ir dr. Dianai Vaičiūtei už jų svarbų indėlį rengiant disertaciją. Jų moksliniai patarimai, žinios, daugybė įžvalgių diskusijų ir pasiūlymų leido šiai disertacijai pasiekti dienos šviesą. Ačiū, Igori, už tavo laiką ir kantrybę šlifuojant mano mokslinio rašymo įgūdžius, už nesuskaičiuojamą daugybę el. laiškų ir atidų dėmesį detalėms. Diana, ačiū, už buvimą tavo komandos dalimi, už visapusišką palaikymą ir visą patirtį, kuria su manimi daliniesi.

Dėkoju Klaipėdos universiteto Ekologijos ir aplinkotyros doktorantūros komitetui už naudingus patarimus ir rekomendacijas rengiant daktaro disertaciją. Nuoširdžiai vertinu doktorantūros pirmininko prof. dr. Dariaus Daunio motyvavimą judėti į priekį. Taip pat ypatinga padėka skiriama prof. habil. dr. Sergej Olenin už skirtą laiką ir vertingus komentarus tobulinant disertaciją.

Esu nuoširdžiai dėkinga prof. dr. Kai Myrberg už pasidalintas mokslines žinias ir draugiškus gyvenimo ir mokslinius patarimus.

Labai vertinu daugybę Gamtos mokslų katedros ir Jūros tyrimų instituto ekspertų ir kolegų, kurie mane lydėjo doktorantūros kelyje. Ypatingas ačiū dr. Loretai Kelpšaitei-Rimkienei, kuri yra mano „pirmoji pagalba“ daugelyje stresinių situacijų. Taip pat prof. habil. dr. Olegai Pustelnikovai, prof. habil. dr. Marija Eidukevičiene ir prof.dr. Albertai Bitinai – ačiū už jūsų įkvepiančius pavyzdžius.

Taip pat norėčiau padėkoti Talino technologijos universiteto Bangų inžinerijos laboratorijos nariams, ypač prof.dr. Tarmo Soomere ir dr. Nicole Delpeche-Ellmann už tai, kad suteikė man galimybę tapti jų laboratorijos dalimi ir už pasidalintą patirtį.

Nuostabių žmonių, kuriuos sutikau per savo doktorantūros metus, yra per daug, kad visus išvardinčiau. Bet esu tikrai dėkinga jiems visiems už mažus pokalbius, kavos pertraukėles ir pietus kartu. Tačiau yra keletas, kurie negali būti paminėti. Nuoširdžiai dėkoju Rūtai – už tai, kad praturtina ne tik delfinų, bet ir mano gyvenimą; Gretai S. – už institute praleistus vakarus ir savaitgalius, taip pat už visus pokalbius ir sušių valgymus bei sudegintas kalorijas; Edvardui V. ir Vitalijui – už stovėjimą prie kampo ir už visą mūsų pagamintą vitaminą C; Viktorijai ir Elenai – mano doktorantūros „seserims“, ačiū už supratimą, o Artūrui – už tai, kad primena man, kad kartais gerai būti šiek tiek panašiam į „Honey Badger'į“. Taip pat labai ačiū Eglei N., kad ji mus visus lydi doktorantūros labirintuose, ačiū už nuraminimą ir už kačių vaizdo įrašus bei nuotraukas.

Taip pat dėkoju savo draugams iš JBG – nors mes visi esame išsibarstę po pasaulį, aš žinau, kad visada galiu į jus atsiremti.

Mieli HOK'ai, dėkoju už visas linksmas akimirkas, kurias patyrėme studijų metais. Ypač ačiū Ievai, Pauliui ir „kas tas Marius“, iš „grupiokų“ tapusiais tikrais draugais.

Noriu nuoširdžiai padėkoti mylimoms seserims Aušrai ir Ernestai – už tai, kad visada manimi tikite ir palaikote. Dėl nuolatinių „WhatsApp“ žinučių atstumas tarp mūsų išnyksta. Taip pat dėkoju savo mylimam sūnėnui, kuris visada sugeba mane pralinksminti. P.S. Aušra, gal Pitagoro teorema buvo viso to pradžia?

Ypatingai noriu padėkoti savo mylimam vyrui Domui – už besąlyginę paramą, rūpestį ir meilę. Nors tau teko mane pakęsti niurzgančią, pavargusią, nervingą, nuolat keliaujančią, dirbančią vakarais / savaitgaliais ar atostogų metu – tu visada buvai mano didžiausias ramstis. Ačiū tau už viską.

Taip pat nepamirškime mūsų kačių – pūkuotų laimės rutulių, gebančių nuraminti be žodžių.

Šios disertacijos darbai iš dalies finansuoti H2020 EOMORES (sut. Nr. 730066) ir ESA TODAY (sut. Nr. No. 4000122960/18/NL/SC) projektų. Autorė taip pat dėkinga Lietuvos hidrometeorologijos tarnybai prie Aplinkos ministerijos ir Lietuvos aplinkos apsaugos agentūros Aplinkos tyrimų departamentui už suteiktus duomenis.

TYRIMŲ MEDŽIAGA IR METODAI

Tyrimų vieta

Tyrimų vieta apėmė PR Baltijos jūros priekrantės dalį nuo Kaliningrado srities (Rusija) iki Kolkos rago (Latvija) (5 pav.). Šis regionas pasirinktas kaip atspindintis santykinai tiesų priekrantės ruožą, kuriame apvelingus sukelia Š, ŠR krypčių vėjai. Priekrantės apvelingų šiame regione pasitaiko gana dažnai (Lehmann ir Myrberg, 2008; Lehmann ir kt., 2012), ypač šiltuoju metų laiku, kai vertikali temperatūros stratifikacija yra stipriausia. Ši priekrantės zona yra gana sekli (20–40 m gylis) ir tik centrinės PR Baltijos jūros regiono dalys (maks. gylis 249 m) ir Gdansko įlanka (maks.

gylis 114 m) yra šiek tiek gilesnės. Be to, kaip papildoma tyrimų vieta buvo pasirinktos ir Kuršių marios, vaidinančios itin svarbų vaidmenį Lietuvos pajūrio zonos hidrodinaminiuose ir biologiniuose procesuose.

Duomenys

PR Baltijos jūros priekrantės apvelingų analizei buvo naudoti palydoviniai antro lygio (L2) 1 km erdvinės rezoliucijos infraraudonųjų (IR) spindulių radiometro (*ang. MODerate Imaging Spectrometer* (MODIS)) „Terra / Aqua" jūros paviršiaus temperatūros (SST) žemėlapiai 2000–2015 m. laikotarpiu. Duomenys gauti iš laisvos prieigos NASA MODIS archyvo [http://modis.gsfc.nasa.gov/data/]. Šio produkto validacija su *in situ* duomenimis buvo atlikta Kozlov ir kt. (2014). Kadangi rezultatai parodė labai gerą palydovinių ir tradicinių SST matavimų atitiktį, palydoviniai MODIS jūros paviršiaus temperatūros duomenys buvo pasirinkti Baltijos jūros ir Kuršių marių vandens temperatūros pokyčių apvelingu metu analizei. Palydoviniai MODIS SST žemėlapiai buvo apdorojami ESA BEAM, Mathworks © Matlab programinės įrangos paketais bei ArcGIS 10.5.1 (Esri) programine įranga. Debesų identifikavimui / pašalinimui buvo atliekama vizualinė patikra. Iš viso buvo apdorota apie 1700 palydovinių žemėlapių, apimančių 16 metų stebėjimo periodą šiltuoju (balandžio–rugsėjo mėn.) laikotarpiu, iš kurių 239 debesų nepaveiktos palydovinės SST nuotraukos buvo pasirinktos detaliai apvelingų PR Baltijos jūroje analizei.

Apvelingo sukeltų chlorofilo-*a* (Chl-*a*) koncentracijos pokyčių analizei buvo naudoti MERIS/Envisat 300 m erdvinės rezoliucijos debesų nepaveiktos palydovinės nuotraukos. Chl-*a* koncentracija Baltijos jūros priekrantės vandenyse buvo gauta pritaikius FUB procesorių (1.2.4 versija), kurį sukūrė Vokietijos pakrančių tyrimų institutas (German Institute for Coastal Research, GKSS) kartu su „Brockmann Consult" ir Berlyno laisvuoju universitetu (*vok. Die Freie Universität Berlin*). FUB procesorius yra skirtas Europos pakrančių vandenims ir naudoja MERIS 1b lygio atmosferos spinduliuotę optinių vandens sudedamųjų dalių koncentracijai nustatyti (Schroeder ir kt., 2007). Chl-*a* koncentracijos Kuršių mariose gavimas buvo pagrįstas Giardino ir kt. (2010) ir Bresciani ir kt. (2012 m.) po (INFORM) revizijos.

Vėjo greičio ir krypties duomenys, matuojami kas 3 valandas 10 m aukštyje iš Klaipėdos priekrantės stoties (iš Lietuvos hidrometeorologijos tarnybos prie Aplinkos ministerijos), buvo naudojami siekiant nustatyti apvelingų formavimuisi palankias meteorologines sąlygas. Vandens temperatūros bei druskingumo duomenys iš Nidos ir Palangos hidrometeorologinių stočių (iš Aplinkos apsaugos agentūros Jūros tyrimų departamento (dabar – Aplinkos tyrimų departamentas)) buvo naudojami papildomam apvelingų identifikavimui ir analizei.

Palydoviniais duomenimis grįsta apvelingų analizė

Apvelingo reiškinių identifikavimas buvo atliktas pagal Gidhagen (1987) bei Lehmann ir Andrejev (2003) aprašytą metodiką, laikantis sąlygos, kad apvelingas įvyko tuomet, kai SST priekrantėje sumažėjo ≥2˚C, lyginant su aplinkiniais vandenimis. Ši metodika buvo pasirinkta siekiant eliminuoti lokalius vandens temperatūros pokyčius, nesusijusius su apvelingo reiškiniais. Pirminiai apvelingo parametrai, gauti analizuojant palydovines SST nuotraukas, apėmė: apvelingų dažnumą ir trukmę, temperatūros skirtumus tarp minimalios apvelingo ir apvelingo nepaveiktos teritorijos (ΔT), horizontalius temperatūrinius gradientus, taip pat apvelingo erdvines charakteristikas, tokias kaip, pvz., apvelingo išplitimo atstumas nuo priekrantės į jūrą (bei nuo Klaipėdos sąsiaurio į Kuršių marias), apvelingo paveiktos akvatorijos plotas bei ilgis išilgai pakrantės. Skaičiavimai atlikti aštuoniose transektose PR Baltijos jūroje: viena transekta ties Kaliningrado sritimi, trys transektos ties Lietuvos priekrante (ties Nida, Klaipėda ir Palanga) bei keturios transektos Latvijos pakrantėje (ties Pape, Liepoja, Jūrkalne ir Ventspiliu). Be to, siekiant įvertinti apvelingo poveikį seklioms hipereutrofinėms marioms, viena transekta buvo pasirinkta ir Kuršių mariose. Toks transektų išdėstymas buvo pasirinktas siekiant atspindėti erdvinį apvelingų visoje PR Baltijos jūros priekrantėje išplitimą ir siekiant tiksliau įvertinti apvelingo parametrų kitimo dėsningumus.

Statistinė analizė

Atliekant dviejų grupių (Chl-*a* koncentracija apvelingo zonoje ir aplinkiniuose vandenyse) duomenų lyginimą buvo naudojamas *t*-testas. Apvelingo sukeltiems Chl-*a* koncentracijos pokyčiams įvertinti papildomai buvo naudojami aprašomieji statistiniai duomenys (vidurkis, mediana, mažiausia, maksimali vertė ir standartinis nuokrypis), atspindintys įvertintus parametrus ir jų kintamumą apvelingo zonoje ir aplinkiniuose vandenyse. Netiesinė regresinė analizė (*ang. Generalized Additive Modeling*, GAM) buvo naudojama norint rasti aplinkos veiksnius, geriausiai paaiškinančius Chl-*a* koncentracijos pokyčius apvelingo zonoje.

Ekmano teorija pagrįstas apvelingo indeksas

Ekmano teorija pagrįstas apvelingo indeksas (UI) buvo naudotas kaip papildoma priemonė, leidžianti nustatyti teorinius apvelingo įvykius stebėjimo duomenyse ir įvertinti jų atsaką į meteorologines sąlygas. Šis indeksas parodo vandens tūrį, kuris kyla į paviršių (teigiamos UI vertės) arba grimzta žemyn (neigiamos vertės) (Chenillat ir kt., 2012; Bograd ir kt., 2009). Indekso skaičiavimai buvo atlikti remiantis vėjo greičio ir krypties duomenimis iš Klaipėdos meteorologinės stoties 2000–2015 m. balandžio–rugsėjo mėn. laikotarpiu. Kadangi apvelingui Baltijos jūroje formuotis reikia apytikriai 60 valandų pastovios krypties palankių vėjų (Haapala ir kt.,1994), šiame darbe sąlygos, kuomet teigiamos UI reikšmės buvo stebimos kelias dienas iš eilės, buvo laikomos sąlygomis, kurių metu formuojasi apvelingas.

REZULTATAI

Rezultatai pateikiami 7 skyriuose: 1) Palydoviniai matavimai *versus* matavimai priekrantės stotyse; 2) Meteorologinė situacija iki susiformuojant apvelingui; 3) Pietryčių Baltijos jūros apvelingo statistiniai parametrai; 4) 2006 m. liepos mėn. didysis apvelingas; 5) Apvelingo poveikis Kuršių marių vandens paviršiaus temperatūrai; 6) Priekrantės apvelingo sukelti Chlorofilo-a pasiskirstymo pokyčiai; 7) Apvelingo poveikis Kuršių marių Chlorofilo-a koncentracijai.

Pirmame skyriuje pateikiamas apvelingų identifikavimo palyginimas naudojant palydovinius duomenis (SST), *in situ* duomenis (T_w) bei apvelingo indeksą (UI). Tyrimo rezultatai rodo, kad didžiausi skirtumai tarp apvelingų skaičiaus, identifikuoto palydoviniuose ir *in situ* duomenyse lyginant su skaičiumi, identifikuotu naudojant UI, buvo nustatyti gegužės ir rugsėjo mėnesiais. T.y. pasitelkus apvelingo indeksą buvo identifikuoti 96 apvelingo įvykiai, tuo tarpu palydovinėse nuotraukose buvo fiksuoti 69, o *in situ* matavimuose tik 58 apvelingo įvykiai (6 pav.). Tai parodo, kad gegužės–rugpjūčio mėnesiais, kuomet yra didesnis debesų trukdžiais nepaveiktų palydovinių nuotraukų skaičius, palydoviniai duomenys įgalina identifikuoti 87% apvelingo įvykių, identifikuojamų teoriniais UI skaičiavimais. Tuo tarpu iš priekrantės stočių matavimų identifikuojama tik apie 60% galimų apvelingo įvykių.

Antrame skyriuje analizuojamos apvelingų PR Baltijos jūroje formavimuisi palankios sąlygos. Tyrimo rezultatai rodo, kad apvelingų formavimuisi palankūs šiaurės krypčių vėjai paprastai yra nestiprūs, iki 9 m s^{-1} greičio. Tik balandžio mėnesį fiksuota nedidelė dalis stipresnių, 9–12 m s^{-1} vėjų.

Taip pat matoma, kad ~23% atvejų į palankias vėjo sąlygas apvelingai reaguoja gana greitai ir pirmi šalto vandens požymiai paviršiuje pasirodo praėjus vos vienai dienai po to, kai buvo pradėtos registruoti teigiamos UI vertės, tačiau įprastai reikia 1–3 dienų pastovių šiaurės krypties vėjų (9 a pav.). Maždaug 35% atvejų, daugiausia fiksuotų balandžio ir rugsėjo mėnesiais, apvelingai pasireiškė tik praėjus 4 ar daugiau dienų po to, kai susiformavo palankios vėjo sąlygos (9 c pav.). Be to, silpnesni ir trumpesnės trukmės palankūs vėjai apvelingus formuoja vasaros mėnesiais, kuomet sezoninė termoklina yra sekliau bei vertikali stratifikacija yra stipresnė. Tuo tarpu pavasarį ir rudenį apvelingų formavimuisi yra reikalingas ilgesnės trukmės ir stipresnis vėjo impulsas (9 c pav.)

Trečiame skyriuje su poskyriais yra analizuojamas apvelingų sezoniškumas, pasikartojimo dažnumas, trukmė, apvelingų sukeltos vandens temperatūros variacijos bei erdvinės apvelingų savybės.

Apvelingai įprastai yra identifikuojami balandžio–rugsėjo mėnesiais, kuomet vertikali vandens temperatūrinė stratifikacija yra ryškiausia. Apie 90 % visų apvelingo atvejų yra fiksuojama gegužę–rugpjūtį su aiškiu įvykių piku liepą. Šiuo laikotarpiu apvelingai vidutiniškai fiksuojami 7 dienas per mėnesį.

Įprastai vyrauja trumpi, 2–6 dienų trukmės apvelingo įvykiai (57 % atvejų), tačiau įvykus keleto apvelingų sekai, bendra apvelingo trukmė gali siekti ir iki 23 dienų, kaip, pavyzdžiui, buvo stebėta 2006 ir 2008 m. vasaromis (10 b pav.) Vidutinis bendras apvelingo dienų skaičius per sezoną sudaro apie 16% šiltojo sezono (~30 dienų), tačiau buvo fiksuota ir atvejų, kai bendras apvelingo dienų skaičius apėmė apie 30% šiltojo laikotarpio (10 c pav.)

Tipinis temperatūros pažemėjimas (ΔT) apvelingų metu siekia 2–6 °C, tačiau maksimalios reikšmės gali siekti ir 10–14 °C. 11 c paveiksle galima aiškiai matyti ΔT sezoninį kintamumą, t.y. vidutinis ΔT pavasarį siekia apie 3,5 °C, tuo tarpu vasarą ir rudenį apvelingo sukelti temperatūros skirtumai yra didesni – vidutiniškai apie 5,3 °C (11 c pav.).

Tipiniai horizontalūs SST gradientai apvelingo zonoje kinta nuo 0,2 iki 0, 5 °C km^{-1} (12 a pav.), tačiau 25% apvelingo atvejų jie yra didesni nei 0,6 °C km^{-1} ir gali siekti net iki 1,6 °C km^{-1} intensyvių apvelingų metu. Taip pat yra pastebėti erdviniai SST gradiento skirtumai (12 b pav.), t.y. didesni gradientai fiksuojami ten, kur apvelingo paveikta zona yra siauresnė, pvz. ties Ventspiliu, Palanga ar Klaipėda, o mažiausi vietose, kur apvelingo zona yra plati – pvz. ties Jūrkalne ir Liepoja (13 ir 14 pav.). Be to, pastebi ir sezoniniai SST gradiento svyravimai. Pavasarį vyrauja silpni (<0,25 °C km^{-1}) SST gradientai (52% apvelingo atvejų), o vasarą ir rudenį aiškiai vyrauja didesni nei 0,25 °C km^{-1} SST gradientai (58% atvejų vasarą ir 63% rudenį) (12 c pav.).

Kaip matoma iš 13 a paveikslo, dažniausiai apvelingas palei pakrantę tęsiasi 300–350 km. Horizontalus išplitimas tipiškai yra iki 20 km nuo kranto į jūrą, tačiau susiformavus šalto vandens sraujymėms (*ang. filaments*), šalti apvelingo vandenys gali išplisti ir iki 70 km nuo kranto į jūrą. Apvelingo paveiktas jūros plotas daugumoje atvejų siekia iki 3000 km^2 ir paprastai apima Lietuvos ir Latvijos priekrantės vandenis, tačiau intensyvių apvelingų metų jo plotas gali siekti ir keliolika tūkstančių kvadratinių kilometrų apimdamas didelę Gdansko ir Gotlando baseinų dalį (14 pav.).

Ketvirtame skyriuje pateikiama išsami 2006 liepos mėn. apvelingo analizė – tai didžiausias apvelingo reiškinys per visą tyrimų laikotarpį, turėjęs didelį poveikį jūros bei marių gamtinei aplinkai. Palydovinių nuotraukų seka (15 pav.) įgalino užfiksuoti šio apvelingo vystymąsi nuo aktyvios stadijos, kuomet vyraujantys šiaurės vėjai lėmė šaltų giluminių vandenų iškėlimą į paviršių iki apvelingo relaksacijos, kuomet, pasikeitus vėjo krypčiai, stiprūs temperatūros gradientai išliko dar maždaug dvi savaites. Šio apvelingo metu buvo nustatyti itin ryškūs vandens temperatūros pokyčiai, t.y. vandens temperatūra pažemėjo net 14°C. Be to, kaip apvelingo pasekmė, buvo ir oro temperatūros pažemėjimas per 10°C bei druskingumo padidėjimas 0,5 ‰ (17 pav.).

Penktame skyriuje analizuojamas apvelingo poveikis Kuršių marių vandens paviršiaus temperatūrai. Tyrimo rezultatai rodo, kad iš 69 MODIS SST žemėlapiuose užfiksuotų apvelingų, 18 jų turėjo poveikį ne tik jūros, bet ir marių gamtinei aplinkai, kuomet šalti, druskingi apvelingo vandenys įtekėjo į Kuršių marias. Tokie apvelingo vandenų įtekėjimai paprastai vyksta šiek tiek daugiau nei kartą per sezoną, tačiau kai kuriais metais atvejų, kai Baltijos jūros vandens patekimas į marias sutapo su apvelingo įvykiu, gali būti ir daugiau. Paprastai šie įtekėjimai trunka 1–3 dienas, tačiau kai intensyvūs apvelingo atvejai sutampa su įtekėjimui palankiomis hidrometeorologinėmis sąlygomis, kaip, pavyzdžiui, 2006 liepos mėn., jūrinio vandens įtekėjimai gali trukti ir ilgiau nei savaitę.

Rezultatai rodo, kad ΔT tarp apvelingo paveiktų ir nepaveiktų marių vandenų buvo šiek tiek didesnis nei PR Baltijos pakrantėje, t. y. vidutiniškai svyravo apie 5–7 °C. Tačiau intensyviausio apvelingo metu apvelingo paveiktoje marių dalyje vandens temperatūra pažemėjo net per 16 °C, kas yra labai nebūdinga vandens temperatūra liepos mėnesiui. Kaip rodo 19 a ir b paveikslai, apvelingo poveikis mariose paprastai juntamas šiaurinėje dalyje 10–25 km atstumu nuo Klaipėdos sąsiaurio į marias ir apima 40–100 km^2 akvatorijos plotą.

Šeštame skyriuje analizuojami priekrantės apvelingo sukelti Chlorofilo-*a* koncentracijos pokyčiai Baltijos jūros priekrantės zonoje. Rezultatai rodo, kad apvelingo zonos yra charakterizuojamos reikšmingu Chl-*a* koncentracijos sumažėjimu lyginant su aplinkiniais vandenimis (3 lent., 22 pav.). Statistinis vidutinių Chl-*a* koncentracijų palyginimas rodo, kad daugeliu atvejų (89%) Chl-*a* koncentracijų skirtumas tarp apvelingo zonos ir aplinkinių vandenų buvo statistiškai reikšmingas, t.y. Chl-*a* koncentracija apvelingo zonoje buvo 40–50% mažesnė.

Septintame rezultatų skyriuje pateikiama apvelingo poveikio Kuršių marių Chlorofilo-*a* koncentracijai analizė. Kaip matyti iš palydovinių vaizdų, apvelingo vandenų įtekėjimas daro didelę įtaką Kuršių marių vandens temperatūros ir Chl-*a* koncentracijos pokyčiams. Kai šalti, druskėti ir mažiau produktyvūs Baltijos jūros vandenys įteka į marias, jie nustumia tolyn ir praskiedžia itin didelio produktyvumo Kuršių marių vandenis, tad Chl-*a* koncentracija apvelingo paveiktoje akvatorijos dalyje drastiškai skiriasi nuo aplinkinių marių vandenų. Pavyzdžiui, 2006 liepos mėn. apvelingo įtekėjimo metu Chl-*a* koncentracija aplinkiniuose vandenyse siekė daugiau nei 100 mg m^{-3}, tuo tarpu apvelingo paveiktoje šiaurinėje marių dalyje ji tesiekė vos keletą mg m^{-3}.

DISKUSIJA

Diskusija susideda iš keturių skyrių: 1) Apvelingų identifikavimas: palydovinių bei tradicinių matavimų privalumai ir trūkumai; 2) Priekrantės apvelingas PR Baltijos jūroje: regioninės ypatybės ir pokyčių skalės; 3) Priekrantės apvelingo vaidmuo: jo poveikis aplinkai; 4) Apvelingo poveikis vandens kokybei.

Pirmame diskusijos skyriuje aptariami apvelingų identifikavimo ir analizės palydoviniais duomenimis bei tradiciniais *in situ* matavimais iš priekrantės stočių ir laivų privalumai ir trūkumai. Atlikta studija rodo, kad apvelingų identifikavimui naudojant tradicinius metodus, didelė dalis apvelingų yra neužfiksuojama, nes matavimai iš priekrantės stočių yra atliekami labai arti kranto, o šalto vandens iškėlimas gali vykti ir šiek tiek toliau. Be to, pagal Lietuvos nacionalinį Baltijos jūros monitoringo planą (žr. www.gamta.lt), Baltijos jūros priekrantės ir teritorinės jūros monitoringas, esant palankioms hidrometeorologinėms sąlygoms, vykdomas vidutiniškai kartą per sezoną. Dėl retų *in situ* matavimų laike ir erdvėje monitoringo duomenų nepakanka norint įvertinti vėjo sukelto priekrantės apvelingo statistines savybes, kitimą laike ir erdvėje bei jo poveikį priekrantės aplinkai.

Apvelingo sukelti jūros paviršiaus temperatūros pokyčiai gali būti analizuojami pasitelkus nuotolinius tyrimų metodus. Tiesa, palydoviniais infraraudonųjų spindulių jutikliais gaunami duomenys yra itin jautrūs įvairiems atmosferos trukdžiams. Pagrindinė problema, su kuria susiduriama identifikuojant apvelingus palydoviniuose SST žemėlapiuose, yra debesys. Be to, palydovinės technologijos įgalina stebėti tik jūros paviršiaus būsenos pokyčius, o apvelingo sukeltų pokyčių gilesniuose sluoksniuose analizei visgi yra reikalingi tradiciniai matavimai. Tačiau, netgi su atmosferos trukdžių ar matavimų gilesniuose sluoksniuose apribojimais, didelės erdvinės rezoliucijos palydoviniai duomenys suteikia itin reikšmingos informacijos apie vandenų būklę (Vazquez-Cuervo ir kt., 2017). Nors apvelingų identifikavimas įprastiniais metodais ar teoriniais skaičiavimais yra gana efektyvus esant debesuotumui, šie metodai nesuteikia jokios informacijos apie erdvines apvelingų savybes. Tuo tarpu vienas iš pagrindinių nuotolinio stebėjimo pranašumų yra ekonomiškai efektyvus gebėjimas surinkti ilgo laikotarpio SST duomenų sekas, apimančias dideles geografines teritorijas ir taip leidžiančias analizuoti apvelingų savybes laike ir erdvėje.

Antrame diskusijos skyriuje aptariamos priekrantės apvelingų PR Baltijos jūroje regioninės savybės bei kitimo skalės, taip pat pateikiamas apvelingų PR Baltijos jūros priekrantėje palyginimas su apvelingais kituose Baltijos jūros bei pasaulio regionuose.

Tyrimo rezultatai rodo, kad vidutiniškai bendra apvelingo trukmė šiltuoju periodu (balandžio–rugsėjo mėn.) yra ilgesnė, nei buvo pristatyta kitų autorių (pvz. Lehmann ir kt. 2012; Golenko ir Golenko, 2012, Bednorz ir kt., 2013) darbuose. Vieno apvelingo trukmė vidutiniškai yra nuo kelių dienų iki savaitės (2–6 d.), tačiau fiksuojama ir atvejų, kai vienas apvelingo įvykis seka dar nepasibaigus ankstesniam ir susidarius tokiai įvykių grandinei bendra apvelingo trukmė gali gerokai pailgėti. Tuomet net kelias savaites gali vyrauti sąlygos, nebūdingos to mėnesio daugiametėms hidrologinėms normoms. Nors ir gana retai pasitaikantys, tokie ilgalaikiai apvelingo įvykiai gali turėti didelę reikšmę visam regionui, t.y. jo gamtinei (pvz., orams, ekosistemoms) ir socialinei bei ekonominei (pvz., turizmas) pakrančių aplinkai.

Ankstesniuose darbuose (pvz. Lehmann ir Myrberg, 2008) buvo nustatyta, kad apvelingo sukeltas temperatūros pažemėjimas ties Lietuvos ir Latvijos pakrantėmis siekia 4–8 °C ir atitinka šiame tyrime gautus rezultatus, tačiau šiame darbe fiksuoti maksimalūs temperatūros pokyčiai (ΔT) yra žymiai didesni, nei buvo užfiksuota iki šiol. Be to, šiame darbe fiksuotas apvelingo išplitimas palei pakrantę (tipiškai 300–350 km) taip pat yra didesnis, nei buvo pateikta ankstesniuose darbuose (pvz. Bychkova ir Viktorov, 1987; Gidhagen, 1987; ar Lehmann ir kt. 2012).

PR Baltijos jūros pakrantėje apvelingas dažniausiai fiksuojamas siauroje priekrantės juostoje, kurios plotas paprastai yra maždaug 10–20 km (13 d pav.). Šis atstumas yra labai artimas Baltijos jūroje nustatytam Rosbio deformacijos spinduliui (*ang. Rossby radius*) (2–10 km) (Lepparanta ir Myrberg, 2009). Tačiau labai intensyvių apvelingų metu apvelingo skersmuo gali siekti net 60–70 km (13 d pav.), ypač susiformavus šalto vandens sraujymėms. Tuomet apvelingo skersmuo smarkiai viršija Rosbio deformacijos spindulį, tipišką vasaros sezonui (Fennel ir kt., 1991). Tokios plačios apvelingo zonos formavimasis yra itin svarbus priekrantės ir atvirų vandenų maišymuisi ir, ko gero, yra susijęs su dugno topografija, dėl kurios formuojasi vandens sraujymės, išnešančios apvelingo vandenis į atvirą jūrą.

Trečiame diskusijos skyriuje aptariamas apvelingo vaidmuo gamtinėje aplinkoje, jo poveikis rūšių sudėčiai, Chl-*a* koncentracijos pasiskirstymui, visai abiotinei aplinkai bei Kuršių marių vandenims.

Kitose Baltijos jūros dalyse atlikti tyrimai rodo, kad pakrantės apvelingas sąlygoja maisto medžiagų papildymą viršutiniame vandens sluoksnyje, vandens masių pasikeitimą, maišymąsi bei vandens temperatūros pokyčius, kurie, savo ruožtu, gali paveikti ne tik atskiras fitoplanktono rūšis, bet gali sąlygoti ir visos fitoplanktono bendrijos pokyčius (pvz. Lips ir Lips, 2010; Laanemets ir kt., 2004). Apvelingo sukeltas priekrantės ir atvirų vandenų maišymasis neršto metu taip pat gali turėti įtakos vietinių populiacijų dinamikai (Reddin ir kt., 2015)

Tyrimo rezultatai taip pat rodo aiškų apvelingo poveikį Chl-*a* koncentracijos pokyčiams. Įdomu pastebėti, kad pirminis apvelingo Baltijos jūroje poveikis yra priešingas esančiam apvelingo sistemose Pasauliniame vandenyne. Apvelingo zonose viršutinio vandens sluoksnio papildymas maistinėmis medžiagomis įprastai skatina fitoplanktono augimą (Ishizaka ir kt., 1983), tačiau Baltijos jūroje apvelingas yra siejamas su Chl-*a* koncentracijos mažėjimu. PR Baltijos jūros priekrantėje Chl-*a* koncentracija apvelingo zonoje buvo apie 40–50% mažesnė, nei aplinkiniuose vandenyse. Analogiški Chl-*a* koncentracijos pokyčiai apvelingo metu buvo ir kituose Baltijos jūros regionuose, pvz., prie Lenkijos krantų (Krężel ir kt., 2005). Šis pirminis Chl-*a* koncentracijos sumažėjimas yra siejamas su fiziniu produktyvių vandens masių pernešimu iš priekrantės zonos, kurioje formuojasi apvelingas, į atvirus vandenis (Franks, 1992) bei su staigiais temperatūros pokyčiais.

Taip pat buvo pastebėta, kad vandens temperatūros pokyčiai atliepia ir oro temperatūrą, kaip, pvz., 2006 liepos mėn. apvelingo metu vandens temperatūrai pažemėjus per 14°C, oro temperatūra pažemėjo net dešimčia laipsnių (17 pav.). Savo ruožtu, tokie vandens ir oro temperatūros pažemėjimai vasaros sezono metu gali turėti neigiamos įtakos turizmui pajūrio regionuose, kuriuose apvelingų būna gana dažnai (Lehmann ir kt., 2012). Apvelingai taip pat turi įtakos rūkų formavimuisi (Leeparanta ir Myrberg, 2009; Dietze ir Loptien, 2016), kurie, savo ruožtu, daro poveikį, pavyzdžiui, jūrų uostų veiklai. Be to, apvelingų metu pastebimas druskingumo padidėjimas per 0.5 ‰.

Tiriamuoju laikotarpiu buvo užfiksuota 18 apvelingo atvejų, turėjusių poveikį Kuršių marių vandenims. Iš jūros į marias įtekantis vanduo čia pakeičia biotines ir abiotines sąlygas, taip darydamas didelį poveikį chlorofilo bei pirminės produkcijos pokyčiams. Kaip rodo tyrimo rezultatai, įtekėjimo į marias greičiai yra gana dideli (siekia net iki 0,16 m s^{-1}), tad Kuršių marių ekosistema turi itin staigiai prisitaikyti prie besikeičiančių sąlygų. Šis poveikis aplinkai yra gana reikšmingas, nes mariose įprastai dominuoja gėlavandenės tiek fitoplanktono, tiek zooplanktono rūšys (Gasiūnaitė ir kt., 2005). Be to, kadangi mariose temperatūra bei Chl-*a* koncentracija šiltuoju sezonu yra įprastai didesnė, nei jūroje, čia apvelingo poveikis įtekėjimo metu yra netgi didesnis, nei Baltijos jūros priekrantėje.

Ketvirtajam diskusijos skyriuje atkreipiamas dėmesys į apvelingo svarbą įgyvendinant įvairias Europos Sąjungos direktyvas, kaip, pavyzdžiui, Jūros strategijos pagrindų direktyva ar Vandens pagrindų direktyva 2000/60 / EB (VPD).

Baltijos jūros hidrodinamika pasižymi savitais bruožais, vienas iš jų – erdviniu ir laiko atžvilgiu gana dažnai pasikartojantis priekrantės apvelingo reiškinys. Jo metu staiga pakitusios hidrofizinės ir hidrocheminės savybės įneša „triukšmo“ į laiko duomenų eilutes ir tai tampa iššūkiu direktyvų įgyvendinimui vykdomose monitoringo programose. Pavyzdžiui, apvelingo paveiktose zonose sumažėjus Chl-*a* koncentracijai šie vandenys, pagal VPD vandens kokybės klases, yra charakterizuojami kaip „geros“ ar net „puikios“ būklės. Itin drastiški vandens kokybės pokyčiai apvelingo vandenų įtekėjimo metu būna Kuršių mariose. Čia šalti apvelingo vandenys pasižymi „puikia“ vandens kokybe pagal vandens kokybės VPD klases, o aplinkiniai apvelingo nepaveikti vandenys gali būti apibūdinami net kaip „labai blogos“ būklės (29 pav.). Nors vandens kokybės pagerėjimas apvelingo metu yra trumpalaikis įvykis, jis gali netiesiogiai prisidėti prie aplinkos, kuri yra patrauklesnė turizmo veiklai dėl padidėjusio skaidrumo ar sumažėjusio dumblių žydėjimo. Tačiau į apvelingus turėtų būti atsižvelgta vertinant bendrą aplinkos būklę, nes vandens kokybės rodiklių matavimai apvelingų metu gali labai skirtis nuo tipiškų aplinkos sąlygų ir gali visiškai neatspindėti realios aplinkos būklės.

IŠVADOS

1. Įprastai reikia maždaug 1–3 dienų šiaurės krypčių vėjų, kad priekrantės apvelingas būtų fiksuojamas PR Baltijos jūros paviršiaus temperatūros žemėlapiuose. Vasarą apvelingus sukelia švelnesni, mažesnės trukmės vėjai, o pavasarį ar rudenį stipresni palankios krypties vėjai turi laikytis ilgiau.
2. Palydoviniuose infraraudonųjų spindulių spektro SST duomenyse PR Baltijos apvelingas patikimiausiai yra fiksuojamas gegužės–rugsėjo mėnesiais, kuomet dėl ryškios temperatūrinės stratifikacijos ir santykinai mažo debesuotumo yra fiksuojama net 87 % visų pagal teorinį apvelingo indeksą identifikuotų apvelingo įvykių.
3. 90 % visų tiriamuoju 2000–2015 m. laikotarpiu įvykusių apvelingo įvykių buvo fiksuota gegužės–rugpjūčio mėnesiais su apvelingų piku liepą. Trumpalaikių (2–6 d. trukmės) įvykių pasitaiko dažniausiai, jų bendra trukmė apima 16 % viso šiltojo (balandžio–rugsėjo mėn.) sezono.
4. Pastebimi žymūs erdviniai apvelingo sukeltų SST gradientų pokyčiai, kurių tipinės reikšmės yra apie 0,2–0,5 °C km^{-1}. Be to, vasarą ir rudenį vyrauja didesni SST gradientai nei pavasarį. Didžiausios SST gradientų reikšmės (>0,75 °C km^{-1}) yra fiksuojamos vasaros periodu.
5. Tipiškai apvelingas apima Lietuvos ir Latvijos priekrantės vandenis, tačiau ekstremalių apvelingų metu gali apimti ir gana reikšmingą Gdansko ir rytinę Gotlando baseinų dalį. Apvelingo plotis nuo priekrantės į jūrą svyruoja nuo 5 iki 70 km ir priklauso nuo vyraujančių dugno topografijos ypatybių.
6. Gana aiškiai pasireiškiantys apvelingo vandenų įtekėjimai į Kuršių marias vyksta 1–2 kartus per sezoną ir vidutiniškai trunka 1–3 dienas. Šie įtekėjimai įprastai būna vyraujant šiaurės krypčių vėjams, kuomet sumažėja vandens lygis šiaurinėje marių dalyje. Apvelingo poveikis Kuršių marių vandens temperatūrai yra didesnis, nei Baltijos jūros vandenims.
7. Apvelingo paveikta Kuršių marių dalis vidutiniškai apima 10–25 km nuo Klaipėdos sąsiaurio į marias, tačiau gali siekti ir 40 km apimdama apie 200 km^2 marių paviršiaus ploto.
8. Apvelingo zonoje Chl-*a* koncentracija sumažėja 40–50 %. Pagrindiniai veiksniai, lemiantys Chl-*a* koncentracijos pokyčius, yra apvelingo sukelti SST pokyčiai ir priekrantės vandenų pernešimas į atvirą jūrą.
9. Apvelingų įtekėjimo metu Chl-*a* koncentracija Kuršių mariose gali sumažėti net iki 10 kartų ir šie pokyčiai yra drastiškesni nei Baltijos jūros priekrantės vandenyse.

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Toma Dabulevičienė
WIND-INDUCED COASTAL UPWELLING IN THE SOUTH-EASTERN BALTIC SEA: SPATIO-TEMPORAL VARIABILITY AND IMPLICATIONS FOR THE COASTAL ENVIRONMENT
Doctoral dissertation

VĖJO SUKELTAS PRIEKRANTĖS APVELINGAS PIETRYČIŲ BALTIJOS JŪROJE: KITIMAS LAIKE IR ERDVĖJE BEI JO POVEIKIS PRIEKRANTĖS APLINKAI
Daktaro disertacija

Klaipėda, 2019

SL 1335. 2019 09 19. Apimtis 10,11 sąl. sp. l. Tiražas 22 egz.
Išleido ir spausdino Klaipėdos universiteto leidykla, Herkaus Manto g. 84, 92294 Klaipėda
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