Introductory guidance to atmospheric correction for use over coastal and inland waters

The signal measured by a satellite sensor is the sum of the three components (Fig. 1): 1/ Contribution from the atmosphere (including the scattering of sunlight by air molecules (Rayleigh scattering), aerosols, and the coupling between air molecules and aerosols); 2/ Contribution from the air-water interface (from foams and the reflection of the Sun and skylight on the water's surface); 3/ Contribution of the water body. The purpose of the atmospheric correction process is to remove the contribution of the atmosphere to the signal measured by the remote sensor, leading to the estimation of the radiance emanating from a water body (i.e., inland, coastal, or open ocean environment).The output of the atmospheric correction processing is the remote sensing reflectance, i.e. the ratio of the water-leaving radiance over downwelling plane irradiance. This signal can then be used to derive water bio-optical properties (e.g., total absorption and backscattering coefficients), biogeochemical variables (e.g., chlorophyll-*a*, sediments, and dissolved organic carbon concentration), as well as measures of transparency (see the introductory and advanced user's guides on bio-optical algorithms. Thus, the accuracy of the atmospheric correction step directly impacts the accuracy of any subsequent data processing steps. Some contributions (from air molecules, foams, reflection of the Sun and sky, atmospheric gases attenuation) can be estimated using ancillary data and viewing geometry (Mobley et al., 2016).

This document provides an introductory overview of atmospheric correction over coastal and inland waters. More in-depth guidance on advantages and limitations of each algorithm's type, intended for a more experienced audience, can be found in our companion document. Other issues that occur over coastal and inland waters are addressed in the same document: 1/ absorbing aerosols and trace gases (urban pollution, dust) and 2/ adjacency effects.

Over open ocean waters, the contribution of the ocean to the total signal can be considered negligible (black pixel assumption) in the near-infrared (NIR) bands so the total signal is equal to the contribution of the atmosphere. Using the NIR bands allows aerosol models and optical properties to be estimated; these can in turn be used to estimate the atmospheric contribution to the measured signal in the visible bands. Once the contribution of the atmosphere is known, the estimation of the signal from the ocean is straightforward.

The black pixel assumption is not valid in more optically-complex waters (coastal and inland waters), where backscattering from suspended particles or from the seabed in shallow waters contributes to non-zero water reflectance in the red and NIR wavelengths (IOCCG, 2010). To overcome this challenge, many atmospheric correction algorithms were developed for ocean color remote sensors (SeaWiFS, MODIS-Aqua, MERIS, VIIRS, OLCI/S3/A/B) and high-spatial resolution sensors (OLI/L8 and MSI/S2A/B).

They can be grouped into seven different categories:

(1) assumption of homogeneity of atmospheric and oceanic properties over a region of interest (De Keukelaere et al., 2018; Hu et al., 2000; Ruddick et al., 2000, 2006; Sterckx et al., 2015; Vanhellemont and Ruddick, 2021; Wang et al., 2021)

(2) use of the shortwave infrared bands (Chen et al., 2014; He and Chen, 2014; Wang and Shi, 2005; Wang and Shi, 2007; Wang, 2007; Shi and Wang, 2009)

(3) use of blue or ultra-violet bands (Oo et al., 2008; He et al., 2012; Wang and Jiang, 2018)

(4) correction or modeling of the non/negligible signal from the ocean in the NIR (Moore et al., 1999; Siegel et al., 2000; Stumpf et al., 2003; Lavender et al., 2005; Bailey et al., 2010)

(5) coupled ocean/atmosphere inversion based on artificial neural networks (Doerffer and Schiller, 2007; Schroeder et al., 2007; Fan et al., 2017) or optimization techniques (Brajard et al., 2006, 2012; Chomko and Gordon, 1998, 2001; Jamet et al., 2004; Kuchinke et al., 2009; Stamnes et al., 2003; Steinmetz et al., 2011)

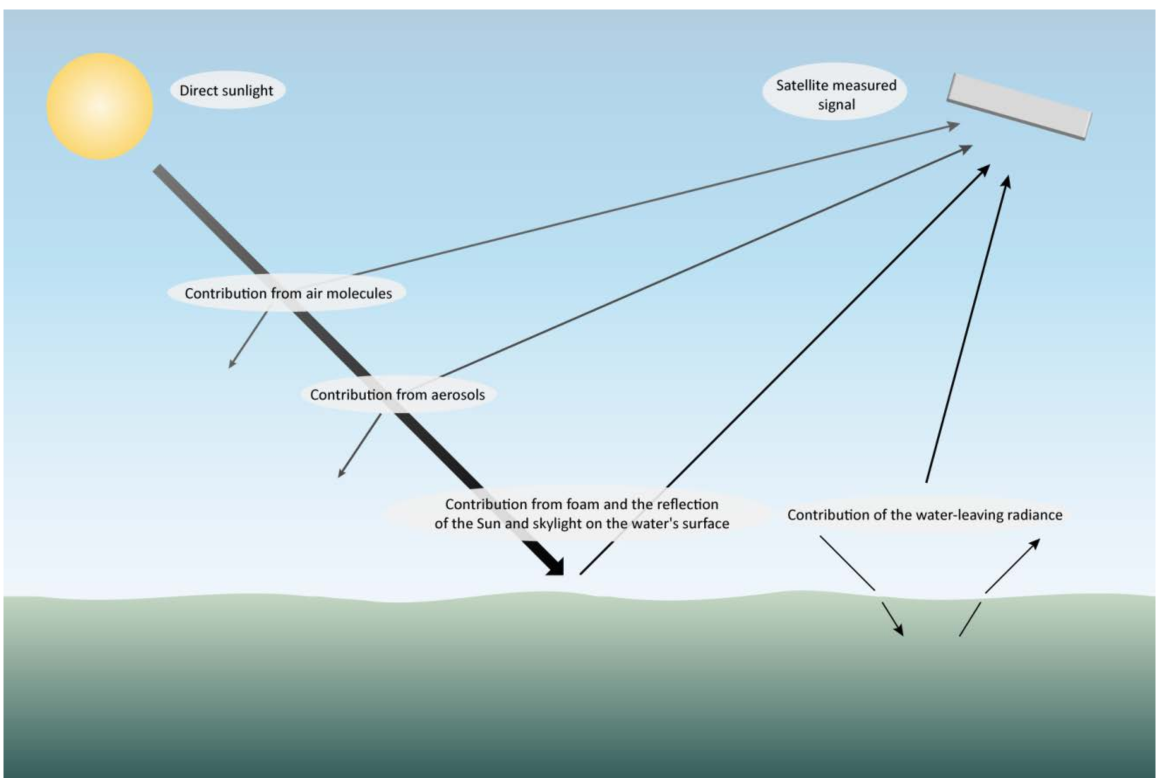

Figure 1. Schematic path of the sunlight through the atmosphere and the water body as seen by a space-borne sensor.

(6) based on statistical relationships/hypothesis to estimate the aerosol and water components (Gossn et al., 2019, 2021; He and Chen, 2014; Ibrahim et al., 2019; Saulquin et al., 2016; Singh and Shanmugam, 2014).

(7) based on observations from multiple observation angles (Xu et al., 2016; Wang et al. 2020)

Validations through match-up exercises have been provided for ocean color sensors (Jamet et al., 2011; Goyens et al., 2013; IOCCG report #10 and in preparation) and high-spatial resolution sensors (Pahlevan et al., 2021; Xu et al., 2020).

Authorship information

This user's guide was produced on behalf of the AquaWatch Algorithm Focus Group. We acknowledge Cédric Jamet (LOG/ULCO), Daniela Gurlin (Wisconsin DNR), Nima Pahlevan (NASA GSFC), Maria Tzortziou (City University of New York), Zhong-Ping Lee (Boston University), Arnold G. Dekker (SatDek), Tiit Kutser (University of Tartu), and Anders Knudby (University of Ottawa) for their contributions. We encourage interested or critical members of the public to provide feedback via email with the subject line: **Introductory Atmospheric Correction Feedback** to: Mbneely@geoaquawatch.org.

Date

2021-12-15

References

Bailey, S.W., Franz, B.A., and Werdell, P.J., 2010. Estimation of near-infrared water-leaving reflectance for satellite ocean color data processing. Opt. Expr. 18(7), 7521-7527, https://doi.org/10.1364/OE.18.007521.

Brajard, J., Jamet, C., Moulin, C., and Thiria, S., 2006. Use of a neuro-variational inversion for retrieving oceanic and atmospheric constituents from satellite ocean colour sensor: Application to absorbing aerosols. Neural Net. 19(2), 178-185, https://doi.org/10.1016/j.neunet.2006.01.015.

Brajard, J., Santer, R., Crépon, M., and Thiria, S., 2012. Atmospheric correction of MERIS data for case-2 waters using a neuro-variational inversion. Remote Sens. Environ. 126, 51-61, https://doi.org/10.1016/j.rse.2012.07.004.

Chen, J., Yin, S., Xiao, R., Xu, Q., Lin, C., 2014. Deriving remote sensing reflectance from turbid Case II waters using green-shortwave infrared bands based model. Adv. Space Res. 53 (8), 1229-1238, https://doi.org/10.1016/j.asr.2014.01.014.

Chomko, R.M., Gordon, H.R., Maritorena, S., and Siegel, D.A., 2003. Simultaneous retrieval of oceanic and atmospheric parameters for ocean color imagery by spectral optimization: a validation. Remote Sens. Environ. 84(2), 208-220, https://doi.org/10.1016/S0034-4257(02)00108-6.

De Keukelaere, L., Sterckx, S., Adriaensen, S., Knaeps, E., Reusen, I., and Giardino, C., 2018. Atmospheric correction of Landsat-8/OLI and Sentinel-2/MSI data using iCOR algorithm: Validation for coastal and inland waters. Eur. J. Remote Sens. 51(1), 525-542, https://doi.org/10.1080/22797254.2018.1457937.

Doerffer, R., and Schiller, H., 2007. The MERIS case 2 water algorithm. Inter. J. Remote Sens. 28(3-4), 517-535, https://doi.org/10.1080/01431160600821127.

Fan, Y., Li, W., Gatebe, C.K., Jamet, C., Zibordi, G., Schroeder, T., and Stamnes, K., 2017. Atmospheric correction and aerosol retrieval over coastal waters using multilayer neural networks. Remote Sens. Environ. 199, 218-240, https://doi.org/10.1016/j.rse.2017.07.016.

Gossn, J.I., Ruddick, K.G., Dogliotti, A.I., 2019. Atmospheric correction of OLCI imagery over extremely turbid waters based on the red, NIR and 1016 nm bands and a new baseline residual technique. Remote Sens. 11(3), 220, https://doi.org/10.3390/rs11030220.

Gossn, J.I., Frouin, R., and Dogliotti, A.I., 2021. Atmospheric correction of satellite optical imagery over the Río de la Plata highly turbid waters using a SWIR-based principal component decomposition technique. Remote Sens. 13(6), 1050, https://doi.org/10.3390/rs13061050.

Goyens, C., Jamet, C., and Schroeder, T., 2013. Evaluation of four atmospheric correction algorithms for MODIS-Aqua images over contrasted coastal waters. Remote Sens. Environ. 131, 63-75, https://doi.org/10.1016/j.rse.2012.12.006.

He, Q., and Chen, C., 2014. A new approach for atmospheric correction of MODIS imagery in turbid coastal waters: a case study for the Pearl River Estuary. Remote Sens. Lett. 5(3), 249-257, https://doi.org/10.1080/2150704X.2014.898192.

He, X., Bai, Y. Pan, D. Tang, J., and Wang, D., 2012. Atmospheric correction of satellite ocean color imagery using the ultraviolet wavelength for highly turbid waters. Opt. Expr. 20(18), 20754-20770, https://doi.org/10.1364/OE.20.020754.

Hu, C., Carder, K.L. and Muller-Karger, F.E., 2000. Atmospheric correction of SeaWiFS imagery over turbid coastal waters: a practical method. Remote Sens. Environ. 74(2), 195-206, https://doi.org/10.1016/S0034-4257(00)00080-8.

Ibrahim, A., Franz, B.A., Ahmad, Z., and Bailey, S.W., 2019. Multiband atmospheric correction algorithm for ocean color retrievals. Front. Earth Sci. 7, 166, https://doi.org/10.3389/feart.2019.00116.

IOCCG (2010). Atmospheric Correction for Remotely-Sensed Ocean-Colour Products. Wang, M. (ed.), Reports of the International Ocean-Colour Coordinating Group, No. 10, IOCCG, Dartmouth, Canada.

Jamet., C., Thiria, S., Moulin, C., and Crepon, M., 2004. Use of a neurovariational inversion for retrieving oceanic and atmospheric constituents from ocean color imagery: a feasibility study. J. Atmos. Ocean. Tech. 22(4), 460-475, https://doi.org/10.1175/JTECH1688.1.

Jamet, C., Loisel, H., Kuchinke, C.P., Ruddick, K., Zibordi, G., and Feng, H., 2011. Comparison of three SeaWiFS atmospheric correction algorithms for turbid waters using AERONET-OC measurements. Remote Sens. Environ. 115(8), 1955-1965, https://doi.org/10.1016/j.rse.2011.03.018.

Kuchinke, C.P., Gordon, H.R., Harding, L.W., and Voss, K.J., 2009. Spectral optimization for constituent retrieval in Case 2 waters I: Implementation and performance. Remote Sens. Environ. 113(3), 571-587, https://doi.org/10.1016/j.rse.2008.11.001.

Lavender, S.J., Penkerton, M.H., Moore, G.F., Aiken, J., and Blondeau-Patissier, D., 2005. Modification to the atmospheric correction of SeaWiFS ocean colour images over turbid waters. Cont. Shelf Res. 25(4), 539-555, https://doi.org/10.1016/j.csr.2004.10.007.

Mobley, C.D., Werdell, J., Franz, B., Ahmad, Z., and Bailey, S., 2016. Atmospheric correction for satellite ocean color radiometry - A tutorial and documentation of the algorithms used by the NASA Ocean Biology Processing Group, NASA report, 80 pages.

Moore, G.F., Aiken, J., and Lavender, S.J., 1999. The atmospheric correction of water colour and the quantitative retrieval of suspended particulate matter in Case II waters: Application to MERIS, Inter. J. Remote Sens. 20(9), 1713-1733, https://doi.org/10.1080/014311699212434.

Oo, M., Vargas, M., Gilerson, A., Gross, B., Moshary, F., and S., Ahmed, S., 2008. Improving atmospheric correction for highly productive coastal waters using the short wave infrared retrieval algorithm with water-leaving reflectance constraints at 412 nm. Appl. Opt. 47(21), 3846-3859, https://doi.org/10.1364/AO.47.003846.

Pahlevan, N., Mangin, A., Balasubramanian, S.V., Brandon, S., Krista, A., Kohei, A., Bélanger, S., Binding, C., Bresciani, M., Giardino, C., Gurlin, D., Fan, Y., Harmel, T., Hunter, P., Ishikaza, J., Kratzer, S., Lehmann, M., Ligi, M., Ma, R., Warren, M., 2021. ACIX-Aqua: A global assessment of atmospheric correction methods for Landsat-8 and Sentinel-2 over lakes, rivers, and coastal waters. Remote Sens. Environ. 258, 112366, https://doi.org/10.1016/j.rse.2021.112366.

Ruddick, K., Ovidio, F., and Rijkeboer, M., 2000. Atmospheric correction of SeaWiFS imagery for turbid coastal and inland waters. Appl. Opt. 39(6), 897-912, https://doi.org/10.1364/AO.39.000897.

Ruddick, K., Cauwer, V. D., Park, Y., and Moore, G., 2006. Seaborne measurements of near infrared water-leaving reflectance: The similarity spectrum for turbid waters. Limnol. Oceano. 51(2), 1167-1179, https://doi.org/10.4319/lo.2006.51.2.1167.

Saulquin, B., Fablet, R., Bourg, L., Mercier, G., and Fanton d'Andon, O., 2016. MEETC2: Ocean color atmospheric corrections in coastal complex waters using a Bayesian latent class model and potential for the incoming sentinel 3 – OLCI mission. Remote Sens. Environ. 172, 39-49, https://doi.org/10.1016/j.rse.2015.10.035.

Schroeder, T., Behnert, I. Schaale, M., Fischer, J., and R. Doerffer, R., 2007. Atmospheric correction algorithm for MERIS above case-2 water. Inter. J. Remote Sens. 28(7), 1469-1486, https://doi.org/10.1080/01431160600962574.

Shi, W., and Wang, M., 2009. An assessment of the black ocean pixel assumption for MODIS SWIR bands. Remote Sens. Environ. 113(8), 1587-1597, https://doi.org/10.1016/j.rse.2009.03.011.

Siegel, D. A., Wang, M., Maritorena, S., and Robinson, W., 2000. Atmospheric correction of satellite ocean color imagery: the black pixel assumption. Appl. Opt. 39(21), 3582-3591, https://doi.org/10.1364/AO.39.003582.

Singh, R.K., and Shanmugam, P., 2014. A novel method for estimation of aerosol radiance and its extrapolation in the atmospheric correction of satellite data over optically complex oceanic waters. Remote Sens. Environ. 142, 188-206, https://doi.org/10.1016/j.rse.2013.12.001.

Stamnes, K., Li, W., Yan, B., Eide, H., Barnard, A., Pegau, W.S., and J.J., Stamnes, J.J., 2003. Accurate and self-consistent ocean color algorithm: simultaneous retrieval of aerosol optical properties and chlorophyll concentrations. Appl. Opt. 42(6), 939-951, https://doi.org/10.1364/AO.42.000939.

Steinmetz, F., Deschamps, P.-Y., and Ramon, D., 2011. Atmospheric correction in presence of sun glint: application to MERIS. Opt. Exp. 19(10), 9783-9800, https://doi.org/10.1364/OE.19.009783.

Sterckx, S. Knaeps, E. Kratzer, S., and Ruddick, K., 2015. SIMilarity Environment Correction (SIMEC) applied to MERIS data over inland and coastal waters. Remote Sens. Environ. 157, 96-110, https://doi.org/10.1016/j.rse.2014.06.017.

Stumpf, R.P., Arnone, R.A., Gould, R.W., Martinolich, P., and Ransibrahmanakul, V., 2003. Algorithm updates for the fourth SeaWiFS data reprocessing, Eds. S.B., Hooker, in SeaWiFS Post-Launch Technical Report Series, NASA Technical Memorandum 2003-206892, 51-59.

Vanhellemont, Q., and Ruddick, K., 2018. Atmospheric correction of metre-scale optical satellite data for inland and coastal water applications. Remote Sens. Environ. 216, 586-597, https://doi.org/10.1016/j.rse.2018.07.015.

Vanhellemont, Q., 2019. Adaptation of the dark spectrum fitting atmospheric correction for aquatic applications of the Landsat and Sentinel-2 archives. Remote Sens. Environ. 225, 175-192, https://doi.org/10.1016/j.rse.2019.03.010.

Vanhellemont, V., and Ruddick, K., 2021. Atmospheric correction of Sentinel-3/OLCI data for mapping of suspended particulate matter and chlorophyll-a concentration in Belgian turbid coastal waters. Remote Sens. Environ. 256, 112284, https://doi.org/10.1016/j.rse.2021.112284.

Wang, M., and Shi, W., 2005. Estimation of ocean contribution at the MODIS near-infrared wavelengths along the east coast of the U.S.: Two case studies. Geophys. Res. Lett. 32(13), L13606, https://doi.org/13160.11029/12005GL022917.

Wang, M., and Shi, W., 2007. The NIR-SWIR combined atmospheric correction approach for MODIS ocean color data processing. Opt. Exp. 15(24), 15722-15733, https://doi.org/10.1364/OE.15.015722.

Wang, M., and Jiang, L., 2018. Atmospheric correction using the information from the short blue band. IEEE Trans. Geosci. Remote Sens. 56(10), 6224-6237, https://doi.org/10.1109/TGRS.2018.2833839.

Wang, J., Lee, Z.-P., Wei, J., and Du, K., 2020. Atmospheric correction in coastal region using same-day observations of different sun-sensor geometries with a revised POLYMER model. Opt. Expr. 28(18), 26953-26976, https://doi.org/10.1364/OE.393968.

Wang, Y., Lee, Z.-P., Wei, J., Shang, S., Wang, M., Lai, W., 2021. Extending satellite ocean color remote sensing to the near-blue ultraviolet bands, Remote Sens. Environ. 253, 112228, https://doi.org/10.1016/j.rse.2020.112228.

Xu, F., Dubovik, O., Zhai, P.-W., Diner, D. J., Kalashnikova, O. V., Seidel, F. C., Litvinov, P., Bovchaliuk, A., Garay, M. J., van Harten, G., and Davis, A. B., 2016. Joint retrieval of aerosol and water-leaving radiance from multispectral, multiangular and polarimetric measurements over ocean. Atmos. Meas. Tech. 9(7), 2877-2907, https://doi.org/10.5194/amt-9-2877-2016.

Xu, Y., Feng, L., Zhao, D., Lu, J., 2020. Assessment of Landsat atmospheric correction methods for water color applications using global AERONET-OC data. Inter. J. Appl. Earth Obs. Geoinfo. 93, 102192 , https://doi.org/10.1016/j.jag.2020.102192.