Dear Editors

Trying to meet the high standards of quality of the publication in the journal Ocean Science, I have twice responded to reviewers' comments. After the review made by the Reviewer 1, along with the response, I attached an updated article that included suggested corrections. Reviewer 2 reported his comments to the revised version of our article. For this reason, I enclose separate responses to two reviews by separately selecting the suggestions suggested by the Reviewer 1 and by the Reviewer 2.

Answer to Reviewer 1

First of all, we want to thank the Reviewer for their time taken to improve and comment on this publication. Below we quote the review text (in black) giving answers to each comment (in red). In the article (MS Word document) we have added comments about Specific Comments from review 1, so that you can easily identify corrected parts of the text.

Anonymous Referee #1

General Comments

The authors of the manuscript have conducted large number of polarimetric simulations of water conditions in the Baltic sea, over two seasons, and three different water types. An analysis is conducted which looks at the relationship between the absorption to attenuation of the water, and the upwelling polarization signal. It is determined that a correlation exists, and that it also depends on the Sun angle and the wind speed. A discussion about the direction of maximum DoP is also given.

The authors should be commended for the large amount of work that obviously went into this analysis, and especially for the inclusion of light polarization, which many scientists avoid.

That being said, however, I believe there to be several fundamental scientific problems with this manuscript that must be addressed before it is suitable for publication. I wish to convey to the authors that, although I have written many comments, it is because I am both familiar and passionate about the subject, and wish to see it properly conducted and thereby make an impactful contribution to the field.

Thank you for the positive and passionate feedback. Based on the specific comments the manuscript was thoroughly revised and improved. We have changed the references, we have completed the captions of the figures and the controversial fragments have simply been removed

My critique may be distilled down to a few main issues:

1. I found the literature cited by the manuscript very lacking. Almost all citations are prior to ~2012, and there has been many advances in the field in recent years.

We agree, thank you for your remark and suggestions. The citations have been revised and corrected.

2. The analysis focuses on “max(DoP)”. The maximum DoP is almost always either in, or near, the specular reflection point for above water simulations due to the inherent Fresnel reflectivity of the mean sea surface. (Figs 2,3,4,5,6 of this manuscript) This is an infeasible place to be measuring polarization for ocean color, since any measured signal from the ocean will be overwhelmed by the reflectance of the Sun. Ocean color satellites will not measure at this geometry. The paper would be much more applicable if the max(DoLP) were limited to feasibly measurable angles.

It's true that our analysis focuses on "max (DoP)" and satellites scan the surface of the Earth at different zenith angles. However, as illustrated in Figures 2,3,4, we show the DoP of radiances in all directions of the hemisphere, and in Figures 5 and 6 in all directions of the principal plane. In this first approach we decided to address the commonly analyzed max(DoP) in order to find and describe seasonal correlations. In future we will extend the study to consider angles more applicable to the remote sensors.

3. I believe that the contribution made by section 3.5 of the manuscript is marginal at best. Most of the conclusions about the direction of max(DoP) are ‘known’, or can be determined easily from Snell’s law and the knowledge that the maximum DoP occurs at scattering angles near 90 degrees. The underwater simulations are illustrative, but the explanations given for the direction of the DoP are inaccurate. See the specific comments below for further details.

We agree that the contribution of subsection 3.5 to the entire article is not very significant. For this reason, and because of the specific comments 32-38, we decided to remove this subsection.

Specific Comments

1. Pg 2 line 1-2: Garaba and Zielinkski, 2013 have very little to say about the polarization of above surface light. Nothing about improving the accuracy using polarization. This seems a poor choice of citation.

SC1. We corrected the citation.

2. Pg 2 line 2: Ibrahim et al 2012 do not make any beneath surface measurements, it is entirely based on radiative transfer simulations.

SC2. We corrected the statement.

3. Ibrahim et al have improved the work after 2012. A citation to the more recent work should be included:

a. A. Ibrahim, A. Gilerson, J. Chowdhary, and S. Ahmed, "Retrieval of macro- and micro-physical properties of oceanic hydrosols from polarimetric observations," Remote Sensing of Environment, vol. 186, pp. 548-566, 2016.

SC3. We included the citation accordingly.

4. Pg2 line 6: Reduction of Sun glints: Requires more references. There is a wealth of literature on this subject beyond Zhou et al, 2017. Too many to list here.

SC4. We added more recent references as suggested.

5. Pg2 line 8-9 Insufficient citations about polarized surface reflection, see also:

a. T. Harmel et al., "Polarization impacts on the water-leaving radiance retrieval from above-water radiometric measurements," Applied Optics, vol. 51, no. 35, pp. 8324-8340, Dec 10 2012.

b. T. Harmel and M. Chami, "Estimation of the sunglint radiance field from optical satellite imagery over open ocean: Multidirectional approach and polarization aspects,"Journal of Geophysical Research: Oceans, vol. 118, no. 1, pp. 76-90, 2013.

c. C. D. Mobley, "Polarized Reflectance and Transmittance Properties of Wind-blown Sea Surfaces," Applied Optics, vol. 54, no. 15, pp. 4828-4849, 2015.

d. M. Hieronymi, "Polarized reflectance and transmittance distribution functions of the ocean surface," Optics Express, vol. 24, no. 14, pp. A1045-A1068, 2016/07/11 2016.

e. R. Foster and A. Gilerson, "Polarized Transfer Functions of the Ocean Surface for Above-Surface Determination of the Vector Submarine Light Field," Applied Optics, vol. 55, no. 33, pp. 9476-9494, 11/16/2016 2016.

f. D. D'Alimonte and T. Kajiyama, "Effects of light polarization and waves slope statistics on the reflectance factor of the sea surface," Optics Express, vol. 24, no. 8, pp. 7922-7942, 2016/04/18 2016.

SC5. We complemented the references accordingly.

6. Pg 3 line 1: There are many RT models that include light polarization:

a. B. Lafrance and M. Chami, "OSOAA (Ocean Successive Orders with Atmosphere - Advanced) Users Manual," Université Pierre et Marie Curie Laboratoire d'Océanographie de Villefranche, France 2016-11-04 2016.

b. A. A. Kokhanovsky et al., "Benchmark results in vector atmospheric radiative transfer," Journal of Quantitative Spectroscopy and Radiative Transfer, vol. 111, no. 12-13, pp. 1931-1946, 2010. [And references therein]

c. S. Korkin, A. Lyapustin, A. Sinyuk, B. Holben, and A. Kokhanovsky, "Vector radiative transfer code SORD: Performance analysis and quick start guide," Journal of Quantitative Spectroscopy and Radiative Transfer, vol. 200, pp. 295-310, 2017/10/01/ 2017.

d. Y. Ota, A. Higurashi, T. Nakajima, and T. Yokota, "Matrix formulations of radiative transfer including the polarization effect in a coupled atmosphere–ocean system," Journal of Quantitative Spectroscopy and Radiative Transfer, vol. 111, no. 6, pp. 878-894, 2010.

e. F. M. Schulz, K. Stamnes, and F. Weng, "VDISORT: An improved and generalized discrete ordinate method for polarized (vector) radiative transfer," Journal of Quantitative Spectroscopy and Radiative Transfer, vol. 61, no. 1, pp. 105-122, 1999/01/01 1999.

SC6. We corrected the statement and complemented the references accordingly.

7. Pg 3, line 2-4. This is a false statement. Polarized radiative transfer has been happening for decades, and polarized radiative transfer of the ocean since the 1970s (Plass and Kattawar). One example:

a. G. W. Kattawar and C. N. Adams, "Stokes vector calculations of the submarine light field in an atmosphere-ocean with scattering according to a Rayleigh phase matrix: Effect of interface refractive index on radiance and polarization," Limnology and Oceanography, vol. 34, no. 8, pp. 1453-1472, 1989.

SC7. We apologize for the misinformation. We corrected the statement.

8. Pg 3, line 9: The 90 degree relative azimuth plane has been in use for a long time prior to Piskozub and Freda, see for example:

a. C. D. Mobley, "Estimation of the remote-sensing reflectance from above-surface measurements," Applied Optics, vol. 38, no. 36, pp. 7442-7455, 1999.

SC*. Yes, but Mobley's Hydrolight model does not include polarization, and we show (Piskozub and Freda) that the polarization remote sensing may be useful in a plane tilted 90° from the solar azimuth angle.

9. Pg 3, line 13-15. There have been many studies about the measurement and modeling of light polarization in coastal areas (to name only a few):

a. S. Sabbah, A. Barta, J. Gál, G. Horváth, and N. Shashar, "Experimental and theoretical study of skylight polarization transmitted through Snell's window of a flat water surface," Journal of the Optical Society of America A, vol. 23, no. 8, pp. 1978-1988, 2006/08/01 2006.

b. A. Tonizzo et al., "Polarized light in coastal waters: hyperspectral and multiangular analysis," Optics Express, vol. 17, no. 7, pp. 5666-5683, 2009/03/30 2009.

c. A. Tonizzo, A. Gilerson, T. Harmel, and A. Ibrahim, "Estimating particle composition and size distribution from polarized water-leaving radiance," Applied Optics, vol. 6, no. 10, pp. 5047-5058, January 2011.

d. A. Lerner, S. Sabbah, C. Erlick, and N. Shashar, "Navigation by light polarization in clear and turbid waters," Philosophical Transactions of the Royal Society B: Biological Sciences, vol. 366, no. 1565, pp. 671-679, 2011.

e. T. Harmel et al., "Polarization impacts on the water-leaving radiance retrieval from above-water radiometric measurements," Applied Optics, vol. 51, no. 35, pp. 8324-8340, Dec 10 2012.

f. Y. Gu et al., "Polarimetric imaging and retrieval of target polarization characteristics in underwater environment," Applied Optics, vol. 55, no. 3, pp. 626-637, 2016/01/20 2016.

g. A. El-habashi and S. Ahmed, "Chlorophyll fluorescence and the polarized underwater light field: comparison of vector radiative transfer simulations and multi-angular hyperspectral polarization field measurements," vol. 9827, p. 98270U, 2016.

h. J. Liu et al., "Polarization characterics of underwater, upwelling radiance of suspended particulate matters in turbid waters based on radiative transfer simulation," SPIE Remote Sensing, vol. 10784, p. 7, 2018.

i. A. C. R. Gleason, K. J. Voss, H. R. Gordon, M. S. Twardowski, and J.-F. Berthon, "Measuring and Modeling the Polarized Upwelling Radiance Distribution in Clear and Coastal Waters," Applied Sciences, vol. 8, no. 12, p. 2683, 2018.

SC9. We corrected the paragraph and complemented the references accordingly.

10. Pg 4, line 18: Piskozub and Freda (2013) only write 2 paragraphs about their Monte Carlo algorithm; I would hardly call this a "description". I would have liked to see (or have been pointed to) some benchmark results comparing the code to others, so that the reader can have confidence the code is physically correct.

SC10. We are the users of the code, not the creators. Although we can't provide any published benchmark comparison to other such codes, we can assure about its correctness on the basis of:

- the scientific experience of the author of the code, Prof. Jacek Piskozub and the internal tests he performed in order to verify its correctness;

- the polarized radiative transfer code was written as a new version of a code used for over 20 years in works published together with world-wide ocean optics authorities (e.g. J.R, Zaneveld, D. McKee, R. Rottgers, D. Stramski)

- the unmodified version of the algorithm was successfully used, with results published in:

a. McKee D., Piskozub J., Rottgers, and R., Reynolds, R.A.: Evaluation and Improvement of an Iterative Scattering Correction Scheme for in situ Absorption and Attenuation Measurements, Journal of Atmospheric and Oceanic Technology, 30, 1527-1541, doi:10.1175/JTECH-D-12-00150.1, 2013.

b. McKee D., Piskozub J., and Brown, I.: Scattering error corrections for in situ absorption and attenuation measurements, Optics Express 16, 19480-19492, doi: 10.1364/OE.16.019480, 2008.

c. Piskozub J., and, McKee D.: Effective scattering phase functions for the multiple scattering regime, Optics Express, 19, 4786-4794, doi:10.1364/OE.19.004786, 2011.

d. Stramski D., and, Piskozub J.: Estimation of scattering error in spectrophotometric measurements of light absorption by aquatic particles from 3-D radiative transfer simulations, Applied Optics, 42, 3634-3646, doi: 10.1364/AO.42.003634, 2003.

e. Piskozub J., Flatau P.J., and Zaneveld J.R.V.: Monte Carlo study of the scattering error of a quartz reflective absorption tube, Journal of Oceanic and Atmospheric Technology, 18, 438-445, doi: 10.1175/1520-0426(2001)018<0438:MCSOTS>2.0.CO;2, 2001.

11. Pg 5, line 2-3: While in general the V component is negligible, the biggest source of circular polarization is total internal reflection of upwelling light by the sea surface. The off-diagonal elements in Voss and Fry are indeed zero, but this has to do with scattering only, and is not by itself justification for saying the V component is negligible.

SC11. We agree, corrected.

12. Pg 5, line 6: Reflection and refraction by flat surfaces are described completely by the Fresnel equations, not ‘basically’.

SC12. We agree, corrected.

13. Pg 5, line 10-12: I am confused about which particle scattering Mueller matrices the authors are using. They state (line 11) that Voss and Fry 1984 is used for the water, and Volten et al (2001) is used for the aerosols. Then, the following sentence says that Mie theory is used for the phase functions. Only

the (1,1) element of the Mie calculations were used? What parameters were used for the Mie calculations? How were they determined and are they representative for the Baltic Sea?

SC13. We use Voss and Fry (1984) for seawater and Volten (2001) for aerosols. Additionally Rayleigh for molecular scattering both in atmosphere and water. The sentence about Mie theory is a mistake - has been deleted.

14. Pg 5, line 14: All results are specified in the principle plane. This seems to be incorrect, since polar plots of all azimuth angles are given thoughout.

SC14. True, sentence corrected.

15. Pg 5, line 20: There is a new ‘recommended data processing’ for ac-9 and ac-s instruments, the PROP-RR method, which may be applied to previously acquired data. It may be worth investigating whether this has a significant impact on the results given that the ratio of a/c is being analyzed. See:

a. N. D. Stockley, R. Röttgers, D. McKee, I. Lefering, J. M. Sullivan, and M. S. Twardowski, "Assessing uncertainties in scattering correction algorithms for reflective tube absorption measurements made with a WET Labs ac-9," Optics Express, vol. 25, no. 24, pp. A1139-A1153, 2017/11/27 2017.

SC15. Yes, we are familiar with this paper and the new correction method. However, Baltic Sea is a very unique water basin from the optical point of view and application of new method to historical data needs to be verified and validated first. As the authors conclude, " but for waters where other types of non-algal absorbing particles may be present in higher proportions, it is unclear whether the PROP-RR relationship will remain appropriate."

Our dataset includes data verified using spectroscopic methods (absorption measured with 1nm resolution - see Sagan 2008). Moreover in this study we use averaged data over seasons, therefore application of this new method (whether proper or not) to the single measurements would not affect them in a considerable degree.

16. Pg 5, line 29-31: I am very confused about these sentences. Why is aw subtracted and then added again? Perhaps subscripts should be added to clarify? (a_t) for a total, and (a_pg) particulate + CDOM absorption for a - aw. Or perhaps make it a formal equation that makes sense mathematically. Put a sigma (sum) symbol if sum is meant. Same for pg 6, line 1.

SC16. We modified the equation and the description to make it more clear, according to the suggestions. (We used the AC-9 dataset where a_w was already subtracted from the total absorption, this is why we had to add it again.)

17. Pg 6, line 13: In my opinion, using the isotropic Cox-Munk slope distribution is preferable to choosing an arbitrary directional wind value. A directional wind will introduce an asymmetry into the above-surface light field, the effect of which is not being analyzed.

SC17. The wind is directional by nature, this is why we simply decided to model the directional wind applying the same direction to all simulations. In our opinion the asymmetry of the light field caused by directional wind does not affect the above-surface light field in a significant degree.

From the previous studies (e.g. Haule et al. 2017) we know that wind direction changes can modify the remote sensing reflectance (which is proportional to water-leaving radiance) for less than 1.3% at the wind speed of 5 m/s.

The asymmetry is not clearly visible at our polar plots. That is why we do not see any need for changes.

18. Pg 6, line 13: I would suggest choosing a more reasonable second wind speed other than 15 m/s. The limit of applicability of Cox-Munk wave slopes is 14 m/s, and when the wind is this strong, gravity waves will introduce significant uncertainty into the polarimetric measurements (in-situ) due to strong tilts in the instantaneous sea surface. TOA measurements should be unaffected, however.

SC18. Cox and Munk obtained their probability density function for slopes of waves for wind speed from 1 to 14 m/s. However, several times higher values, e.g. 15 m/s, have been used in the literature:

a) Knut Stamnes, Gary E. Thomas, Jakob J. Stamnes: “Radiative Transfer in the Atmosphere and Ocean” at pages 162-163
b) Giles D'Souza, Alan S. Belward, Jean-Paul Malingreau “Advances in the Use of NOAA AVHRR Data for Land Applications” at page 82 and below.
c) Alexander Gilerson, Carlos Carrizo, Robert Foster, and Tristan Harmel, "Variability of the reflectance coefficient of skylight from the ocean surface and its implications to ocean color," Opt. Express 26, 9615-9633 (2018), doi: 10.1364/OE.26.009615
d) Doi: 10.1175/JCLI3973.1
e) Doi: 10.1175/1520-0426(2003)020<1697:MROTCD>2.0.CO;2
f) Doi: 10.1088/0256-307X/26/9/094102

Or even 20m/s:

g) Doi: 10.1088/0256-307X/26/9/094102

In our model we usually set 5 m/s as a typical (most common) wind speed in the Baltic Sea and 15 m/s as the maximal (border) value for measurements. Our results show a mathematically similar dependence between a/c ratio and max(DoP) for both wind speeds.

19. Pg 8, Fig 2: The projection of the polar plots, or at least the zenith values of the concentric circles should be indicated.

SC19. We agree, corrected.

20. Pg 8, Fig 2: The wind-speed used (5 or 15 m/s) is not indicated.

SC20. Corrected.

21. Pg 8, Fig 2: What aerosol optical thickness was used for the simulations at each wavelength? What is the spectral relationship (or angstrom coefficient) used to determine it? Was it based on seasonally averaged measurements?

SC21. We used here a single Aerosol Optical Thickness value equal to 0.12 independent of the wavelength and the same for both seasons. We did it on purpose, because introducing more realistic variability of AOT would cause an additional source of DoP changes and would not allow conclusions to be drawn about the causes of correlation.

22. Pg 8, Fig 2c-2d: I am suspicious of the 1000x increase (10ˆ3/10ˆ0.04) in maximum upwelling radiance from the summer to the winter. The authors should double check that these intensities are correct.

SC22. We understand the mistrust, however, the data have been checked before manuscript submission. The difference of several orders of magnitude in the maximal values of the total upwelling radiance is caused by different directions of incident sunlight (SZA). Also, the upwelling irradiance computed here contains the water-leaving part and the reflected part. The water-leaving part itself can vary of less than 1 order of magnitude due to different SZAs, but the reflected part can vary much more. For most of directions radiance intensities values are comparable.

23. Pg 8, line 1-2 : Intensity is stated to be irradiance, but units of radiance are given.

SC23. This was an error, it is radiance; corrected.

24. Pg 9, Fig 3: No wind speed, aerosol optical thickness values, or zenith labels are given.

SC24. Corrected.

25. Pg 13, line 11-13: I am not convinced that any increase in wind speed (and therefore an increase in the surface roughness) would cause an increase in the DoP. I just don’t see any way in which a rougher surface will result in more polarization than a smooth one. Any increase in roughness should cause at least a partial de-polarization of the reflected/transmitted light field. This is also stated by the authors on pg 16, line 19. For example, see:

a. R. Foster and A. Gilerson, "Polarized Transfer Functions of the Ocean Surface for Above-Surface Determination of the Vector Submarine Light Field," Applied Optics, vol. 55, no. 33, pp. 9476-9494, 11/16/2016 2016.

SC25. Yes, we agree, in general the DOP decreased with wind speed. Here we speak about local and spectral values. We observed the modifications in the DOP's spectral shape at higher wind speeds but only in backward directions relative to sun positions. This is the result of the reflection of light from higher wave slopes.

26. Pg 13, line 22: “The type of water has less influence on the DoP than the season and its representative SZA.” This would seem to contradict the title of the article.

SC26. The title of the article is related to interesting correlation described in the next section. The sentence describes well the results illustrated in figure 6. In our study absorption-to-attenuation ratio varies more between seasons than between 3 considered water types within each season. We show that the character of the DoP dependence on a/c remains the same for different seasons, but the equation parameters are the same for all water types within one season.

27. Pg 14, line 12: This sentence seems to contradict also with the previous comment.

SC27. We believe that the answer above explains also this comment.

28. Pg 15, lines 6-11: The authors are (partially) correct that the Fresnel reflection matrix depends only the refractive index of the medium and the incidence angle (but also on the refractive index of the air, and the imaginary part of each refractive index, which governs absorption). However, the authors are incorrect to use that as justification that the observed differences come only from the water-leaving component of the radiance. The polarization of the reflected component intrinsically depends on the polarization [I,Q,U,V] of the downwelling skylight. The reflected Stokes vector is the downwelling Stokes vector multiplied by the reflection matrix. Therefore significant DoLP variability may be introduced in the reflected component due to polarization of the skylight component, which is then combined with DoLP variability coming from the water-leaving part.

SC28. Yes, we agree. We still believe that the impact of reflected part is minor within a season, because we set the same AOT for all simulations. However we decided to remove the paragraph as its input to the discussion is marginal.

29. Pg 15, lines 16-17: Although I disagree with the reason given for the non-linearity, more importantly, the DoP may never be greater than one. If this occurs in any case, there is a significant problem with the simulations which should be addressed, or a better explanation must be given.

SC29. We do not know the reason of nonlinearity. And we have never received the DoP value equal to one or more. We simply suspect that the physical reason for the lack of linearity can be related to the limit value of DoP, which is one.

30. Pg 15, line 23-24: I believe the reason for the wavelength independence is because the max(DoLP) is always looking at the direct reflection of the Sun, which has little to do with the water body. See General comment #2.

SC30. In my opinion the existence of the maximum DoP in this place is certainly related to the direct reflection of the Sun. However the reflection alone does not explain the existing clear correlation with IOPs.

31. Pg 16, line 13: Generally speaking, the DoLP tends to decrease after multiple scattering events because of the number of photons originating from different directions (and with different polarization), however the authors statement is not universally true and strongly depends on the scattering angle. For example, unpolarized light scattered by Rayleigh particles at 90 degrees becomes fully polarized. Individual scattering events often increase the polarization of the scattered light.

SC31. We agree that only molecular scattering (Rayleigh) raises the DoP of the beam of light. I do not consider a single photon here. In this sentence, by particle matter, we meant suspensions in sea water. However, to be exact, we change this sentence.

32. Pg 17, line 5-7: This is the expected behavior. The underwater SZA corresponding to above-water SZA of 45 and 75 degrees is 30 and 45 degrees, respectively. Since the planes of constant DoLP are orthogonal to the SZA (in single scattering), this results in a 'tilt' of the planes of constant underwater DoLP of 60 and 45 degrees (from the horizontal).

SC32. Refers to deleted subsection

33. Pg 18, line 16-17: More likely the reason is that the measurement of Tonizzo et al, 2009 included scattering by hydrosols with different phase matrices than the Voss-Fry matrices used here.

SC33. Refers to deleted subsection

34. Pg 19, line 7-8: The "HPR" for a flat surface, should be exactly the Brewster angle, which is 53 degrees, not 58. Additionally, the refractive index of the water used should be specified somewhere.

SC34. Refers to deleted subsection

35. Pg 19, lines 5-14: I am not certain this paragraph adds anything to the discussion. I am not aware of any significance to SZA + Zenith = 2 * Brewster angle, and the "HPR" has no information about the water body, since (as defined by the authors) it is 'reflected' radiance.

SC35. Refers to deleted subsection

36. Pg 20, line 25 to Pg 21, line 2: This statement is inaccurate. I believe there is a misunderstanding by the authors about the nature of the relationship between the reflection matrix (or Fresnel amplitude coefficients for parallel and perpendicular directions) and the reflected light field (and polarization thereof). The perpendicular and parallel Fresnel coefficients alone do not dictate the degree of polarization of reflected light. Only when they are applied to an incident light field is the DoP of the reflected light known exactly. They can say something about the possible ranges of DoP, but barring a

few specific cases the actual reflected DoP may only be known after consideringthe coefficients and the incident light field together.

SC36. Refers to deleted subsection

37. Pg 20, line 16-17: I disagree with this statement. When the SZA is very high (winter), the “HPM”, in the authors terminology (the angles of highest underwater DoP), are allowed to propagate upward through the surface, because they fall within Snell’s window (cone of angles less than the critical angle). When the Sun is higher in the sky (lower SZA), the peak DoP falls outside Snells window and is internally reflected by the sea surface, and therefore does not propagate above the water. This would seem to contradict the statement by the authors. See also Fig 4 of:

a. A. Ibrahim, A. Gilerson, T. Harmel, A. Tonizzo, J. Chowdhary, and S. Ahmed, "The relationship between upwelling underwater polarization and attenuation/absorption ratio," Optics Express, vol. 20, no. 23, pp. 25662-25680, Nov 05 2012.

SC37. Refers to deleted subsection

38. Pg 21, line 6-9: Isn’t Fig 8 a simulation of below water? This would seem to be directly comparable with Ibrahim, 2012.

SC38. Refers to deleted subsection

Technical Corrections

1. Pg 3 line 1: I do not see an entry in the references for Chami, 2001. Also, see specific comment #7, because this citation is out of date. (see LaFrance and Chami, 2016)

TC1. Corrected, but in place of manual guide we cited: Chami, M., Lafrance, B., Fougnie, B., Chowdhary, J., Harmel, T., and Waquet, F.: OSOAA: a vector radiative transfer model of coupled atmosphere-ocean system for a rough sea surface application to the estimates of the directional variations of the water leaving reflectance to better process multi-angular satellite sensors data over the ocean, Opt. Express 23, 27829-27852, doi:10.1364/OE.23.027829, 2015.

Corrections in the manuscript suggested by the reviewer 1

On the role of the seawater absorption to attenuation ratio in the radiance polarization above the Southern Baltic surface

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Abstract. Information about polarization of light leaving the ocean surface has the potential to improve the quality of the bio-optical parameters retrieval from ocean color remote sensing (OCRS). This improvement can be applied in numerous ways such as limiting of sun glints and obtaining information about atmospheric aerosol properties for atmospheric correction as well as increasing the accuracy of the algorithms based on the water-leaving signal. Polarization signals at the top of the atmosphere (ToA) that include the water-leaving signal are strongly influenced by atmospheric molecular scattering and by direct sun and sky reflections from the sea surface. For these reasons, it is necessary to better understand the factors that change the polarization of light in the atmosphere-ocean system, especially in coastal zones affected by dynamic changes. In this paper, the influence of seasonal variability of light absorption and scattering coefficients (inherent optical properties, IOPs) of seawater, wind speed and solar zenith angle (SZA) on the polarization of upwelling radiance over the sea surface in the visible light bands is discussed. The results come from a polarized radiative transfer model based on the Monte Carlo code and applied to the atmosphere-ocean system using averaged IOPs as input data. The results, presented in the form of polar plots of the total upwelling radiance degree of polarization (DoP), indicate that regardless of the wavelength of light and type of water, the highest value of the above water DoP is strongly correlated with the absorption-to-attenuation ratio. The correlation is a power function that depends on both the SZA and the wind speed. The correlation versatility for different wavelengths of light is very unusual in optics of the sea and is therefore worth emphasizing.

1 Introduction

Satellite ocean color radiometry has been developed for decades to study the interaction of a light field within the visible part of the spectrum (i.e., 400-700 nm) with the different optically significant constituents of sea water. The research has been focusing on information coming from the intensity of water-leaving light - its measurement, retrieval, correlations and interpretation (e.g., Volpe et al., 2012; Zibordi et al., 2013; Sammartino et al., 2015). However, in addition to the light intensity, consideration of light polarization has been demonstrated to improve the accuracy of the information from a variety of remote sensing applications, i.e., in remote radar measurements (Hajnsek et al., 2003; Soloviev et al., 2012; Benassai et al., 2013), and in atmospheric correction algorithms (Chowdhary et al., 2002).

Komentarz [W1]: SC1, SC2

Vector radiative transfer simulations have shown that the polarization of the underwater light field is sensitive to the nature of the suspended marine particles. Ibrahim et al. (2012) and Ibrahim et al. (2016) demonstrated that the attenuation-to-absorption ratio influences the polarization of upwelling radiance below the sea surface. Polarized measurements have also been performed near and above the sea surface. Reduction of sun glints to improve the ocean color retrieval has been studied by He et al. (2014), Zhou et al. (2017) or Shaw and Vollmer (2017) and limitation of sky reflections by observation of sea surface at the Brewster angle from the ship board has been examined by Wood and Cunningham (2001) and by Cunningham et al. (2002). Polarization distribution of skylight reflected off the rough sea surface has been examined by Zhou et al. (2013), Harmel et al. (2012), Harmel and Chami (2013), Mobley (2015), Hieronymi (2016), Foster and Gilerson (2016) and by D'Alimonte and Kajiyama (2016). Zhou et al. (2013) simulated the degree of polarization as well as the angle of polarization (AoP) for reflected parts of upwelling radiance and discussed its variability with SZA for 0°, 30°, 60° and 90°. Moreover, Zhou et al. (2013) showed the influence of wind speed and direction on the polarization pattern of reflected radiance. Radiative transfer simulations have shown the effect of marine suspensions on the polarization of light recorded above the sea surface (see Chami et al.,2005; Chami, 2007). Further studies have also shown the possibility of knowing the composition of the suspension, i.e., the ratio of mineral to organic suspension, using polarization properties of water-leaving radiance (see Gilerson et al., 2006; Chami, 2007; Tonizzo et al., 2011). The intent of the authors was to show the seasonal variability of polarization of the upwelling radiance above the sea surface.

The most challenging part in the analysis of the signal registered by passive radiometric sensors at the top of the atmosphere is to remove the contribution of the reflected photons at the air-sea interface as well as the contribution of the atmosphere. To assess the water-leaving radiance, $L_w(\lambda)$ on the level of accuracy required to derive accurate estimates of the desired water components, other characteristics and methods that support the advanced atmospheric correction and parameter retrieval have been searched, i.e., the black pixel assumption (Siegel et al., 2000), using near infrared and shortwave infrared bands (Wang et al., 2007), using unpolarized ToA reflectance (Frouin et al., 1994), or using polarized water-leaving radiance (Zhai et al. 2017). The latter showed that, in general, the polarized signal at the ToA is 2-3 times higher than its water-leaving part because of the influence of molecular scattering in the atmosphere. Discussions on the use of remote polarization measurements to determine the aerosol properties that can then be used for atmospheric correction are included in Chowdhary et al. (2002), Mishchenko and Travis (1997) as well as Hasekamp and Landgraf (2005). Pust et al. (2011) showed that measurements of the degree of polarization of the sky (made from the ground) can also be helpful in obtaining aerosol parameters. He et al. (2014) proposed to measure the parallel polarization radiance (PPR) instead of radiance intensity at ToA. According to them, such measurements would enhance the OCRS capability. Liu et al. (2017), based on radiative transfer modeling and laboratory measurement, showed that the concentration of particulate matter influences the PPR measured at ToA.

Polarized signal can be measured from the satellite sensors, e.g., POLarization and Directionality of the Earth's Reflectances sensor (POLDER-2), above water using a polarization imaging camera (Freda et al., 2015) or underwater as by Loisel et al. (2008) and Harmel et al. (2008). The measurements are often supported by numerical modeling. Although there are many

Komentarz [W2]: SC2
Komentarz [W3]: SC3
Komentarz [U4]: SC4
Komentarz [W5]: SC5

ongoing numerical radiative transfer models applied to ocean-atmosphere system, only some of them include light polarization (Schulz et al. 1999; Ota et al. 2010; Piskozub and Freda, 2013; Chami et al. 2015; and Korkin et al. 2017). Kokhanovsky (2010) compared several vector radiative transfer models.

Komentarz [U6]: SC6

Polarized radiative transfer has been applied for the ocean-atmospheric system since the 1970s. See for example Kattawar et al. (1973). Chami et al. (2015) applied the polarized radiative transfer to retrieve the polarizing properties of the marine phytoplankton and minerals for different water conditions. Their analysis revealed that the application of the polarization of light in ocean color algorithms might significantly improve the retrieval of hydrosol properties, especially in coastal waters. Piskozub and Freda (2013) applied their polarized radiative transfer model to the Baltic Sea. They examined how scattering properties of seawater represented by a single scattering albedo affected the polarization of water-leaving radiance. They demonstrated the impact of air bubble layers of various concentrations on the degree of polarization of water-leaving light. They also concluded that polarization remote sensing should be performed on a plane tilted approximately 90° from the solar azimuth angle to avoid sun glints.

Komentarz [U7]: SC7

Komentarz [U8]: SC8

The involvement of polarization in radiative transfer analysis seems to be especially important in coastal areas, knowing that they undergo dynamic changes due to human proximity (Drozdowska et al., 2017), river inflows and the occurrence of pollution, including optically significant oil pollution (Drozdowska et al., 2013). There has been several significant studies performed in coastal zones of New York Harbor (Tonizzo et al. 2009), of Long Island Sound (Harmel et al. 2012) or of selected few places from the East Coast and Gulf of Mexico (Tonizzo et al. 2011). Nevertheless, little attention has been paid to the measurement and modeling of light polarization in some coastal areas and closed water basins like the Baltic Sea characterized by optically complex waters. The Baltic Sea represents a region of a great economic importance, extremely high marine traffic and the impact of inflows from nine different surrounding countries. Inherent optical properties of Baltic seawater and its constituents have been in the spotlight for oceanographers for two decades. In addition to regular measurements of depth profiles of absorption and attenuation coefficients, measurements for different components of seawater have been performed. Colored dissolved organic matter (CDOM) is known to be the primary absorber in the Baltic Sea (Kowalczuk et al., 2010), and its impact on the total absorption coefficient for blue light can reach up to 80% (Kowalczuk et al., 2005). Kowalczuk (1999) and Kowalczuk and Kaczmarek (1996) found that the high absorption of CDOM in spring and low absorption in winter is due to the biological cycle as well as the seasonal variability of the inlet with river water and its mixing. The search for a better correlation of the spectral remote sensing reflectance R_{rs} ratio with the absorption coefficient of CDOM has been intensively searched within the SatBaltic system (Meler et al., 2016a). Measurements of suspended matter IOPs in the Baltic, i.e., particle absorption and particle scattering coefficients, have been compared with biogeochemical characteristics of suspended matter such as concentrations of suspended particulate matter, particulate organic matter, particulate organic carbon and chlorophyll a (Woźniak et al., 2011). Meler et al. (2016b) concluded that absorption properties of non-algal particles undergo larger regional than seasonal variability. In addition to the absorption and attenuation coefficients, the volume scattering functions (VSFs) were also measured in the waters of the Southern Baltic (Freda et al., 2007; Freda and Piskozub, 2007; Freda, 2012). Unique measurements have been performed by

Komentarz [W9]: SC9

the prototype volume scattering meter, characterized by an angular resolution of 0.3º and a range of scattering angles from 0.6º to 177.9º, described by Lee and Lewis (2003). The same instrument has also been used by Chami et al. (2005) in the Black Sea and by Berthon et al. (2007) in the Adriatic Sea. Baltic Sea waters are often affected by small-scale oil pollution (Rudź et al., 2013). The influence of dispersed oil droplets on the absorption coefficient of seawater was researched by Otremba (2007) as well as Haule and Freda (2016), while their influence on scattering properties has been tested by Freda (2014). The consequences of changes in IOPs for remote detection of dispersed oil pollution have been discussed by Otremba et al. (2013), Otremba (2016), and Haule et al. (2017) based on radiative transfer modeling. Knowledge and datasets collected in the Baltic throughout the past two decades helped us to perform a unique study on polarized radiation above the southern Baltic sea surface. This study shows the application of a polarized radiative transfer model in three optically different regions, two seasons and two different sea states. The study highlights the possibilities and consequences of including polarization information in bio-optical models of seawater.

2 Methods

The difficulty of comparison of upwelling radiance DoP over a wind-roughened southern Baltic surface for various seasons is caused by the small number of sunny days in winter and too many variable weather factors that would make it difficult to explain the differences. These undesirable weather factors are different aerosol optical depths, sky overcast, and changing speed and direction of wind relative to the position of the sun. For those reasons, we applied a polarized radiative transfer model based on the Monte Carlo code to describe the effect of seasonal changes on the polarization of upwelling radiance. The simulations involved seasonally averaged measurements of inherent optical properties from the Southern Baltic basin and were run for constant weather conditions. For a detailed description of the inputs and conditions under which the simulation is performed, see the following subsections.

2.1 Polarized radiative transfer model - theoretical background

Numerical simulations were carried out using the Monte Carlo algorithm created by Jacek Piskozub and applied previously in Piskozub and Freda (2013). The algorithm solves the vector radiative transfer equation for the atmosphere-ocean system using the successive orders of scattering method and the Stokes formalism to track the polarization of photons. The algorithm collects information about virtual photons involved statistically in optical processes: reflection at the rough sea surface, refraction at the air-water interface, scattering and absorption within the water body and reaching the ToA. Moreover, the original Monte Carlo algorithm has been modified to track polarization changes of each photon during these processes. The unmodified version of the algorithm was successfully used, with results published in: Piskozub et al. (2001), Stramski and Piskozub, (2003), McKee et al. (2008), McKee et al. (2013) or Piskozub and McKee, (2013).

Komentarz [W10]: SC10

Polarization information is described by four elements of the Stokes vector: $S = [I,Q,U,V]^T$, where I is the total radiance of light, Q describes the radiance of linearly polarized light (vertical to horizontal), U describes the radiance of linearly polarized light (diagonal right-skewed to left-skewed), V describes the circular polarization (clockwise to counterclockwise) and T denotes the transposition. Three elements (Q, U and V) of the Stokes vector may be both positive or negative. The single quantity that characterizes these properties is the degree of polarization:

$$DoP = \frac{\sqrt{Q^2+U^2+V^2}}{I}, \qquad (1)$$

The defined degree of polarization is often replaced by the degree of linear polarization, DoLP.

$$DoLP = \frac{\sqrt{Q^2+U^2}}{I}, \qquad (2)$$

The latter hardly differs from DoP because circular polarization is relatively rare in nature (Cronin and Marshall, 2011). The circular polarization represented by the V element of the Stokes vector does not appear in seawater as a result of scattering, see off-diagonal Mueller matrix elements in (Voss and Fry, 1984). It is measurable in light internally reflected from the underside of the sea's surface (Ivanoff and Watermann 1958).

Our polarized radiative transfer model involves a virtual light source to send randomly polarized photons and track their pathways in the means of the probability of occurrence of the processes mentioned above. Reflection and refraction processes are described by Fresnel equations, and the slopes of the sea surface are characterized by the wind-dependent distribution of Cox and Munk (1956). The probability of processes within the water body is determined by the corresponding coefficients of absorption and scattering (including multiple scattering). Angular distribution of scattered photons is described by phase functions that, for both atmosphere and sea depth, are characterized separately for molecular scattering and particle scattering. Polarization properties of particle scattering are described by Müeller matrices that for sea water are taken from Voss and Fry (1984) and for atmospheric aerosol particles from Volten et al. (2001). The model outputs the angular distribution of the upwelling radiance and its degree of polarization at any desired level, that are presented in form of polar plots. Some of the results are additionally specified in the principal plane.

Komentarz [W11]: SC11

Komentarz [U12]: SC12

Komentarz [E13]: SC14

2.2 Polarized radiative transfer model - input parameters

This section reports the input parameters used in the computations. The data set of the absorption and attenuation coefficients of seawater constituents come from *in situ* measurements in the southern Baltic contained in Sagan (2008). It is the largest dataset of ac-9 (WET Labs) measurements in the southern Baltic that was published in a tabular form of average values, extreme values and standard deviations. The instrument was calibrated in ultrapure water and routinely checked for stability with air readings. The standard recommended data processing was performed (Zaneveld et al. 1994). Absolute precision of measurement is 0.005 m^{-1}, while relative precision is estimated from 4% in clear waters to 12% in the areas of turbid waters. The data have been recorded during cyclical cruises aboard R/V Oceania in 1999 and 2003 to 2005. Measurements were made in different months of the year. The data set was divided into two seasons, called here ‘winter’, for the months from November to March and ‘summer’, the months from April to October. The summer season is characterized by strong phytoplankton growth and the winter season by low biological activity. In addition, Sagan (2008) distinguished three regions: open Baltic, gulfs (Gulf of Gdańsk and Pomeranian Gulf) and coastal waters. The measuring stations, divided into these three types of water, are shown in Figure 1. For defined regions – open Baltic and coastal areas – those two data sets are statistically significantly different for all optical parameters (*t* test for means) at the level $p<0.05$ by Sagan (2008).

Total absorption coefficient taken to the simulation is a sum $a_t = a_{pg} + a_w$, where a_{pg} is an average absorption coefficient (particle and dissolved fraction) of the N number of measured depth profiles (see Table 1) made with the ac-9 after Sagan (2008), and a_w is the pure water absorption coefficient and comes from Pope and Fry (1997). Similarly, the total attenuation coefficient is defined as $c_t = c_{pg} + a_w + b_w$, where the component c_{pg} comes directly from Sagan (2008), but to get the total attenuation coefficient, it was enlarged by clean water components of absorption a_w and scattering b_w (Smith and Baker, 1981). According to Sagan (2008), the highest values of IOPs and their highest variability are observed for the water of gulfs and estuaries of rivers that are located nearby. The simulations are carried out at nine wavelengths, namely, 412 nm, 440 nm, 488 nm, 510 nm, 532 nm, 555 nm, 650 nm, 676 nm and 715 nm, which correspond to the ac-9 and are commonly dedicated to ocean color analysis.

Komentarz [U14]: SC16

Komentarz [U15]: SC16

Solar zenith angles in the southern Baltic region depend strongly on the season. In months described by Sagan (2008) as the summer season, the highest sun position over the horizon, that means the minimum of SZA during sun culmination, varies between 31º in June (the longest day of the year) and 69º at the end of October. In the modeling, a single value of 45º was chosen as a summer SZA. For months of the winter season, the minimum of SZA varies between 50º in the end of March and 78º in December (the shortest day). Given values are reached at approximately noon and are higher in the rest of the days. That is why SZA of 75º is chosen as a representative for the winter season. Computations are performed for the direction of wind twisted by 45º from the sun reflection plane, chosen arbitrarily. Two wind speeds of 5 m/s and 15 m/s are considered. Aerosol Optical Thickness of 0.12 independent of the wavelength and the same for both seasons was applied to all simulations. This allowed us to observe DoP variations and correlations that were not affected by aerosol changes.

Komentarz [W16]: SC21

Here and in the following figures, the celestial hemisphere and its reflection patterns are represented in a two-dimensional coordinate system. The zenith and the nadir are at the origin and the horizon is represented by the outermost circle. The zenith angle and azimuth angle are measured radially and tangentially, respectively. The solar azimuth angle is always set to 0.

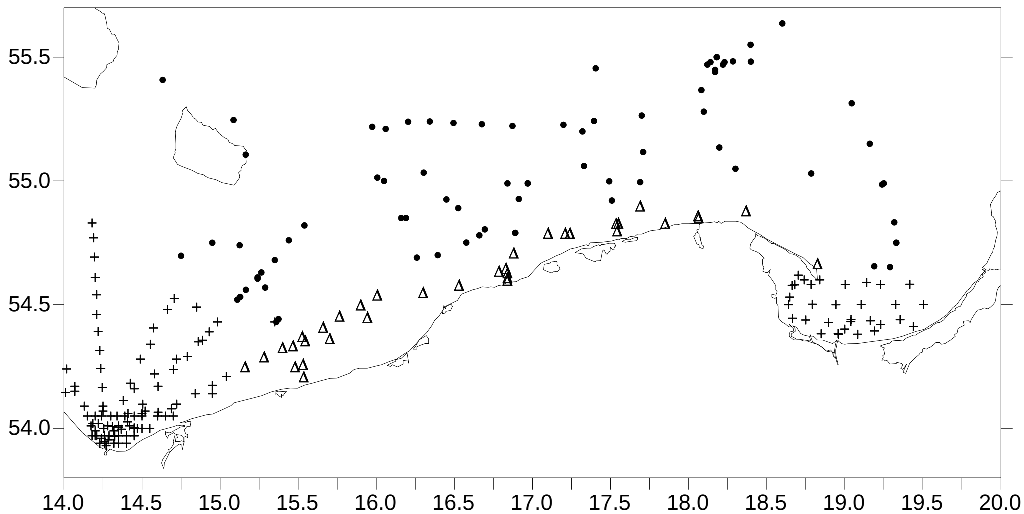


Figure 1. The area of the southern Baltic Sea, on which the positions of measurement stations are marked, divided into three areas: Pomeranian Gulf and Gulf of Gdańsk (+), coastal water (Δ) and open Baltic water (•).

Table 1. Average values of total absorption coefficients, total attenuation coefficients, their standard deviations and their ratios. All values measured by Sagan (2008) in southern Baltic in 1999 and 2003 to 2005 are averaged for depths 0 to 5 meters and then averaged for N measuring stations

Summer Season															
λ	Baltic, N=930					Gulfs, N = 1428					Coastal Waters, N = 132				
[nm]	$a(\lambda)$	σ_a	$c(\lambda)$	σ_c	$\frac{a(\lambda)}{c(\lambda)}$	$a(\lambda)$	σ_a	$c(\lambda)$	σ_c	$\frac{a(\lambda)}{c(\lambda)}$	$a(\lambda)$	σ_a	$c(\lambda)$	σ_c	$\frac{a(\lambda)}{c(\lambda)}$
412	0.595	0.12	1.230	0.40	0.483	1.095	0.65	2.560	1.64	0.428	0.615	0.12	1.470	0.52	0.418
440	0.396	0.10	0.999	0.37	0.396	0.786	0.52	2.209	1.48	0.356	0.416	0.10	1.249	0.52	0.333
488	0.214	0.07	0.817	0.34	0.262	0.444	0.32	1.887	1.35	0.236	0.214	0.06	1.027	0.46	0.209
510	0.183	0.05	0.785	0.33	0.233	0.353	0.23	1.825	1.31	0.193	0.173	0.04	0.995	0.46	0.173
532	0.155	0.04	0.756	0.32	0.205	0.285	0.18	1.756	1.28	0.162	0.155	0.03	0.946	0.44	0.163
555	0.140	0.03	0.731	0.31	0.192	0.240	0.13	1.711	1.26	0.140	0.140	0.03	0.911	0.42	0.153
650	0.380	0.02	0.921	0.29	0.413	0.430	0.08	1.811	1.20	0.237	0.380	0.02	1.071	0.38	0.355
676	0.518	0.05	1.029	0.28	0.503	0.638	0.19	1.909	1.18	0.334	0.508	0.03	1.169	0.38	0.435
Winter Season															
λ	Baltic, N = 234					Gulfs, N = 540					Coastal Waters, N = 36				
[nm]	$a(\lambda)$	σ_a	$c(\lambda)$	σ_c	$\frac{a(\lambda)}{c(\lambda)}$	$a(\lambda)$	σ_a	$c(\lambda)$	σ_c	$\frac{a(\lambda)}{c(\lambda)}$	$a(\lambda)$	σ_a	$c(\lambda)$	σ_c	$\frac{a(\lambda)}{c(\lambda)}$
412	0.485	0.03	0.680	0.015	0.713	0.755	0.31	1.760	1.04	0.429	0.585	0.14	1.250	0.68	0.468
440	0.296	0.02	0.479	0.015	0.618	0.496	0.22	1.469	0.95	0.338	0.376	0.10	1.009	0.63	0.373
488	0.154	0.02	0.337	0.015	0.459	0.264	0.13	1.217	0.86	0.217	0.194	0.06	0.817	0.57	0.238
510	0.133	0.02	0.315	0.014	0.421	0.213	0.10	1.165	0.83	0.182	0.163	0.05	0.785	0.55	0.207
532	0.125	0.02	0.296	0.013	0.421	0.185	0.08	1.106	0.81	0.167	0.145	0.04	0.756	0.54	0.191
555	0.120	0.01	0.291	0.013	0.411	0.170	0.06	1.071	0.79	0.158	0.140	0.03	0.731	0.52	0.191
650	0.370	0.01	0.521	0.012	0.711	0.400	0.04	1.211	0.73	0.330	0.370	0.01	0.931	0.46	0.398
676	0.478	0.02	0.629	0.012	0.760	0.528	0.08	1.299	0.72	0.407	0.488	0.02	1.039	0.45	0.470

3 Results and discussion

3.1 Extreme values of the degree of polarization

Examples of simulation results are presented in Figures 2a and 2b in the form of polar plots of the degree of polarization of upwelling radiance just above the sea surface. Figure 2a shows the DoP for the average IOPs measured in the open waters of the Baltic Sea for a wavelength of 412 nm in the summer season, while Figure 2b depicts an analogous case for the winter season. These two plots are characterized by one of the highest values of the peak of DoP of 0.88 for summer and 0.84 for winter. The azimuth position of the sun is 0° in all cases. Corresponding values of computed upwelling radiance I (in units of $Wm^{-2}sr^{-1}nm^{-1}$) are shown on the plots of Figures 2c and 2d on the logarithmic scale (due to their high angular variability).

Komentarz [W17]: SC23

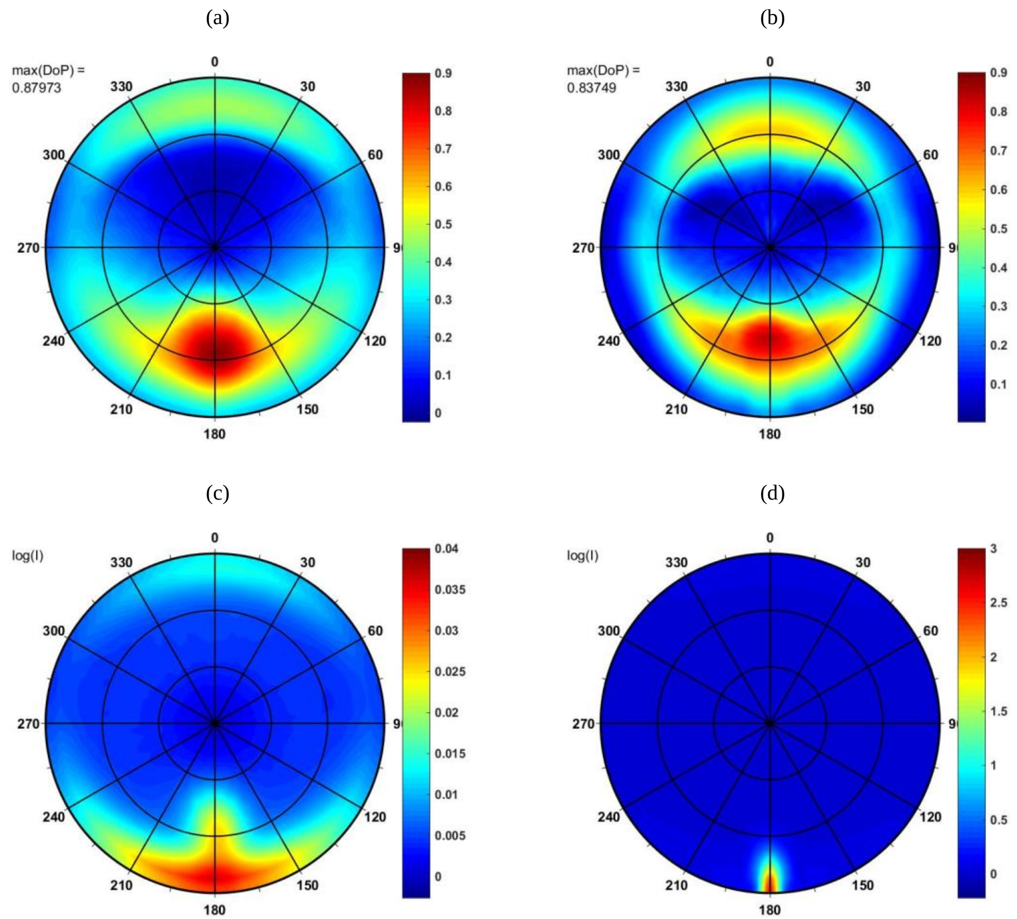


Figure 2. Simulation results of above-water upwelling radiance for average IOPs of open waters of the southern Baltic, wavelength 412 nm, for speed of wind of 5 m/s: a) DoP in the summer season, SZA 45°, b) DoP in the winter season, SZA 75°, c) decimal logarithm of upwelling radiance in the summer season, SZA 45°, d) decimal logarithm of upwelling radiance in the winter season, SZA 75°. Concentric circles inside mean zenith angles 30° and 60° respectively.

Komentarz [W18]: SC20

Komentarz [W19]: SC19

The small SZA of the summer season (45º) resulted in low values of upwelling radiance that are stretched from the direct reflection point to the horizon, where it is extended both left and right from the azimuth of 180º. The high SZA of the winter season (75º) resulted in much higher values of reflected light, which are also stretched from reflection point to the horizon. Examples of the lowest values of the maximum DoP, referred to as max(DoP), are shown in Figures 3a and 3b. They were obtained for the regions of Gulf of Gdańsk and Pomeranian Gulf, simulated for the spectral band of 555 nm, for the summer season (Figure 3a) and for the winter season (Figure 3b).

(a) (b)

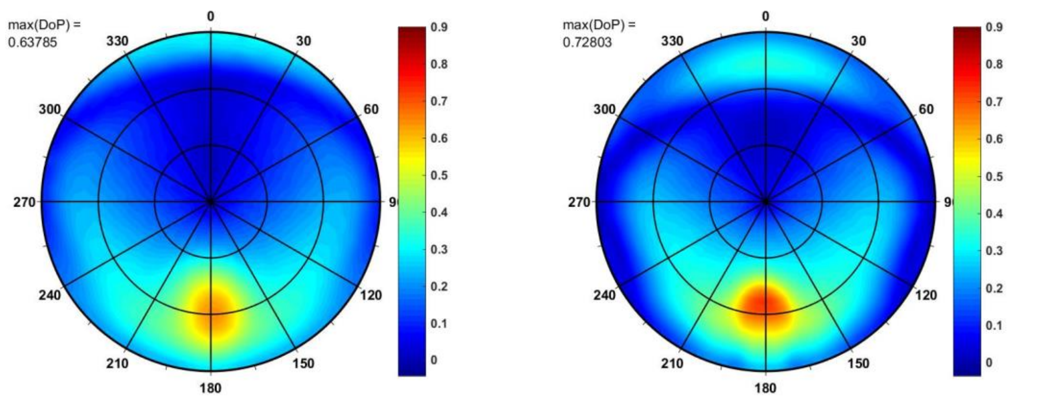


Figure 3. Simulation results of above-water upwelling radiance for average IOPs of gulf waters of the southern Baltic, wavelength 555 nm, for speed of wind of 5 m/s: a) DoP in the summer season, SZA 45°, b) DoP in the winter season, SZA 75°. Concentric circles inside mean zenith angles 30° and 60° respectively.

Komentarz [W20]: SC24

Komentarz [W21]: SC24

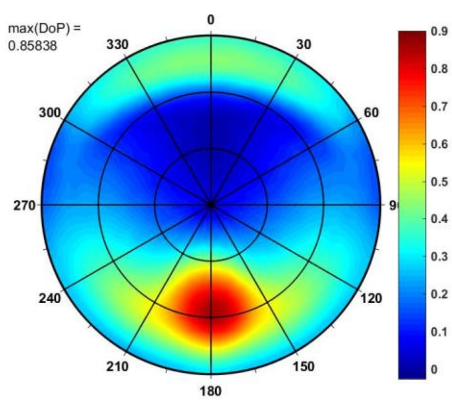
The maximum values of DoP presented in Figure 2a (summer season, open Baltic waters) are visible for azimuth angles close to 180º (direction of reflected sun) and a zenith angle of approximately 55º although the solar zenith angle is 45º, while the max(DoP) in Figure 3a (summer season, waters of gulfs) is visible for zenith angle of approximately 60º. In contrast to the summer season case, the maximum DoPs in the winter season are close to the zenith angle of 48º (Figure 2b) and 54º (Figure 3b), while SZA is 75º. The lower position of the sun results in a higher position of the maximum DoP of upwelling radiation than its reflection angle, and a higher position of the sun results in a lower position of the maximum DoP. Another interesting effect is the higher DoP observed for directions close to the incident rays of the sun (azimuth 0º). In general, in the winter season, the values of DoP are higher than in summer, and zenith angles of this effect are lower in the winter than in the summer season.

3.2 Spectral variability of the degree of polarization

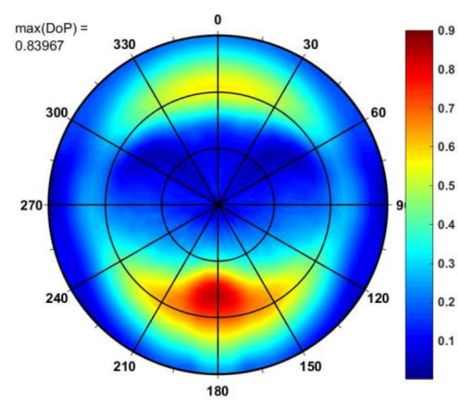
The results of Monte Carlo simulations of angular characteristics of DoP of upwelling radiance are presented in Figure 4. These results are obtained for average IOPs of open Baltic waters for wind speed of 5 m/s for three wavelengths (440 nm, 555 nm, 650 nm) and for both seasons. Vertical cross-sections of such polar plots for the same type of water (open Baltic Sea) but additionally for all examined wavelengths and for two speeds of wind, 5 m/s and 15 m/s, are presented in Figure 5. Such cross-sections show the DoP in the principal plane, including the direction of incident sun beam (on the left side of the plot), zenith and direction of sun reflection beam for calm sea surface (on the right side). The azimuth direction of the sun position, described as 0° in the polar plots, is marked by negative zenith angles in Figure 5, while azimuth directions of 180° that include the sun reflection beam are marked by positive zenith angles.

summer season | winter season
(a) | (b)

440 nm

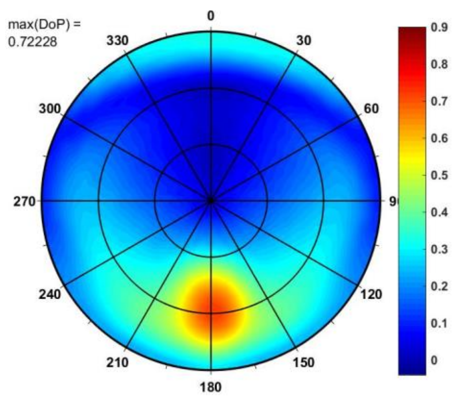


440 nm



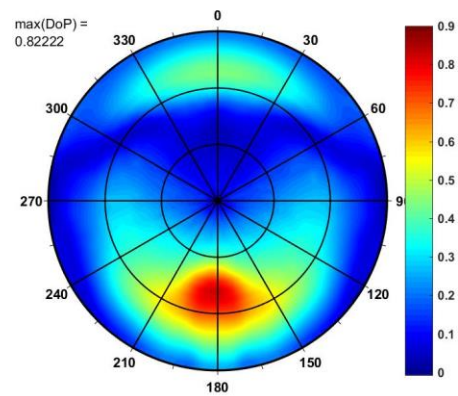
(c)

555 nm



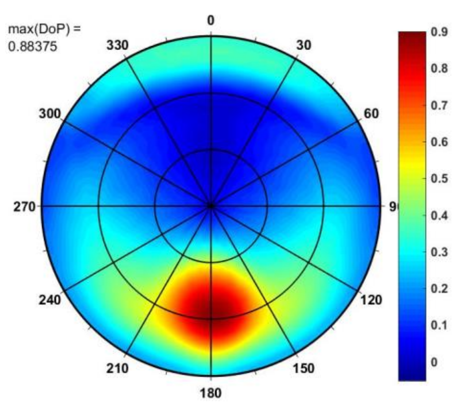
(d)

555 nm



(e)

650 nm



(f)

650 nm

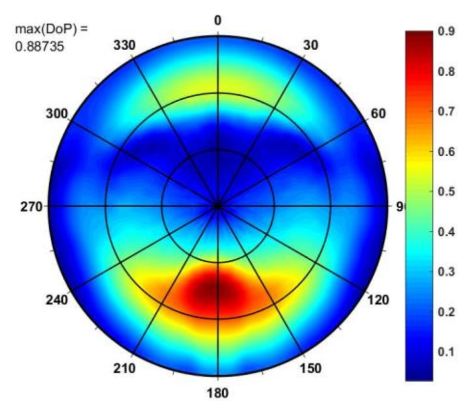


Figure 4. Simulation results of above-water upwelling radiance for average IOPs of open Baltic Sea water, for speed of wind of 5 m/s: a) DoP in the summer season, λ=440 nm, SZA 45°, b) DoP in the winter season, λ=440 nm, SZA 75°, c) DoP in the summer season, λ=555 nm, SZA 45°, d) DoP in the winter season, λ=555 nm, SZA 75°, e) DoP in the summer season, λ=650 nm, SZA 45°, f) DoP in the winter season, λ=650 nm, SZA 75°. Concentric circles inside mean zenith angles 30° and 60° respectively.

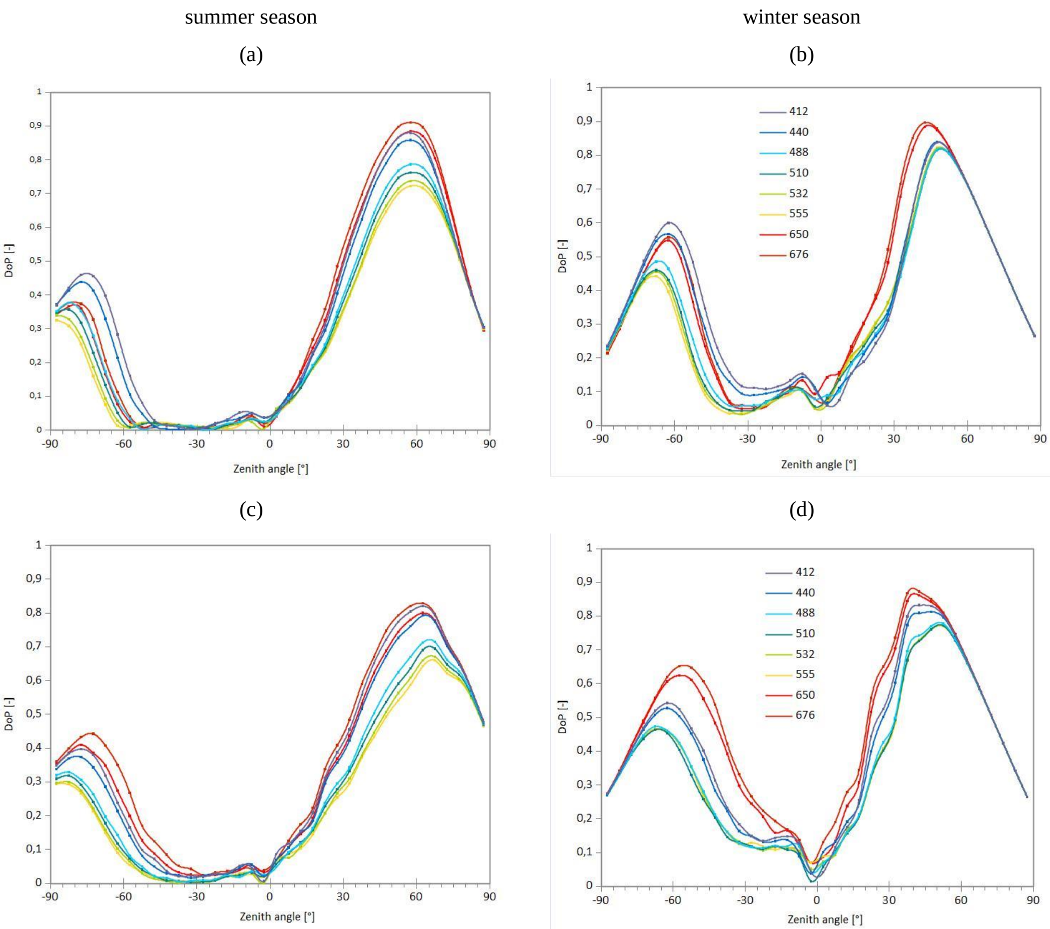


Figure 5. Degree of polarization plotted for the principal plane, e.g., plane containing both incident ray of the sun and zenith direction (cross section through polar plots for azimuths 0° and 180°). Azimuth 0° - azimuth of sun position is marked by negative zenith angles, while azimuth 180° - that contains sun reflection is marked by positive zenith angles. Simulation results for open Baltic Sea water: a) summer season, SZA 45°, wind speed 5 m/s, b) winter season, SZA 75°, wind speed 5 m/s, c) summer season, SZA 45°, wind speed 15 m/s, d) winter season, SZA 75°, wind speed 15 m/s.

The analysis of individual spectral bands shows that high values of DoP correspond to the high absorption-to-attenuation ratio for the total of visible light domain (see Table 1). High values of absorption coefficient for 650-676 nm wavelengths (in the red spectral region) are caused by pure water (see Pope and Fry, 1997) while high absorption coefficients for wavelengths of the blue-green range are caused mainly by CDOM (Kowalczuk et al., 2005). The lowest values of max(DoP) for each type of water and for each season are observed for the 555 nm spectral band. The lowest values of absorption and weak spectral variability of the scattering coefficient implies that the wavelength of 555 nm is characterized by the lowest absorption-to-attenuation ratios due to the existence of a minimum of absorption for seawater containing phytoplankton. Algae cells, depending on the composition of their pigments, may have a minimum of absorption in a wide range of spectral bands from 550 nm to 660 nm (Bricaud et al., 2004). Considering the absorption of pure water that is increasing with wavelength (Pope and Fry, 1997), the minimum of the absorption in Baltic waters for the spectral band of 555 nm results.

The spectral shape of the DoP cross-sections contains two maxima, and their angular positions depend on the absorption-to-attenuation ratio, the season and the wind speed. The angular position of the higher maximum depends mostly on the season, varying from approximately 60º in the summer to 35º-50º in the winter (see Figure 5). The lower maximum we observe at the zenith angles between -70º and -90º in the summer as well as between -55º and -70º in the winter. Higher wind speed of 15 m/s, in comparison to 5 m/s, causes the irregular shape of peaks. Moreover, the higher wind speed causes an increase of the DoP value for a lower maximum in the 650 nm and 676 nm spectral bands and its shift to a higher position (toward the zenith). At the same time, the DoP values for shorter wavelength bands are decreased and shifted to a lower position (toward horizon).

3.3 Regional variability of the degree of polarization

Computations of DoP were carried out in three optically different regions of the southern Baltic. Such a division is justified in previous studies of optical and hydrological properties of the south Baltic waters (Olszewski et al., 1992). They showed a relationship between the measured values of IOPs and their location in relation to river estuaries, distance from the shore or bathymetry of the bottom.

Comparison of water type influence on the DoP is shown in Figure 6 for two wavelengths, 440 nm (Figure 6a) and 555 nm (Figure 6b). The type of water has less influence on the DoP than the season and its representative SZA.

(a) (b)

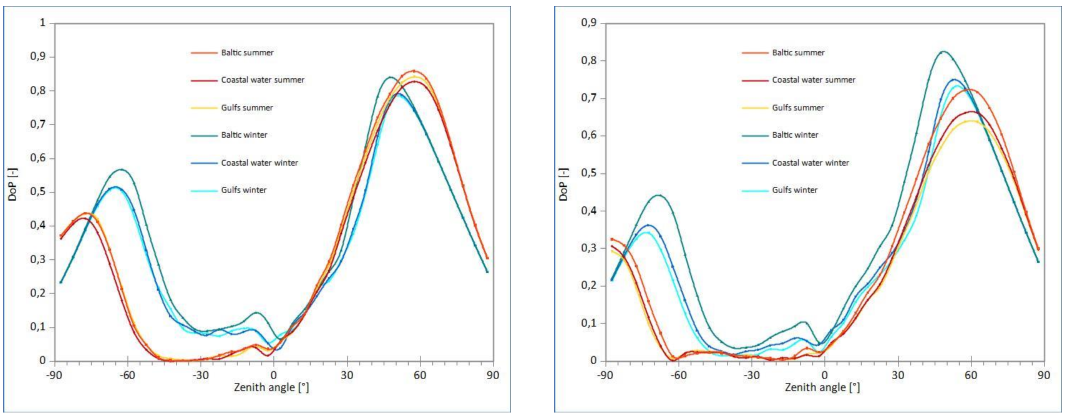


Figure 6. Degree of polarization plotted for the principal plane, i.e., plane containing both incident ray of the sun and zenith direction (cross-section through polar plots for azimuths 0° and 180°). Azimuth 0° is marked by negative zenith angles. Simulation results for wind speed of 5 m/s for all types of water and two seasons: a) 440 nm, and b) 555 nm.

However, the highest values of DoP for most zenith angles and the highest values of its peak max(DoP) for each season are observed for open Baltic Sea water. Coastal waters and gulfs are characterized by similar values of DoP in each season. For the wavelength of 440 nm, in the summer, the differences of max(DoP) between the open Baltic and other regions reach 0.02-0.04, while in the winter those differences exceed 0.05. For the 555 nm band, in the summer the differences of max(DoP) between the open Baltic and other regions reach 0.06-0.09 and in the winter these differences reach 0.07-0.09, respectively. We also observed another regional difference in the angular position of the maxima of DoP that is noticeable in the winter season only. Two maxima of the DoP cross-sections are closer for open Baltic waters than for gulfs and coastal waters.

In the following section, we explain that the degree of polarization depends on the absorption-to-attenuation ratio, and all its regional changes are the result of the absorption-to-attenuation ratio variability.

The results of our simulations are in qualitative agreement with the measurements of above water DoLP of the total upwelling radiance presented by Freda et al. (2015). This agreement is the similarity of the peak of degree of polarization on the polar plots, which are stretched along the azimuth angles. Freda et al. (2015) obtained lower values of measured DoLP with a maximum of 30-40% (see Figures 1 and 2 in (Freda et al., 2015)), which is presumably caused by different weather conditions and unknown environmental parameters during measurements, such as a high absorption coefficient in the waters of the river mouth, different aerosol optical depth, or other parameters. However, despite the differences in the maximum degree of polarization, the angular distribution patterns are similar, with the peak in the vicinity of the sun reflection azimuth angle.

3.4 DoP dependence on the absorption-to-attenuation ratio

This section contains the comparison of the degree of polarization for summer and winter seasons as a function of the absorption-to-attenuation ratio.

The total a(λ)/c(λ) ratio (see Table 1) is higher in the open Baltic water than in other regions because of the low scattering coefficients (Sagan, 2008). The value of the latter is determined mainly by the concentration of suspended matter, which in open waters is significantly lower than in gulfs or coastal/near-shore waters. According to Sagan (2008), the average particle scattering coefficient does not depend strongly on wavelengths, and in open Baltic waters in the winter season it varies between 0.15 (for 676 nm) and 0.19 (for 412 nm). In the same season, but in the waters of gulfs, the average particle scattering coefficient varies between 0.77 (for 676 nm) and 1.00 (for 412 nm). For the influence of water type on DoP, regardless of the wavelength and wind speed, the lowest max(DoP) values in winter are observed in the waters of gulfs. These waters are characterized by the highest scattering coefficients because of the high inflow of particulate matter with river waters. However, in the summer season, the lowest peak of DoP is observed for spectral bands from 412 nm to 532 nm in coastal waters, and in wavelengths from 555 nm to 676 nm in gulfs. The values of a(λ)/c(λ) for these types of water differ by less than 5% except for the 650 nm and 676 nm spectral bands.

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All the values of maximum DoP of above-water upwelling radiance obtained for each absorption-to-attenuation ratio are collected in Figure 7. The summer season case is depicted in Figure 7a while the winter case is depicted in Figure 7b. The water types are marked with different symbols, and two wind speeds are marked with different colors. The correlations of the max(DoP) to the ratio of a(λ)/c(λ) are approximately linear. However, correlation coefficient analysis has shown that the power functions are better matched. The reason for the nonlinearity of this correlation may be related to the potential obtaining or even exceeding one by the value of DoP for certain combinations of absorption and attenuation coefficients. The trend line for the plot depicted in Figure 7a shows the relationship of the maximum of DoP to the ratio of a(λ)/c(λ) for the summer season and in Figure 7b for the winter season, respectively. The trend lines presented may be described by power functions:

$$\max(DoP) = \mathrm{A}\left(\frac{a(\lambda)}{c(\lambda)}\right)^{\mathrm{B}}, \qquad (3)$$

whose parameters are collected in Table 2. These correlations are obtained for various spectral channels. Hence, they are wavelength-independent for the examined visible spectral range.

Table 2. Parameters of equation (3), which describes the power trend lines in Figures 4 (a) and 4 (b)

Simulation Conditions	A	B	R^2
SZA 45°, wind speed 5 m/s	1.102	0.262	0.973
SZA 45°, wind speed 15 m/s	0.997	0.250	0.996
SZA 75°, wind speed 5 m/s	0.903	0.117	0.906
SZA 75°, wind speed 15 m/s	0.914	0.173	0.990

(a) (b)

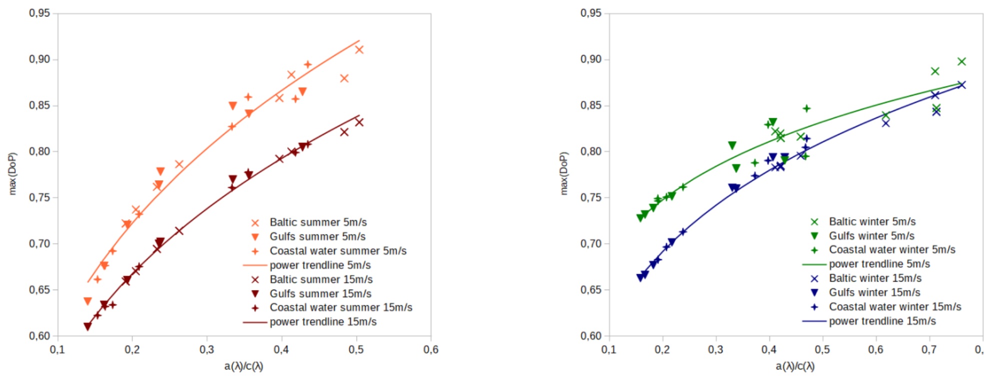

Figure 7. Values of maximum of degree of polarization against absorption to attenuation ratios a(λ)/c(λ) for average values of IOPs presented in Table 1, plotted for (a) the summer season and (b) the winter season.

An analysis of all collected data shows that higher values of maximum DoP are observed for lower wind speed. Moreover, max(DoP) has a higher range of variability in the summer season than in the winter. Figure 7a (summer season) shows that values of max(DoP) are between 0.64 and 0.91 for the wind speed of 5 m/s, and between 0.61 and 0.83 for the wind speed of 15 m/s. However, in Figure 7b (winter season), the values are between 0.73 and 0.9 for the wind speed of 5 m/s, and between 0.66 and 0.87 for the wind speed of 15 m/s. Power trend lines for the same wind speed for summer and winter seasons (in Figures 7a and 7b) intersect. For a wind speed of 5 m/s, by a(λ)/c(λ) equal to 0.26, both power functions reach the same max(DoP) of 0.77. For a wind speed of 15 m/s, by a(λ)/c(λ) equal to 0.32, both power functions reach the same value of 0.75. For lower absorption-to-attenuation ratios, winter DoPs have higher values than summer and for higher a(λ)/c(λ) values, the summer DoPs are higher.

The reason for the correlation of the maximum DoP with the absorption-to-attenuation ratio is the occurrence of multiple scattering in water depth. The degree of polarization tends to decrease after multiple scattering events. A high absorption-to-attenuation ratio means simply low scattering-to-attenuation impact and, hence, shallow penetration of light in the water column and low participation in multiple scattering that decreases the DoP. Such conclusion is in accordance wi th Piskozub

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and Freda (2013), who examined the influence of single scattering albedo on the polarization of water-leaving radiance. Their results show that in the sun reflection plane, the highest value of DoP is observed when the total scattering coefficient is the lowest (see Figure 3 in Piskozub and Freda (2013)).

The influence of wind speed on the DoP values shown in Figures 7a and 7b is very clear: sea surface roughness depolarizes the reflected light. Zhou et al. (2013) demonstrated that wind speed and wind direction can change the polarization patterns of reflected skylight from a rough sea surface to a certain extent. Our study shows, in particular, that high wind speed results in lower values of max(DoP) of the total upwelling radiance. Such regularity is filled for all types of water and all spectral bands.

The results of the correlation of the maximum DoP with the absorption-to-attenuation ratio seem to be coincident with the results of Ibrahim et al., (2012) who studied the degree of linear polarization just below the air-water interface. Their correlation of attenuation-to-absorption ratio with DoLP displays a hyperbolic-like shape (see Figures 5 to 8 in Ibrahim et al. 2012). Therefore, for an inverted ratio of absorption-to-attenuation, it would be near-linear. The modeling results of Ibrahim et al. cannot be compared directly to the results presented in this paper because they received DoLP just below the sea surface, and we focused on DoP just above the surface. However, our choice of seawater absorption-to-attenuation ratio, which can be called the relative absorption value (to total attenuation), as a parameter correlated to degree of polarization seems to be more suitable.

5 Conclusions

In this paper, we have investigated the relationship between the seawater absorption-to-attenuation ratio and the degree of radiance polarization above the rough sea surface. Using a Monte Carlo polarized radiative transfer model, we compared/analyzed simulated polarization patterns in three optically different regions in the southern Baltic (i.e., open Baltic, gulfs, coastal waters), two seasons (defined by their typical solar zenith angles: 45º for summer and 75º for winter), and two wind speeds of 5 m/s and 15 m/s, each for nine visible spectral bands (412 nm, 440 nm, 488 nm, 510 nm, 532 nm, 555 nm, 650 nm, 676 nm, 715 nm). The use of the modeling tool allowed us to exclude unwanted and unpredictable variables (such as weather conditions and aerosol optical thickness) and to conduct undisturbed comparison of the DoPs of combined water-leaving and reflected components of upwelling radiance.

We found that the variability of the maximum of DoP depends more on seasonal than regional changes and can be explained to a large degree by the absorption-to-attenuation ratio. A thorough analysis has shown that there is a strong correlation between max(DoP) and the ratio mentioned previously. The correlation is well described (R^2>0.90) by a power function with factor A close to one and factor B depending more on SZA than on the wind speed. In our study, seasonal variability of the degree of polarization is higher/more significant than regional variability. However, this may be true only in the southern Baltic region due to the characteristically different SZA ranges in the winter and summer seasons.

For the ocean color remote sensing application, only the water-leaving part of the upwelling radiance carries useful information about bio-optical parameters of seawater, although it is a small fraction of the total upwelling radiance. Polarized radiative transfer modeling makes it possible to separate the water-leaving part and, in this case, noise-inducing reflected part and therefore to enhance the quality of information on the seawater optically active components retrieved by above-water sensors – airborne or satellites. Our study is a step toward inclusion of polarization properties in the bio-optical models in the Baltic Sea. However, the conclusions from the research, in our opinion, should be universal and apply also to other water bodies.

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Anonymous Referee #2

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"On the role of seawater absorption to attenuation ratio in the radiance polarizationabove the Southern Baltic surface" by Wlodzimierz Freda, Kamila Haule, and SlawomirSagan

My review refers to the revised manuscript version from February 26, 2019. This version includes changes in response to the very detailed and competent first review. The suggested additional references have been included. However, at some points I would have wished more discussion with their content. Generally, the discussion comes a bit short and the first reviewer listed many reference points worth to discuss, but not mentioned in the new version (e.g. all comments >#32). I suggest adding some moreC1discussion and context of the findings. Specific comments: The used wind speed of 5m/s is plausible; it's approximately the annual global mean and therefore basis of many ocean colour applications, e.g. atmospheric correction of water algorithms. In contrast, a wind speed of 15 m/s (7Bft) is typically considered as high wind, moderate or neargale, and is of less relevance for remote sensing or in situ measurements. In this case, we would have additional depolarization due to enhanced whitecap fraction (e.g. Hu et al., 2008), air bubble entrainment and possibly more sea spray generation. In the coastal regions of interest, we would not expect fully developed wind seas, but considering the large sun zenith angle of 75◦, results based on the Cox-Munk model must be seen very carefully (Mobley, 2015; Hieronymi, 2016). Assuming that the applied Monte Carlo model nevertheless works properly, we will have increased multiple scattering at the sea surface in the winter case with large zenith angle. This can be an important source for depolarization. I find it not helpful to combine the effects of changing IOPs and zenith angle. The main difference in terms of season seems to be the sun zenith angle and not IOPs or ratios. There is also no need to restrict the findings to this particular region (also not in the title). Thus, it is hard to differentiate the individual effects on maximum DoP or polarization pattern.

Hu, Y., Stamnes, K., Vaughan, M., Pelon, J., Weimer, C., Wu, D., ... & Omar, A.(2008). Sea surface wind speed estimation from space-based lidar measurements. Atmospheric Chemistry and Physics, 8(13), 3593-3601.

We are grateful that Reviewer 2 commented on the second version of the article in which we have included a number of corrections suggested by the Reviewer 1.

Reply to the comments contained in the review 2:

1. Assuming, according to Reviewer 1, that the contribution made by section 3.5 of the manuscript “is marginal at best and most of the conclusion are known”, we have removed this part of the article without discussion with comments 32-37. We still think that the discussion of the direction of the highest polarization radiance could be meaningful for rough sea surface. However, it would require considering more SZAs, and that is why we decided to include such discussion in a separate article.
2. The comment regarding additional depolarization at low sun position and strong wind (high waves) is helpful. Our Monte Carlo algorithm does not take into account wave heights, and whitecaps, but only the slope of the wave during transmission/reflection from the surface. We do not take into account the additional depolarization effect and information about this has been added to the article (see red text added at pages: 5, 17 and 21)
3. We agree that the results of our modeling should be universal, independent of the region. However, our IOPs came from measurements made in the Southern Baltic, where the absorption and attenuation values are high in comparison to typical oceanic waters, that is why we decided to keep this information in the title.
4. Separating the impact of IOPs and the angular position of the sun is a good idea. However, we originally wanted to show the seasonal variability of the upwelling polarization radiance above the surface of the Baltic Sea. In the shortest days, the sun reaches, unfortunately, only 12 degrees above the horizon there. We therefore decided there is no sense to use the variability of the sun position for winter IOPs.
5. An additional discussion with the content of the cited articles suggested by reviewer 1 has been added. (See red text at pages 2 and 3)

The text of the article after corrections has been added below.

On the role of the seawater absorption to attenuation ratio in the radiance polarization above the Southern Baltic surface

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Abstract. Information about polarization of light leaving the ocean surface has the potential to improve the quality of the bio-optical parameters retrieval from ocean color remote sensing (OCRS). This improvement can be applied in numerous ways such as limiting of sun glints and obtaining information about atmospheric aerosol properties for atmospheric correction as well as increasing the accuracy of the algorithms based on the water-leaving signal. Polarization signals at the top of the atmosphere (ToA) that include the water-leaving signal are strongly influenced by atmospheric molecular scattering and by direct sun and sky reflections from the sea surface. For these reasons, it is necessary to better understand the factors that change the polarization of light in the atmosphere-ocean system, especially in coastal zones affected by dynamic changes. In this paper, the influence of seasonal variability of light absorption and scattering coefficients (inherent optical properties, IOPs) of seawater, wind speed and solar zenith angle (SZA) on the polarization of upwelling radiance over the sea surface in the visible light bands is discussed. The results come from a polarized radiative transfer model based on the Monte Carlo code and applied to the atmosphere-ocean system using averaged IOPs as input data. The results, presented in the form of polar plots of the total upwelling radiance degree of polarization (DoP), indicate that regardless of the wavelength of light and type of water, the highest value of the above water DoP is strongly correlated with the absorption-to-attenuation ratio. The correlation is a power function that depends on both the SZA and the wind speed. The correlation versatility for different wavelengths of light is very unusual in optics of the sea and is therefore worth emphasizing.

1 Introduction

Satellite ocean color radiometry has been developed for decades to study the interaction of a light field within the visible part of the spectrum (i.e., 400-700 nm) with the different optically significant constituents of sea water. The research has been focusing on information coming from the intensity of water-leaving light - its measurement, retrieval, correlations and interpretation (e.g., Volpe et al., 2012; Zibordi et al., 2013; Sammartino et al., 2015). However, in addition to the light intensity, consideration of light polarization has been demonstrated to improve the accuracy of the information from a variety of remote sensing applications, i.e., in remote radar measurements (Hajnsek et al., 2003; Soloviev et al., 2012; Benassai et al., 2013), and in atmospheric correction algorithms (Chowdhary et al., 2002).

Vector radiative transfer simulations have shown that the polarization of the underwater light field is sensitive to the nature of the suspended marine particles. Ibrahim et al. (2012) and Ibrahim et al. (2016) demonstrated that the attenuation-to-absorption ratio influences the polarization of upwelling radiance below the sea surface. Polarized measurements have also been performed near and above the sea surface. Reduction of sun glints to improve the ocean color retrieval has been studied by He et al. (2014), Zhou et al. (2017) or Shaw and Vollmer (2017) and limitation of sky reflections by observation of sea surface at the Brewster angle from the ship board has been examined by Wood and Cunningham (2001) and by Cunningham et al. (2002). Polarization distribution of skylight reflected off the rough sea surface has been recently examined in many independent studies, e.g. byZhou et al. (2013), Harmel et al. (2012), Mobley (2015), Hieronymi (2016), Foster and Gilerson (2016) and by D'Alimonte and Kajiyama (2016). Zhou et al. (2013) simulated the degree of polarization as well as the angle of polarization (AoP) for reflected parts of upwelling radiance and discussed its variability with SZA for 0°, 30°, 60° and 90°. Moreover, Zhou et al. (2013) showed the influence of wind speed and direction on the polarization pattern of reflected radiance. Harmel et al. (2012) showed that knowledge of the polarization field of the diffuse skylight significantly improves above-water radiometry estimates, in particular in the blue part of the spectrum where the reflected skylight is dominant. Mobley (2015) and Hieronymi (2016) applied polarized radiative transfer in order to show the role of sky polarization in the retrieval of radiance and irradiance reflectance of the windblown sea surface. Likewise D'Alimonte and Kajiyama (2016) discussed joint effect of polarization and the sea-surface statistics on the in situ water-leaving radiance. Foster and Gilerson (2016) provided transfer functions for surface-reflected polarized skylight and upward transmission of light through the sea surface and estimated the sensitivity of polarized components to environmental conditions. Furthermore, polarized radiative transfer simulations have shown the effect of marine suspensions on the polarization of light recorded above the sea surface (see Chami, 2007; Chami et al., 2015;). Further studies have also shown the possibility of knowing the composition of the suspension, i.e., the ratio of mineral to organic suspension, using polarization properties of water-leaving radiance (see Gilerson et al., 2006; Chami, 2007; Tonizzo et al., 2011). The intent of the authors was to show the seasonal variability of polarization of the upwelling radiance above the sea surface.

The most challenging part in the analysis of the signal registered by passive radiometric sensors at the top of the atmosphere is to remove the contribution of the reflected photons at the air-sea interface as well as the contribution of the atmosphere. To assess the water-leaving radiance, $L_w(\lambda)$ on the level of accuracy required to derive accurate estimates of the desired water components, other characteristics and methods that support the advanced atmospheric correction and parameter retrieval have been searched, i.e., the black pixel assumption (Siegel et al., 2000), using near infrared and shortwave infrared bands (Wang et al., 2007), using unpolarized ToA reflectance (Frouin et al., 1994), or using polarized water-leaving radiance (Zhai et al. 2017). The latter showed that, in general, the polarized signal at the ToA is 2-3 times higher than its water-leaving part because of the influence of molecular scattering in the atmosphere. Discussions on the use of remote polarization measurements to determine the aerosol properties that can then be used for atmospheric correction are included in Chowdhary et al. (2002), Mishchenko and Travis (1997) as well as Hasekamp and Landgraf (2005). Harmel and Chami (2013) demonstrated that polarization-based atmospheric correction improves the retrieval of the aerosol properties over open ocean waters. Pust et al. (2011) showed that measurements of the degree of polarization of the sky (made from the ground) can also be helpful in obtaining aerosol parameters. He et al. (2014) proposed to measure the parallel polarization radiance (PPR) instead of radiance intensity at ToA. According to them, such measurements would enhance the OCRS capability. Liu et al. (2017), based on radiative transfer modeling and laboratory measurement, showed that the concentration of particulate matter influences the PPR measured at ToA.

Polarized signal can be measured from the satellite sensors, e.g., POLarization and Directionality of the Earth's Reflectances sensor (POLDER-2), above water using a polarization imaging camera (Freda et al., 2015) or underwater as by Loisel et al. (2008) and Harmel et al. (2008). The measurements are often supported by numerical modeling. Although there are many ongoing numerical radiative transfer models applied to ocean-atmosphere system, only some of them include light polarization (e.g. Schulz et al. 1999; Ota et al. 2010; Piskozub and Freda, 2013; Chami et al. 2015; and Korkin et al. 2017). Kokhanovsky (2010) compared several vector radiative transfer models.

Polarized radiative transfer has been applied for the open ocean-atmospheric system since the 1970s(see for example Kattawar et al.,1973), however its significance in coastal zone remote sensing has been highlighted in the last decade. Chami et al. (2015) applied the polarized radiative transfer to retrieve the polarizing properties of the marine phytoplankton and minerals for different water conditions. Their analysis revealed that the application of the polarization of light in ocean color algorithms might significantly improve the retrieval of hydrosol properties, especially in coastal waters. Piskozub and Freda (2013) applied their polarized radiative transfer model to the Baltic Sea. They examined how scattering properties of seawater represented by a single scattering albedo affected the polarization of water-leaving radiance. They demonstrated the impact of air bubble layers of various concentrations on the degree of polarization of water-leaving light. They also concluded that polarization remote sensing should be performed on a plane tilted approximately 90° from the solar azimuth angle to avoid sun glints. The involvement of polarization in radiative transfer analysis seems to be especially important in coastal areas, knowing that they undergo dynamic changes due to human proximity (Drozdowska et al., 2017), river inflows and the occurrence of pollution, including optically significant oil pollution (Drozdowska et al., 2013). There has been several significant studies performed in coastal zones of New York Harbor (Tonizzo et al. 2009), of Long Island Sound (Harmel et al. 2012) or of selected few places from the East Coast and Gulf of Mexico (Tonizzo et al. 2011). Nevertheless, little attention has been paid to the measurement and modeling of light polarization in some coastal areas and closed water basins like the Baltic Sea characterized by optically complex waters. The Baltic Sea represents a region of a great economic importance, extremely high marine traffic and the impact of inflows from nine different surrounding countries. Inherent optical properties of Baltic seawater and its constituents have been in the spotlight for oceanographers for two decades. In addition to regular measurements of depth profiles of absorption and attenuation coefficients, measurements for different components of seawater have been performed. Colored dissolved organic matter (CDOM) is known to be the primary absorber in the Baltic Sea (Kowalczuk et al., 2010), and its impact on the total absorption coefficient for blue light can reach up to 80% (Kowalczuk et al., 2005). Kowalczuk (1999) and Kowalczuk and Kaczmarek (1996) found that the high absorption of CDOM in spring and low absorption in winter is due to the biological cycle as well as the seasonal variability of the inlet with river water and its mixing. The search for a better correlation of the spectral remote sensing reflectance R_{rs} ratio with the absorption coefficient of CDOM has been intensively searched within the SatBaltic system (Meler et al., 2016a). Measurements of suspended matter IOPs in the Baltic, i.e., particle absorption and particle scattering coefficients, have been compared with biogeochemical characteristics of suspended matter such as concentrations of suspended particulate matter, particulate organic matter, particulate organic carbon and chlorophyll a (Woźniak et al., 2011). Meler et al. (2016b) concluded that absorption properties of non-algal particles undergo larger regional than seasonal variability. In addition to the absorption and attenuation coefficients, the volume scattering functions (VSFs) were also measured in the waters of the Southern Baltic (Freda et al., 2007; Freda and Piskozub, 2007; Freda, 2012). Unique measurements have been performed by the prototype volume scattering meter, characterized by an angular resolution of 0.3º and a range of scattering angles from 0.6º to 177.9º, described by Lee and Lewis (2003). The same instrument has also been used by Chami et al. (2005) in the Black Sea and by Berthon et al. (2007) in the Adriatic Sea. Baltic Sea waters are often affected by small-scale oil pollution (Rudź et al., 2013). The influence of dispersed oil droplets on the absorption coefficient of seawater was researched by Otremba (2007) as well as Haule and Freda (2016), while their influence on scattering properties has been tested by Freda (2014). The consequences of changes in IOPs for remote detection of dispersed oil pollution have been discussed by Otremba et al. (2013), Otremba (2016), and Haule et al. (2017) based on radiative transfer modeling. Knowledge and datasets collected in the Baltic throughout the past two decades helped us to perform a unique study on polarized radiation above the southern Baltic sea surface. This study shows the application of a polarized radiative transfer model in three optically different regions, two seasons and two different sea states. The study highlights the possibilities and consequences of including polarization information in bio-optical models of seawater.

2 Methods

The difficulty of comparison of upwelling radiance DoP over a wind-roughened southern Baltic surface for various seasons is caused by the small number of sunny days in winter and too many variable weather factors that would make it difficult to explain the differences. These undesirable weather factors are different aerosol optical depths, sky overcast, and changing speed and direction of wind relative to the position of the sun. For those reasons, we applied a polarized radiative transfer model based on the Monte Carlo code to describe the effect of seasonal changes on the polarization of upwelling radiance. The simulations involved seasonally averaged measurements of inherent optical properties from the Southern Baltic basin and were run for constant weather conditions. For a detailed description of the inputs and conditions under which the simulation is performed, see the following subsections.

2.1 Polarized radiative transfer model - theoretical background

Numerical simulations were carried out using the Monte Carlo algorithm created by Jacek Piskozub and applied previously in Piskozub and Freda (2013). The algorithm solves the vector radiative transfer equation for the atmosphere-ocean system using the successive orders of scattering method and the Stokes formalism to track the polarization of photons. The algorithm collects information about virtual photons involved statistically in optical processes: reflection at the rough sea surface, refraction at the air-water interface, scattering and absorption within the water body and reaching the ToA. Moreover, the original Monte Carlo algorithm has been modified to track polarization changes of each photon during these processes. The unmodified version of the algorithm was successfully used, with results published in: Piskozub et al. (2001), Stramski and Piskozub (2003), McKee et al. (2008), McKee et al. (2013) or Piskozub and McKee (2013).

Polarization information is described by four elements of the Stokes vector: S = $[I,Q,U,V]^T$, where I is the total radiance of light, Q describes the radiance of linearly polarized light (vertical to horizontal), U describes the radiance of linearly polarized light (diagonal right-skewed to left-skewed), V describes the circular polarization (clockwise to counterclockwise) and T denotes the transposition. Three elements (Q, U and V) of the Stokes vector may be both positive or negative. The single quantity that characterizes these properties is the degree of polarization:

$$DoP = \frac{\sqrt{\mathrm{Q}^2+\mathrm{U}^2+\mathrm{V}^2}}{\mathrm{I}}, \quad (1)$$

The defined degree of polarization is often replaced by the degree of linear polarization, DoLP.

$$DoLP = \frac{\sqrt{\mathrm{Q}^2+\mathrm{U}^2}}{\mathrm{I}}, \quad (2)$$

The latter hardly differs from DoP because circular polarization is relatively rare in nature (Cronin and Marshall, 2011). The circular polarization represented by the V element of the Stokes vector does not appear in seawater as a result of scattering, see off-diagonal Mueller matrix elements in (Voss and Fry, 1984). It is measurable in light internally reflected from the underside of the sea's surface (Ivanoff and Watermann 1958).

Our polarized radiative transfer model involves a virtual light source to send randomly polarized photons and track their pathways in the means of the probability of occurrence of the processes mentioned above. Reflection and refraction processes are described by Fresnel equations, and the slopes of the sea surface are characterized by the wind-dependent distribution of Cox and Munk (1956). The algorithm does not take into account additional depolarization due to enhanced whitecap fraction, described by Hu et al. (2008), - that is likely for high wind speed. The probability of processes within the water body is determined by the corresponding coefficients of absorption and scattering (including multiple scattering). Angular distribution of scattered photons is described by phase functions that, for both atmosphere and sea depth, are characterized separately for molecular scattering and particle scattering. Polarization properties of particle scattering are described by Müeller matrices that for sea water are taken from Voss and Fry (1984) and for atmospheric aerosol particles from Volten et al. (2001). The model outputs the angular distribution of the upwelling radiance and its degree of polarization at any desired level, that are presented in form of polar plots. Some of the results are additionally specified in the principal plane.

2.2 Polarized radiative transfer model - input parameters

This section reports the input parameters used in the computations. The data set of the absorption and attenuation coefficients of seawater constituents come from *in situ* measurements in the southern Baltic contained in Sagan (2008). It is the largest dataset of ac-9 (WET Labs, Inc.) measurements in the southern Baltic that was published in a tabular form of average values, extreme values and standard deviations. The instrument was calibrated in ultrapure water and routinely checked for stability with air readings. The standard recommended data processing was performed (Zaneveld et al., 1994). Absolute precision of measurement is 0.005 m^{-1}, while relative precision is estimated from 4% in clear waters to 12% in the areas of turbid waters. The data have been recorded during cyclical cruises aboard R/V Oceania in 1999 and 2003 to 2005. Measurements were made in different months of the year. The data set was divided into two seasons, called here 'winter', for the months from November to March and 'summer', the months from April to October. The summer season is characterized by strong phytoplankton growth and the winter season by low biological activity. In addition, Sagan (2008) distinguished three regions: open Baltic, gulfs (Gulf of Gdańsk and Pomeranian Gulf) and coastal waters. The measuring stations, divided into these three types of water, are shown in Figure 1. For defined regions – open Baltic and coastal areas – those two data sets are statistically significantly different for all optical parameters (t test for means) at the level $p<0.05$ by Sagan (2008).
Total absorption coefficient taken to the simulation is a sum $a_t = a_{pg} + a_w$, where a_{pg} is an average absorption coefficient (particle and dissolved fraction) of the N number of measured depth profiles (see Table 1) made with the ac-9 after Sagan (2008), and a_w is the pure water absorption coefficient and comes from Pope and Fry (1997). Similarly, the total attenuation coefficient is defined as $c_t = c_{pg} + a_w + b_w$, where the component c_{pg} comes directly from Sagan (2008), but to get the total attenuation coefficient, it was enlarged by clean water components of absorption a_w and scattering b_w (Smith and Baker, 1981). According to Sagan (2008), the highest values of IOPs and their highest variability are observed for the water of gulfs and estuaries of rivers that are located nearby. The simulations are carried out at nine wavelengths, namely, 412 nm, 440 nm, 488 nm, 510 nm, 532 nm, 555 nm, 650 nm, 676 nm and 715 nm, which correspond to the ac-9 and are commonly dedicated to ocean color analysis.
Solar zenith angles in the southern Baltic region depend strongly on the season. In months described by Sagan (2008) as the summer season, the highest sun position over the horizon, that means the minimum of SZA during sun culmination, varies between 31º in June (the longest day of the year) and 69º at the end of October. In the modeling, a single value of 45º was chosen as a summer SZA. For months of the winter season, the minimum of SZA varies between 50º in the end of March and 78º in December (the shortest day). Given values are reached at approximately noon and are higher in the rest of the days. That is why SZA of 75º is chosen as a representative for the winter season. Computations are performed for the direction of wind twisted by 45º from the sun reflection plane, chosen arbitrarily. Two wind speeds of 5 m/s and 15 m/s are considered. Aerosol Optical Thickness of 0.12 independent of the wavelength and the same for both seasons was applied to all simulations. This allowed us to observe DoP variations and correlations that were not affected by aerosol changes.

Here and in the following figures, the celestial hemisphere and its reflection patterns are represented in a two-dimensional coordinate system. The zenith and the nadir are at the origin and the horizon is represented by the outermost circle. The zenith angle and azimuth angle are measured radially and tangentially, respectively. The solar azimuth angle is always set to 0.

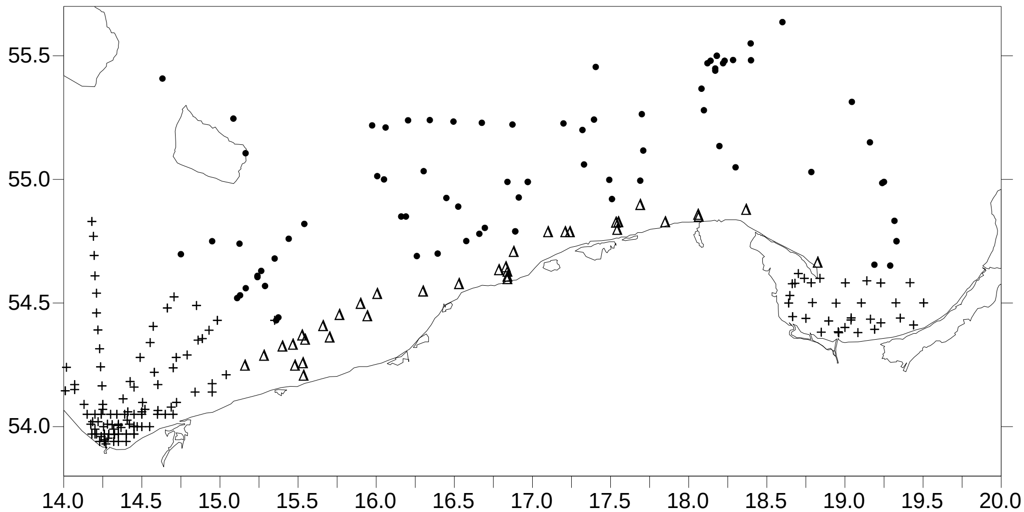


Figure 1. The area of the southern Baltic Sea, on which the positions of measurement stations are marked, divided into three areas: Pomeranian Gulf and Gulf of Gdańsk (+), coastal water (Δ) and open Baltic water (•).

Table 1. Average values of total absorption coefficients, total attenuation coefficients, their standard deviations and their ratios. All values measured by Sagan (2008) in southern Baltic in 1999 and 2003 to 2005 are averaged for depths 0 to 5 meters and then averaged for N measuring stations

Summer Season															
λ	Baltic, N=930					Gulfs, N = 1428					Coastal Waters, N = 132				
[nm]	$a(\lambda)$	σ_a	$c(\lambda)$	σ_c	$\frac{a(\lambda)}{c(\lambda)}$	$a(\lambda)$	σ_a	$c(\lambda)$	σ_c	$\frac{a(\lambda)}{c(\lambda)}$	$a(\lambda)$	σ_a	$c(\lambda)$	σ_c	$\frac{a(\lambda)}{c(\lambda)}$
412	0.595	0.12	1.230	0.40	0.483	1.095	0.65	2.560	1.64	0.428	0.615	0.12	1.470	0.52	0.418
440	0.396	0.10	0.999	0.37	0.396	0.786	0.52	2.209	1.48	0.356	0.416	0.10	1.249	0.52	0.333
488	0.214	0.07	0.817	0.34	0.262	0.444	0.32	1.887	1.35	0.236	0.214	0.06	1.027	0.46	0.209
510	0.183	0.05	0.785	0.33	0.233	0.353	0.23	1.825	1.31	0.193	0.173	0.04	0.995	0.46	0.173
532	0.155	0.04	0.756	0.32	0.205	0.285	0.18	1.756	1.28	0.162	0.155	0.03	0.946	0.44	0.163
555	0.140	0.03	0.731	0.31	0.192	0.240	0.13	1.711	1.26	0.140	0.140	0.03	0.911	0.42	0.153
650	0.380	0.02	0.921	0.29	0.413	0.430	0.08	1.811	1.20	0.237	0.380	0.02	1.071	0.38	0.355
676	0.518	0.05	1.029	0.28	0.503	0.638	0.19	1.909	1.18	0.334	0.508	0.03	1.169	0.38	0.435
Winter Season															
λ	Baltic, N = 234					Gulfs, N = 540					Coastal Waters, N = 36				
[nm]	$a(\lambda)$	σ_a	$c(\lambda)$	σ_c	$\frac{a(\lambda)}{c(\lambda)}$	$a(\lambda)$	σ_a	$c(\lambda)$	σ_c	$\frac{a(\lambda)}{c(\lambda)}$	$a(\lambda)$	σ_a	$c(\lambda)$	σ_c	$\frac{a(\lambda)}{c(\lambda)}$
412	0.485	0.03	0.680	0.015	0.713	0.755	0.31	1.760	1.04	0.429	0.585	0.14	1.250	0.68	0.468
440	0.296	0.02	0.479	0.015	0.618	0.496	0.22	1.469	0.95	0.338	0.376	0.10	1.009	0.63	0.373
488	0.154	0.02	0.337	0.015	0.459	0.264	0.13	1.217	0.86	0.217	0.194	0.06	0.817	0.57	0.238
510	0.133	0.02	0.315	0.014	0.421	0.213	0.10	1.165	0.83	0.182	0.163	0.05	0.785	0.55	0.207
532	0.125	0.02	0.296	0.013	0.421	0.185	0.08	1.106	0.81	0.167	0.145	0.04	0.756	0.54	0.191
555	0.120	0.01	0.291	0.013	0.411	0.170	0.06	1.071	0.79	0.158	0.140	0.03	0.731	0.52	0.191
650	0.370	0.01	0.521	0.012	0.711	0.400	0.04	1.211	0.73	0.330	0.370	0.01	0.931	0.46	0.398
676	0.478	0.02	0.629	0.012	0.760	0.528	0.08	1.299	0.72	0.407	0.488	0.02	1.039	0.45	0.470

3 Results and discussion

3.1 Extreme values of the degree of polarization

Examples of simulation results are presented in Figures 2a and 2b in the form of polar plots of the degree of polarization of upwelling radiance just above the sea surface. Figure 2a shows the DoP for the average IOPs measured in the open waters of the Baltic Sea for a wavelength of 412 nm in the summer season, while Figure 2b depicts an analogous case for the winter season. These two plots are characterized by one of the highest values of the peak of DoP of 0.88 for summer and 0.84 for winter. The azimuth position of the sun is 0º in all cases. Corresponding values of computed upwelling radiance I (in units of $Wm^{-2}sr^{-1}nm^{-1}$) are shown on the plots of Figures 2c and 2d on the logarithmic scale (due to their high angular variability).

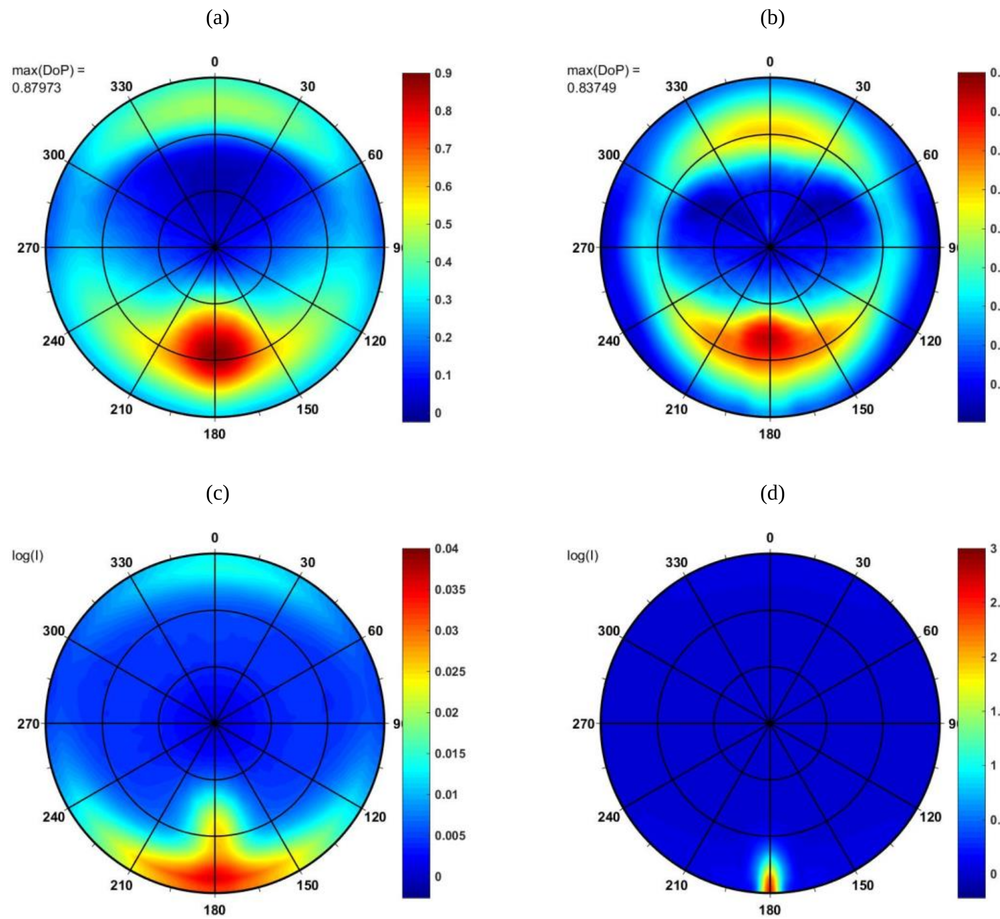


Figure 2. Simulation results of above-water upwelling radiance for average IOPs of open waters of the southern Baltic, wavelength 412 nm, for speed of wind of 5 m/s: a) DoP in the summer season, SZA 45°, b) DoP in the winter season, SZA 75°, c) decimal logarithm of upwelling radiance in the summer season, SZA 45°, d) decimal logarithm of upwelling radiance in the winter season, SZA 75°. Concentric circles inside mean zenith angles 30° and 60° respectively.

The small SZA of the summer season (45º) resulted in low values of upwelling radiance that are stretched from the direct reflection point to the horizon, where it is extended both left and right from the azimuth of 180º. The high SZA of the winter season (75º) resulted in much higher values of reflected light, which are also stretched from reflection point to the horizon. Examples of the lowest values of the maximum DoP, referred to as max(DoP), are shown in Figures 3a and 3b. They were obtained for the regions of Gulf of Gdańsk and Pomeranian Gulf, simulated for the spectral band of 555 nm, for the summer season (Figure 3a) and for the winter season (Figure 3b).

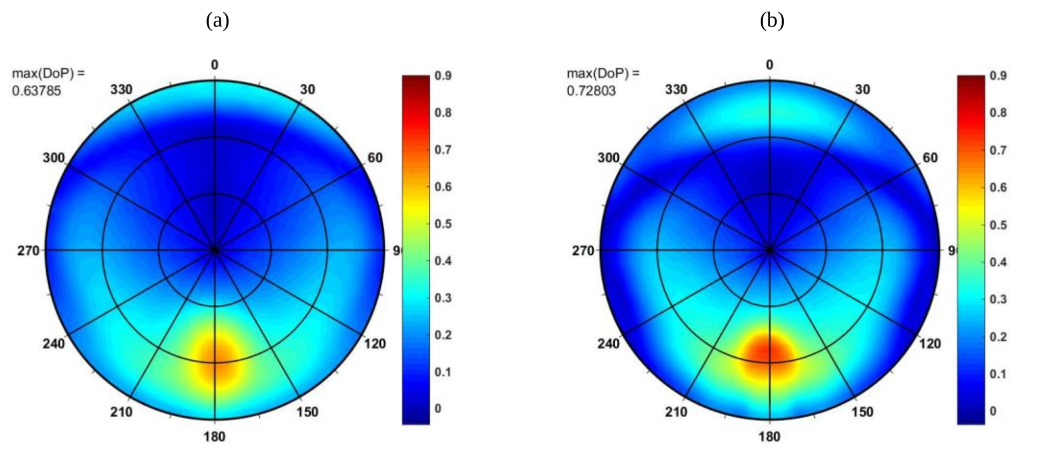


Figure 3. Simulation results of above-water upwelling radiance for average IOPs of gulf waters of the southern Baltic, wavelength 555 nm, for speed of wind of 5 m/s: a) DoP in the summer season, SZA 45°, b) DoP in the winter season, SZA 75°. Concentric circles inside mean zenith angles 30° and 60° respectively.

The maximum values of DoP presented in Figure 2a (summer season, open Baltic waters) are visible for azimuth angles close to 180º (direction of reflected sun) and a zenith angle of approximately 55º although the solar zenith angle is 45º, while the max(DoP) in Figure 3a (summer season, waters of gulfs) is visible for zenith angle of approximately 60º. In contrast to the summer season case, the maximum DoPs in the winter season are close to the zenith angle of 48º (Figure 2b) and 54º (Figure 3b), while SZA is 75º. The lower position of the sun results in a higher position of the maximum DoP of upwelling radiation than its reflection angle, and a higher position of the sun results in a lower position of the maximum DoP. Another interesting effect is the higher DoP observed for directions close to the incident rays of the sun (azimuth 0º). In general, in the winter season, the values of DoP are higher than in summer, and zenith angles of this effect are lower in the winter than in the summer season.

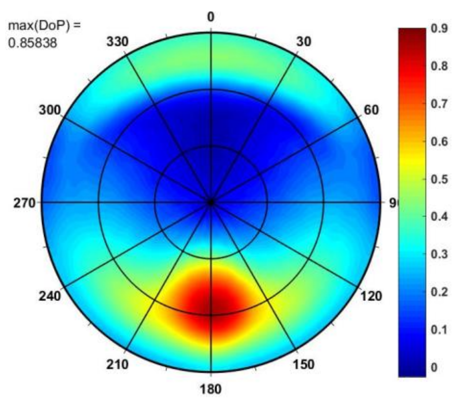
3.2 Spectral variability of the degree of polarization

The results of Monte Carlo simulations of angular characteristics of DoP of upwelling radiance are presented in Figure 4. These results are obtained for average IOPs of open Baltic waters for wind speed of 5 m/s for three wavelengths (440 nm, 555 nm, 650 nm) and for both seasons. Vertical cross-sections of such polar plots for the same type of water (open Baltic Sea) but additionally for all examined wavelengths and for two speeds of wind, 5 m/s and 15 m/s, are presented in Figure 5. Such cross-sections show the DoP in the principal plane, including the direction of incident sun beam (on the left side of the plot), zenith and direction of sun reflection beam for calm sea surface (on the right side). The azimuth direction of the sun position, described as 0° in the polar plots, is marked by negative zenith angles in Figure 5, while azimuth directions of 180° that include the sun reflection beam are marked by positive zenith angles.

summer season

(a)

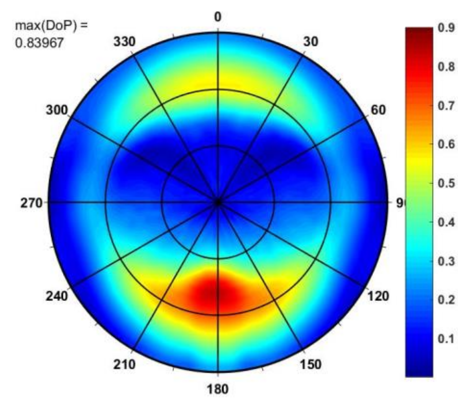
440 nm



winter season

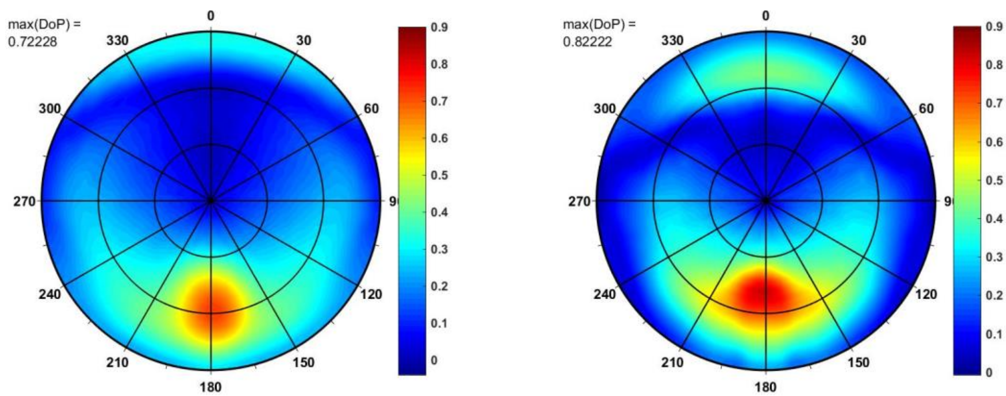
(b)

440 nm



(c) (d)

555 nm 555 nm



(e) (f)

650 nm 650 nm

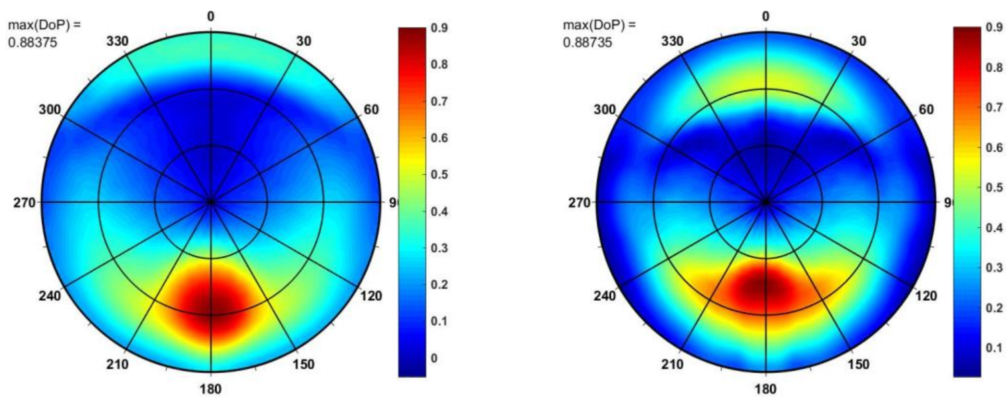


Figure 4. Simulation results of above-water upwelling radiance for average IOPs of open Baltic Sea water, for speed of wind of 5 m/s: a) DoP in the summer season, λ=440 nm, SZA 45°, b) DoP in the winter season, λ=440 nm, SZA 75°, c) DoP in the summer season, λ=555 nm, SZA 45°, d) DoP in the winter season, λ=555 nm, SZA 75°, e) DoP in the summer season, λ=650 nm, SZA 45°, f) DoP in the winter season, λ=650 nm, SZA 75°. Concentric circles inside mean zenith angles 30° and 60° respectively.

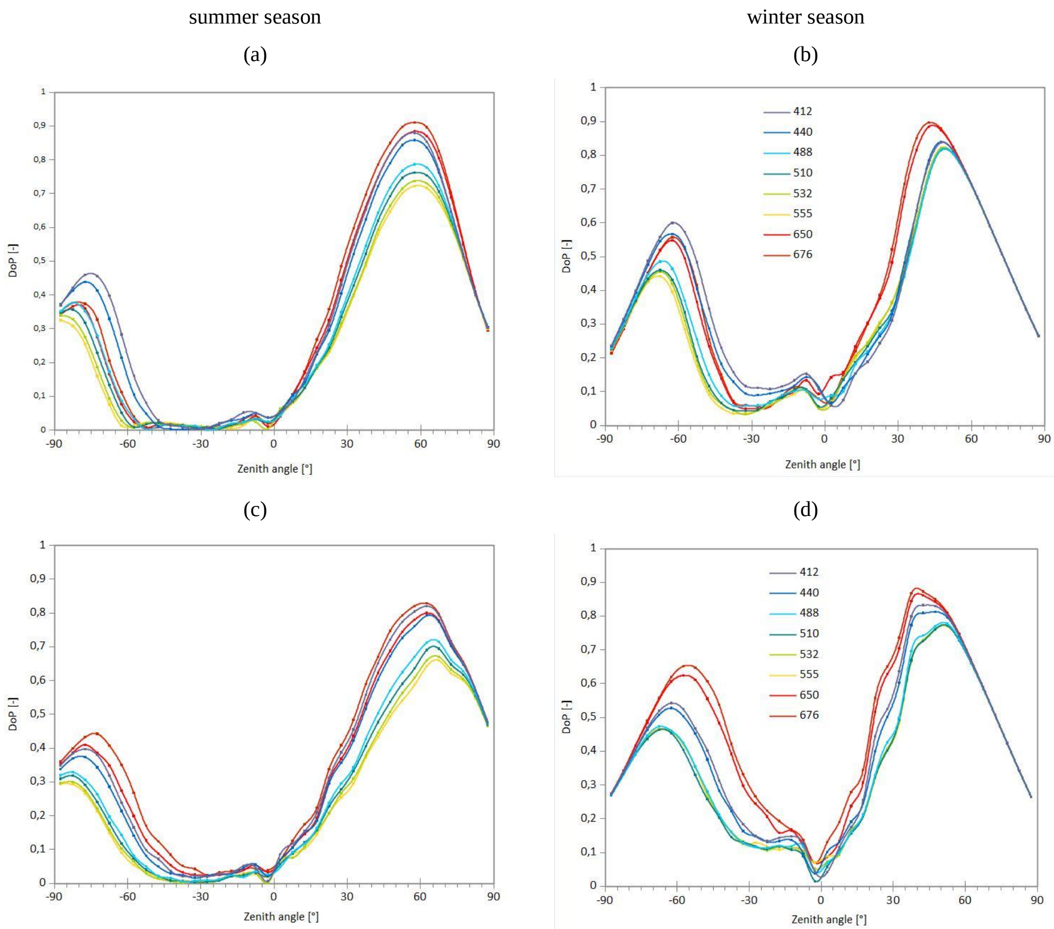


Figure 5. Degree of polarization plotted for the principal plane, e.g., plane containing both incident ray of the sun and zenith direction (cross section through polar plots for azimuths 0° and 180°). Azimuth 0° - azimuth of sun position is marked by negative zenith angles, while azimuth 180° - that contains sun reflection is marked by positive zenith angles. Simulation results for open Baltic Sea water: a) summer season, SZA 45°, wind speed 5 m/s, b) winter season, SZA 75°, wind speed 5 m/s, c) summer season, SZA 45°, wind speed 15 m/s, d) winter season, SZA 75°, wind speed 15 m/s.

The analysis of individual spectral bands shows that high values of DoP correspond to the high absorption-to-attenuation ratio for the total of visible light domain (see Table 1). High values of absorption coefficient for 650-676 nm wavelengths (in the red spectral region) are caused by pure water (see Pope and Fry, 1997) while high absorption coefficients for wavelengths of the blue-green range are caused mainly by CDOM (Kowalczuk et al., 2005). The lowest values of max(DoP) for each type of water and for each season are observed for the 555 nm spectral band. The lowest values of absorption and weak spectral variability of the scattering coefficient implies that the wavelength of 555 nm is characterized by the lowest absorption-to-attenuation ratios due to the existence of a minimum of absorption for seawater containing phytoplankton. Algae cells, depending on the composition of their pigments, may have a minimum of absorption in a wide range of spectral bands from 550 nm to 660 nm (Bricaud et al., 2004). Considering the absorption of pure water that is increasing with wavelength (Pope and Fry, 1997), the minimum of the absorption in Baltic waters for the spectral band of 555 nm results.

The spectral shape of the DoP cross-sections contains two maxima, and their angular positions depend on the absorption-to-attenuation ratio, the season and the wind speed. The angular position of the higher maximum depends mostly on the season, varying from approximately 60º in the summer to 35º-50º in the winter (see Figure 5). The lower maximum we observe at the zenith angles between -70º and -90º in the summer as well as between -55º and -70º in the winter. Higher wind speed of 15 m/s, in comparison to 5 m/s, causes the irregular shape of peaks. Moreover, the higher wind speed causes an increase of the DoP value for a lower maximum in the 650 nm and 676 nm spectral bands and its shift to a higher position (toward the zenith). At the same time, the DoP values for shorter wavelength bands are decreased and shifted to a lower position (toward horizon).

3.3 Regional variability of the degree of polarization

Computations of DoP were carried out in three optically different regions of the southern Baltic. Such a division is justified in previous studies of optical and hydrological properties of the south Baltic waters (Olszewski et al., 1992). They showed a relationship between the measured values of IOPs and their location in relation to river estuaries, distance from the shore or bathymetry of the bottom.

Comparison of water type influence on the DoP is shown in Figure 6 for two wavelengths, 440 nm (Figure 6a) and 555 nm (Figure 6b). The type of water has less influence on the DoP than the season and its representative SZA.

(a) (b)

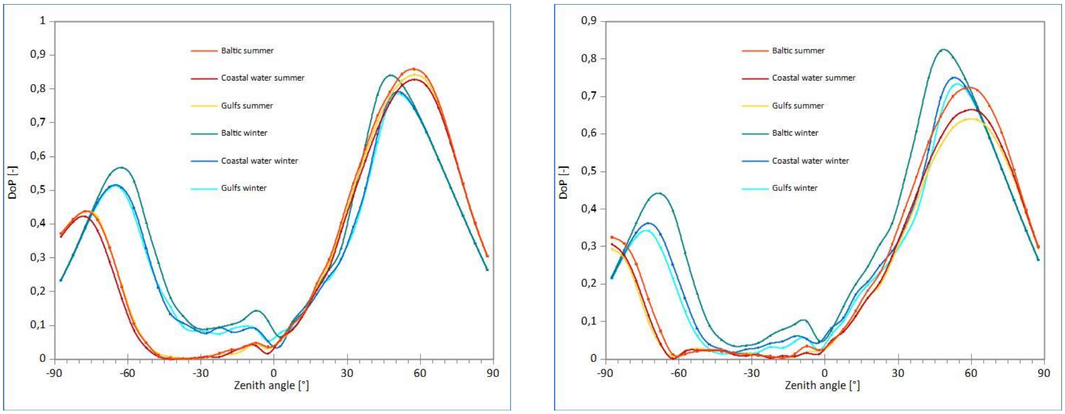


Figure 6. Degree of polarization plotted for the principal plane, i.e., plane containing both incident ray of the sun and zenith direction (cross-section through polar plots for azimuths 0° and 180°). Azimuth 0° is marked by negative zenith angles. Simulation results for wind speed of 5 m/s for all types of water and two seasons: a) 440 nm, and b) 555 nm.

However, the highest values of DoP for most zenith angles and the highest values of its peak max(DoP) for each season are observed for open Baltic Sea water. Coastal waters and gulfs are characterized by similar values of DoP in each season. For the wavelength of 440 nm, in the summer, the differences of max(DoP) between the open Baltic and other regions reach 0.02-0.04, while in the winter those differences exceed 0.05. For the 555 nm band, in the summer the differences of max(DoP) between the open Baltic and other regions reach 0.06-0.09 and in the winter these differences reach 0.07-0.09, respectively. We also observed another regional difference in the angular position of the maxima of DoP that is noticeable in the winter season only. Two maxima of the DoP cross-sections are closer for open Baltic waters than for gulfs and coastal waters.

In the following section, we explain that the degree of polarization depends on the absorption-to-attenuation ratio, and all its regional changes are the result of the absorption-to-attenuation ratio variability.

The results of our simulations are in qualitative agreement with the measurements of above water DoLP of the total upwelling radiance presented by Freda et al. (2015). This agreement is the similarity of the peak of degree of polarization on the polar plots, which are stretched along the azimuth angles. Freda et al. (2015) obtained lower values of measured DoLP with a maximum of 30-40% (see Figures 1 and 2 in (Freda et al., 2015)), which is presumably caused by different weather conditions and unknown environmental parameters during measurements, such as a high absorption coefficient in the waters of the river mouth, different aerosol optical depth, or other parameters. However, despite the differences in the maximum degree of polarization, the angular distribution patterns are similar, with the peak in the vicinity of the sun reflection azimuth angle.

3.4 DoP dependence on the absorption-to-attenuation ratio

This section contains the comparison of the degree of polarization for summer and winter seasons as a function of the absorption-to-attenuation ratio.

The total a(λ)/c(λ) ratio (see Table 1) is higher in the open Baltic water than in other regions because of the low scattering coefficients (Sagan, 2008). The value of the latter is determined mainly by the concentration of suspended matter, which in open waters is significantly lower than in gulfs or coastal/near-shore waters. According to Sagan (2008), the average particle scattering coefficient does not depend strongly on wavelengths, and in open Baltic waters in the winter season it varies between 0.15 (for 676 nm) and 0.19 (for 412 nm). In the same season, but in the waters of gulfs, the average particle scattering coefficient varies between 0.77 (for 676 nm) and 1.00 (for 412 nm). For the influence of water type on DoP, regardless of the wavelength and wind speed, the lowest max(DoP) values in winter are observed in the waters of gulfs. These waters are characterized by the highest scattering coefficients because of the high inflow of particulate matter with river waters. However, in the summer season, the lowest peak of DoP is observed for spectral bands from 412 nm to 532 nm in coastal waters, and in wavelengths from 555 nm to 676 nm in gulfs. The values of a(λ)/c(λ) for these types of water differ by less than 5% except for the 650 nm and 676 nm spectral bands.

All the values of maximum DoP of above-water upwelling radiance obtained for each absorption-to-attenuation ratio are collected in Figure 7. The summer season case is depicted in Figure 7a while the winter case is depicted in Figure 7b. The water types are marked with different symbols, and two wind speeds are marked with different colors. The correlations of the max(DoP) to the ratio of a(λ)/c(λ) are approximately linear. However, correlation coefficient analysis has shown that the power functions are better matched. The reason for the nonlinearity of this correlation may be related to the potential obtaining or even exceeding one by the value of DoP for certain combinations of absorption and attenuation coefficients. The trend line for the plot depicted in Figure 7a shows the relationship of the maximum of DoP to the ratio of a(λ)/c(λ) for the summer season and in Figure 7b for the winter season, respectively. The trend lines presented may be described by power functions:

$$\max(DoP) = \mathrm{A}\left(\frac{a(\lambda)}{c(\lambda)}\right)^{\mathrm{B}}, \qquad (3)$$

whose parameters are collected in Table 2. These correlations are obtained for various spectral channels. Hence, they are wavelength-independent for the examined visible spectral range.

Table 2. Parameters of equation (3), which describes the power trend lines in Figures 4 (a) and 4 (b)

Simulation Conditions	A	B	R^2
SZA 45°, wind speed 5 m/s	1.102	0.262	0.973
SZA 45°, wind speed 15 m/s	0.997	0.250	0.996
SZA 75°, wind speed 5 m/s	0.903	0.117	0.906
SZA 75°, wind speed 15 m/s	0.914	0.173	0.990

(a) (b)

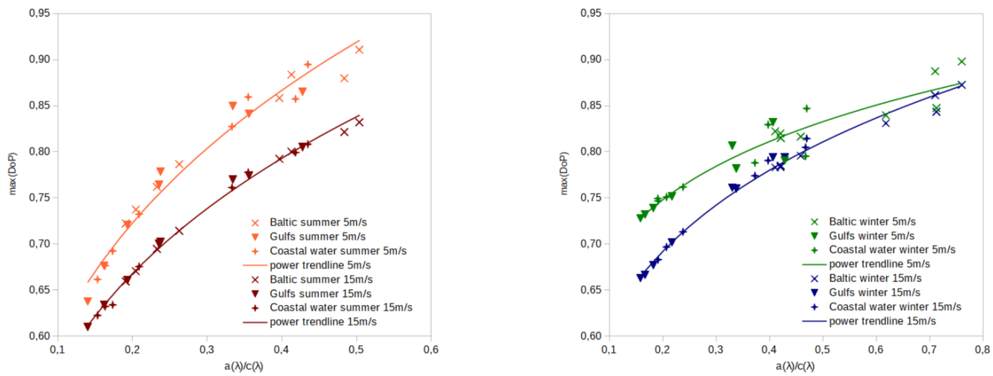


Figure 7. Values of maximum of degree of polarization against absorption to attenuation ratios a(λ)/c(λ) for average values of IOPs presented in Table 1, plotted for (a) the summer season and (b) the winter season.

An analysis of all collected data shows that higher values of maximum DoP are observed for lower wind speed. Moreover, max(DoP) has a higher range of variability in the summer season than in the winter. Figure 7a (summer season) shows that values of max(DoP) are between 0.64 and 0.91 for the wind speed of 5 m/s, and between 0.61 and 0.83 for the wind speed of 15 m/s. However, in Figure 7b (winter season), the values are between 0.73 and 0.9 for the wind speed of 5 m/s, and between 0.66 and 0.87 for the wind speed of 15 m/s. Power trend lines for the same wind speed for summer and winter seasons (in Figures 7a and 7b) intersect. For a wind speed of 5 m/s, by a(λ)/c(λ) equal to 0.26, both power functions reach the same max(DoP) of 0.77. For a wind speed of 15 m/s, by a(λ)/c(λ) equal to 0.32, both power functions reach the same value of 0.75. For lower absorption-to-attenuation ratios, winter DoPs have higher values than summer and for higher a(λ)/c(λ) values, the summer DoPs are higher.

The reason for the correlation of the maximum DoP with the absorption-to-attenuation ratio is the occurrence of multiple scattering in water depth. The degree of polarization tends to decrease after multiple scattering events. A high absorption-to-attenuation ratio means simply low scattering-to-attenuation impact and, hence, shallow penetration of light in the water column and low participation in multiple scattering that decreases the DoP. Such conclusion is in accordance with Piskozub and Freda (2013), who examined the influence of single scattering albedo on the polarization of water-leaving radiance. Their results show that in the sun reflection plane, the highest value of DoP is observed when the total scattering coefficient is the lowest (see Figure 3 in Piskozub and Freda (2013)).

The influence of wind speed on the DoP values shown in Figures 7a and 7b is very clear: sea surface roughness depolarizes the reflected light. Zhou et al. (2013) demonstrated that wind speed and wind direction can change the polarization patterns of reflected skylight from a rough sea surface to a certain extent. Our study shows, in particular, that high wind speed results in lower values of max(DoP) of the total upwelling radiance. Such regularity is filled for all types of water and all spectral bands.

Our algorithm does not consider possible additional depolarization, which is likely especially for high wind speeds (15m/s). This can be caused by whitecaps (Hu et al. 2008), air bubble entrainment and possibly more sea spray generation. Moreover, additional factors that may decrease the DoP value for high SZA (winter season) are wave-shadowing effects of incident and multiple reflected rays (see Hieronymi, 2016), that are not considered in this paper.

The results of the correlation of the maximum DoP with the absorption-to-attenuation ratio seem to be coincident with the results of Ibrahim et al. (2012) who studied the degree of linear polarization just below the air-water interface. Their correlation of attenuation-to-absorption ratio with DoLP displays a hyperbolic-like shape (see Figures 5 to 8 in Ibrahim et al., 2012). Therefore, for an inverted ratio of absorption-to-attenuation, it would be near-linear. The modeling results of Ibrahim et al. cannot be compared directly to the results presented in this paper because they received DoLP just below the sea surface, and we focused on DoP just above the surface. However, our choice of seawater absorption-to-attenuation ratio, which can be called the relative absorption value (to total attenuation), as a parameter correlated to degree of polarization seems to be more suitable.

5 Conclusions

In this paper, we have investigated the relationship between the seawater absorption-to-attenuation ratio and the degree of radiance polarization above the rough sea surface. Using a Monte Carlo polarized radiative transfer model, we compared simulated polarization patterns in three optically different regions in the southern Baltic (i.e., open Baltic, gulfs, coastal waters), two seasons (defined by their typical solar zenith angles: 45º for summer and 75º for winter), and two wind speeds of 5 m/s and 15 m/s, each for nine visible spectral bands (412 nm, 440 nm, 488 nm, 510 nm, 532 nm, 555 nm, 650 nm, 676 nm, 715 nm). The use of the modeling tool allowed us to exclude unwanted and unpredictable variables (such as weather conditions and aerosol optical thickness) and to conduct undisturbed comparison of the DoPs of combined water-leaving and reflected components of upwelling radiance.

We found that the variability of the maximum of DoP depends more on seasonal than regional changes and can be explained to a large degree by the absorption-to-attenuation ratio. A thorough analysis has shown that there is a strong correlation between max(DoP) and the ratio mentioned previously. The correlation is well described (R^2>0.90) by a power function with factor A close to one and factor B depending more on SZA than on the wind speed. In our study, seasonal variability of the degree of polarization is higher/more significant than regional variability. However, this may be true only in the southern Baltic region due to the characteristically different SZA ranges in the winter and summer seasons.

For the ocean color remote sensing application, only the water-leaving part of the upwelling radiance carries useful information about bio-optical parameters of seawater, although it is a small fraction of the total upwelling radiance. Polarized radiative transfer modeling makes it possible to separate the water-leaving part and, in this case, noise-inducing reflected part and therefore to enhance the quality of information on the seawater optically active components retrieved by above-water sensors – airborne or satellites. Our study is a step toward inclusion of polarization properties in the bio-optical models in the Baltic Sea. However, the conclusions from the research, in our opinion, should be universal and apply also to other water bodies.

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