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Multi-sensor ocean colour validation in Belgian waters

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ABSTRACT

Two new AERONET-OC sites have been prepared/installed in Belgian waters for the validation of ocean colour sensors in a multi-sensor perspective. One is located in a nearshore turbid water location, the other further offshore in clearer water. The sites are characterised here in terms of the temporal, spectral and spatial variability of optical properties based on information from past and present satellite sensors, including very high spatial resolution (2m) data.

INTRODUCTION

The mainstream ocean colour remote sensing sensors (MODIS, VIIRS and the future OLCI) require “matchup” data from simultaneous sea-based instruments for validation. In particular validation of the water-leaving radiance reflectance is crucial (Hooker and McClain 2000; Bailey and Werdell 2006): this parameter is the basis of all other marine parameters, including chlorophyll *a*, yet is often severely affected by errors from the atmospheric correction procedure. Experience has shown the importance of continuously measuring instruments, such as those of the AERONET-OC network (Zibordi et al. 2009), for obtaining a sufficient number of matchups to perform a relevant statistical comparison of satellite and in situ data.

Moreover, in addition to the expanding range of mainstream ocean colour sensors, there is a growing interest in exploiting data from other optical remote sensors, including the geostationary meteorological sensors such as SEVIRI onboard MSG giving data every 5 minutes (Neukermans et al. 2009) and high-resolution sensors on polar-orbiters originally designed for land applications, such as Landsat-8/OLI (Vanhellemont and Ruddick 2014; Vanhellemont and Ruddick 2014) giving 30m spatial resolution and Sentinel-2/MSI (10-60m). A single validation site can thus provide information for validation of a large number of spaceborne missions. Conversely the combination of the remotely sensed data in a multi-sensor perspective can enhance the validation analysis for any single sensor. e.g. SEVIRI can provide information on the temporal variation of natural processes (Neukermans et al. 2012) and OLI can provide information on the spatial variation of the sea in the vicinity of a validation site, thus allowing a quantification of the discrepancies caused by spatial and temporal mismatchs between satellite and in situ data. For example the impact of temporal mismatch is illustrated in Figure 7 of (Vanhellemont et al. 2014) and the impact of spatial mismatch between 900m/300m/150m and 30m is illustrated in Supplementary Data 2 of (Vanhellemont and Ruddick 2014), although the latter does not go down to the spatial scales typical of in situ data, e.g. metre scale for abovewater radiometry.

Belgian waters have been a key site for validation of satellite ocean colour radiometry since the launch of MERIS in 2002. Ship-based measurements have been regularly compared with satellite-derived marine reflectance to indicate any performance weaknesses (Ruddick et al.

2002; Park et al. 2003; Park et al. 2006; Ruddick et al. 2008). These measurements are supported by protocol intercomparison studies (Zibordi et al. 2012), which facilitate international integration of measurements, e.g. via the MERMAID database (Barker et al. 2008). However, the ship-based measurements provide only a limited number of matchup measurements per year. The Belgian strategy for ocean colour validation has consequently shifted focus to the setup of continuously measuring systems in order to provide early validation feedback to missions such as Sentinel-3/OLCI and Sentinel-2/MSI.

The radiometric validation of ocean colour data is presented here in a multi sensor perspective with a focus on Belgian waters and the preparation of two new AERONET-OC sites, one in turbid nearshore waters, one further offshore in clearer waters. The two sites are described, including an optical characterisation of the water. The impact of spatial resolution on radiometric validation uncertainties is analysed in detail.

METHODS

New Belgian AERONET-OC sites

Two locations have been chosen for installation of the new Belgian AERONET-OC sites: one in turbid water, on the *Afdeling Kust* MOW1 measurement platform close to the port of Zeebrugge, the other in clearer water further offshore, on the C-Power offshore transformer station at the Thornton Bank. These sites have been selected as a compromise between the scientific value of the location, the quality and quantity of the optical data that can be acquired and more practical issues such as the facility of maintenance and the support of the platform operators.

As regards scientific value, the sites are located either side of a turbidity front. Whereas the aerosol optical properties at the two sites are expected to be quite similar most of the time, the marine optical properties are very different. This provides ideal data for the validation of the turbid water component of an atmospheric correction as already illustrated in (Park et al. 2003), where an artificial jump in retrieved aerosol properties across the turbidity front indicated a problem with the turbid water atmospheric correction of early MERIS imagery. The Zeebrugge site is also one of the most turbid locations currently integrated within AERONET-OC, thus stretching the range of water types covered by the network, and is quite close to land. Proximity to land has traditionally been considered as a drawback for ocean colour validation sites because of the possibility of contamination of satellite data by adjacency effects (Reinersman and Carder 1995; Santer and Schmechtig 2000; Sterckx et al. 2011). On the other hand, there is clearly a need now to exploit and hence validate the satellite data in nearshore regions because of the strong user need there, e.g. for the Water Framework Directive (Gohin et al. 2008).

As regards the quality of optical data it is clearly preferable to mount instruments high on a platform with a limited surface area (reducing the direct contamination of a satellite data pixel by reflectance from the platform itself), with a slender optical profile (reducing the optical perturbation of the water being measured) and in water with horizontally homogeneous optical properties. In a multi-mission perspective and especially when considering data from geostationary satellites it is preferable to have a platform and mounting location with a wide range of acceptable viewing azimuth angles without optical perturbations from the platform itself (Zibordi et al. 1999).

The Zeebrugge/MOW1 AERONET-OC site was installed in February 2014. The system is based on a standard CIMEL SeaPRISM instrument and transmits data to NASA for processing and distribution. To avoid interference with other instruments functioning on the platform the system runs off an independent power supply with solar panels supplying power to a 12V battery. Data is transferred from the CIMEL control box to a rugged Moxa mini-PC and data transmission from the PC is performed by a GPRS Internet connection instead of the more usual METEOSAT transmission. The PC can be accessed remotely. Both PC and GPRS router are switched on only briefly per day to limit power consumption.

The Thornton Bank AERONET-OC system has been tested on land and will be ready for installation in end-2014.

The site characteristics are summarised in Table 1 and the platforms are illustrated in Figure 2.

AERONET-OC Site	Location	Mean water depth	Start Date	Distance from land
Zeebrugge/ MOW1	51.3605°N 03.1182°E	10m	24/02/2014	3.65km
Thornton/ C-Power	51.5329°N 02.9549°E	19m	December 2014	26.25km

Table 1 Summary of the sites used for the new Belgian AERONET-OC sites.

Ocean colour and related satellite missions

Sensor /Satellite	Launch Date	Spatial Resolution	Acquisition Frequency
MODIS-TERRA	18.12.1999	250/1000m	Daily
MODIS-AQUA	04.05.2002	250/1000m	Daily
VIIRS	28.10.2011	370/740m	Daily
Pléiades	17.12.2011 (A) 02.02.2012 (B)	2.8m	On request
SEVIRI/Meteosat	21.12.2005 (M9) 05.07.2012 (M10) *2015 (M11) etc.*	~5km	Every 5 or 15 minutes
Rapideye	29.08.2008 (*5)	5m	On request
Worldview	08.10.2009 (W2) 13.08.2014 (W3)	1.8m (W2) 1.0m (W3)	On request
OLI/Landsat-8	11.02.2013	30m	Every 8 or 16 days
PROBA-V	7.5.2013	100/300m	Daily
OLCI/Sentinel-3	*2015 (A)* *2017 (B)*	300m	Daily with 2 sats
Sentinel-2	*2015 (A)* *2016 (B)*	10m/20m/60m	~Every 3 days with 2 sats

Table 2 Non-exhaustive summary of the missions to be validated by the new Belgian AERONET-OC sites. Acquisition frequency is provided for Belgian waters (~51.5°N) assuming no clouds. Spatial resolution is provided at nadir for polar orbiters and over Belgian waters (~51.5°N) for SEVIRI (geostationary). Future launches are given in italics.

The economy of scale achieved with continuously measuring systems integrated in an international network becomes apparent when considering the number of ocean colour and related satellite missions for which validation data is needed. Table 2 provides a summary of key sensors which are earmarked for validation by the new Belgian AERONET-OC sites. However, this list is non-exhaustive and is limited only by our current ability to predict which missions will be important in the future. AERONET-OC data will in principle be automatically available for validation of any future satellite or airborne missions providing optical remote sensing data over this region.

RESULTS

Satellite data has been acquired for this region since the launch of SeaWiFS in 1997 and more intensively since the launch of MODIS/AQUA and MERIS/ENVISAT in 2002. There is a good understanding of the temporal variation of optical properties and the underlying biological and physical processes (Ruddick and Lacroix 2006) including the dynamics of algal blooms (Rousseau et al. 2006) and sediment transport (Van den Eynde et al. 2007). Seaborne measurements of optical properties were also carried out between 2002 and 2012 in the framework of the BELCOLOUR-1 and -2 projects providing information on, for example, specific optical properties (Astoreca et al. 2006; Astoreca et al. 2006; Astoreca et al. 2012). The optical properties at the two AERONET-OC sites are further characterised in this section in terms of temporal, spectral and spatial variability.

Temporal variability of optical properties

Using the GRIMAS tool (Vanhellemont et al. 2011) time series of Suspended Particulate Matter (SPM) and Chlorophyll a (CHL) concentration have been extracted for the two sites (Figure 3 and Figure 4) showing the temporal variability of these optically important parameters. The CHL time series for both stations show strong algal blooms (CHL>10 mg/m^3) in spring and/or summer in most years. The satellite CHL data is here clearly affected by non-algal particle absorption, which gives an artificial minimal CHL value of about 3 mg/m^3. The SPM concentrations are high at the Zeebrugge site, typically between 5 and 50 g/m^3, with some seasonal variability (April-June minimum) related to reduced wind-induced resuspension and/or increased particle settling (Fettweis et al. 2014) during the spring algal bloom. SPM concentrations are an order of magnitude lower, typically between 0.5 and 10 g/m^3, at the Thornton site with a more pronounced seasonal cycle.

Spectral variability of water reflectance

Water-leaving radiance reflectance spectra from MERIS have been extracted for the two sites and are shown in Figure 5 and Figure 6. At the Zeebrugge site nearly all spectra have a peak at 560nm indicating green turbid water. Median water-leaving radiance reflectance at 620nm and 778nm are ~0.050 and ~0.009 respectively. At the Thornton site most spectra fall into one of two types: a) green turbid water with a spectral peak at 560nm between 0.02 and 0.08 or b) clearer bluer water with reflectance at 560nm less than 0.02 and a spectral peak at 413nm or a relatively flat spectrum between 413nm and 560nm. This corresponds with the seasonal variability of SPM shown in Figure 4. Some spectra for the Thornton site show a local minimum at 443nm caused by chlorophyll *a* absorption. This is generally not visible at the Zeebrugge site because of strong non algal particle absorption.

The number of valid spectra retrieved from MERIS for the Zeebrugge site is less than half those retrieved for the Thornton site due mainly to more frequent problems of atmospheric correction at the more turbid site for this processing algorithm. This suggests that the Zeebrugge site will be particularly useful for testing turbid water atmospheric correction algorithms.

Normalised water-leaving radiance spectra already acquired at the AERONET-OC/Zeebrugge site between 5.3.2014 and 1.5.2014 are shown in Figure 7. This data is currently available only at level 1.5 because the instrument has not yet been returned to NASA for post-deployment calibration. This data confirms that the site has generally turbid green water, as found also in the MERIS spectra of Figure 5.

Spatial variability of water reflectance

The spatial variability of water reflectance is further analysed here with high spatial resolution imagery of the Zeebrugge site from the OLI sensor (30m resolution, Figure 8) onboard Landsat-8 and the Pléiades sensor (2m resolution, Figure 9).

In Figure 8 the effect of reducing spatial resolution from 30m to 900m is clear in the RGB composite. At 30m resolution (see also Figure 1) the Thornton Bank platform can be identified as a red pixel (when the figure is sufficiently enlarged), clearly indicating that satellite data at such a resolution will be contaminated by the platform itself. This impact will obviously reduce as spatial resolution decreases. The impact for an OLCI 300m pixel could be quantified and should be considered in particular for the near infrared wavelengths used for aerosol correction. However, it may be necessary for matchup validation to use satellite pixels slightly displaced from the platform itself or to use a suitably chosen multi-pixel kernel with the platform and adjacency contaminated pixel(s) removed. At 30m resolution the Zeebrugge/MOW1 platform cannot be discerned in the RGB composite, although there is a browner sediment wake to the North East of the platform, similar to the turbid wakes already reported for the London Array wind farm in (Vanhellemont and Ruddick 2014) and visible also in this image for the Thornton Bank wind farm. It is possible to predict the location of this wake from tidal current predictions and, using knowledge of the sun azimuth variation over the day, check that the SeaPRISM instrument does not observe this sediment wake.

In Figure 8 scatterplots are also shown for top of atmosphere reflectance (after removal of land pixels) and water reflectance, using the atmospheric correction of (Vanhellemont and Ruddick 2014 (submitted)). These scatterplots show the uncertainty associated with comparing a 30m spatial average with a 150m (Figure 8b) or a 900m (Figure 8c) spatial average. In situ measurements will generally have a smaller spatial extent than 30m although temporal averaging of in situ measurements would need also to be considered when assessing the validation uncertainty associated with small scale spatio-temporal variability.

The Pléiades imagery shown in Figure 9a shows spatial variability at even shorter space scales, down to 2m (resampled by the satellite data provider from 2.8m instrument resolution). At this scale patchiness in the suspended sediment distribution is seen as well as surface waves and a brown wake of suspended sediments clearly caused by obstruction of the tidal current by the MOW1 platform support. This imagery could be further exploited in a number of ways to improve validation protocols and/or processing algorithms, e.g. by allowing an evaluation of direct (shadow/reflection) and indirect (via hydrodynamics) optical perturbation of the water reflectance by the platform, by allowing direct calculation of the air-water interface “Fresnel” reflection coefficient with resolved waves, by allowing quantification of validation uncertainty associated with the different spatial extents of in situ and satellite measurements, etc.

CONCLUSIONS

Two new AERONET-OC sites have been prepared/installed in Belgian waters for the validation of ocean colour sensors in a multi-sensor perspective. One is located in nearshore turbid water location, the other further offshore in clearer water. The sites have been characterised in terms of the temporal, spectral and spatial variability of optical properties based on information from past and present satellite sensors. The impact of spatial variability at small spatial scales around the Zeebrugge/MOW1 and Thornton/C-Power AERONET-OC sites has been studied in particular, including the impact of spatial resolution on the matching of in situ and satellite data and the impact of the platform itself on satellite data. These platform impacts may include both the direct effect of reflection of light by the platform towards the sensor (possibly extended spatially by instrumental straylight and/or near-forward atmospheric scattering) and indirect effects such as hydrodynamic and/or optical perturbation of the surrounding waters.

ACKNOWLEDGEMENTS

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Giuseppe Zibordi is warmly acknowledged for advice on AERONET-OC operations. Gregory De Schepper, Joan Backers and the RBINS *Meetdienst Oostende* are thanked for advising and helping to prepare the system. The *Maritieme Dienstverlening* section of *Afdeling Kust*, C-Power and their contractors are gratefully acknowledged for logistical support and access to their platforms.

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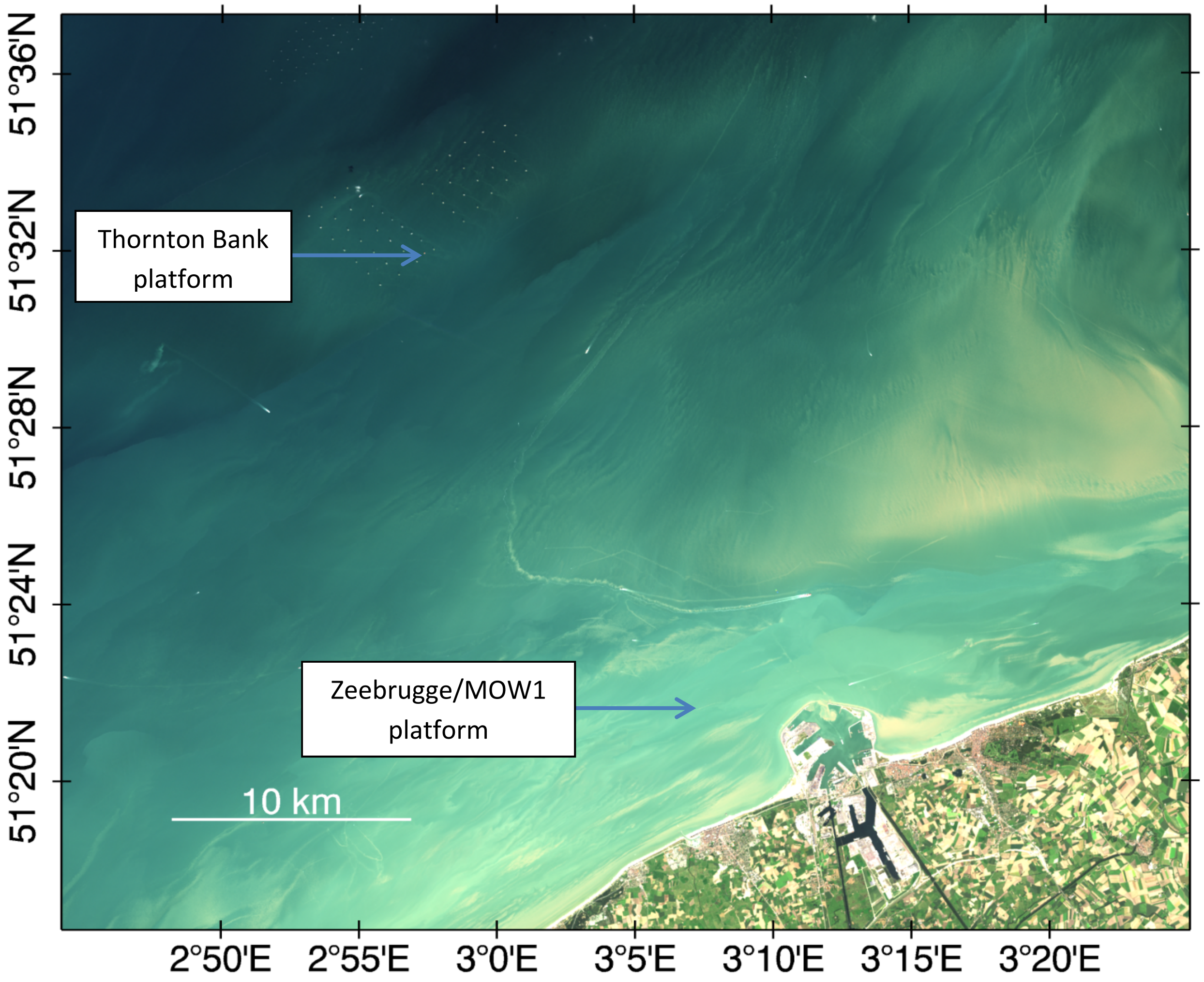

Figure 1 Belgian waters showing the location of the two new AERONET-OC sites. RGB composite from Landsat-8/OLI image of 8.9.2014 at 10:40 UTC is based on Rayleigh-corrected reflectance at bands 4 (630-680nm) , 3 (525-600nm) and 2 (450-515nm).

Figure 2 Photos of the platforms used for the new Belgian AERONET-OC sites: (top-left) Zeebrugge-MOW1 measurement platform, (top-right) Thornton-CPOWER offshore transformer platform, (bottom-left) SeaPRISM instrument location and (bottom-right) SeaPRISM instrument as installed at Zeebrugge-MOW1.

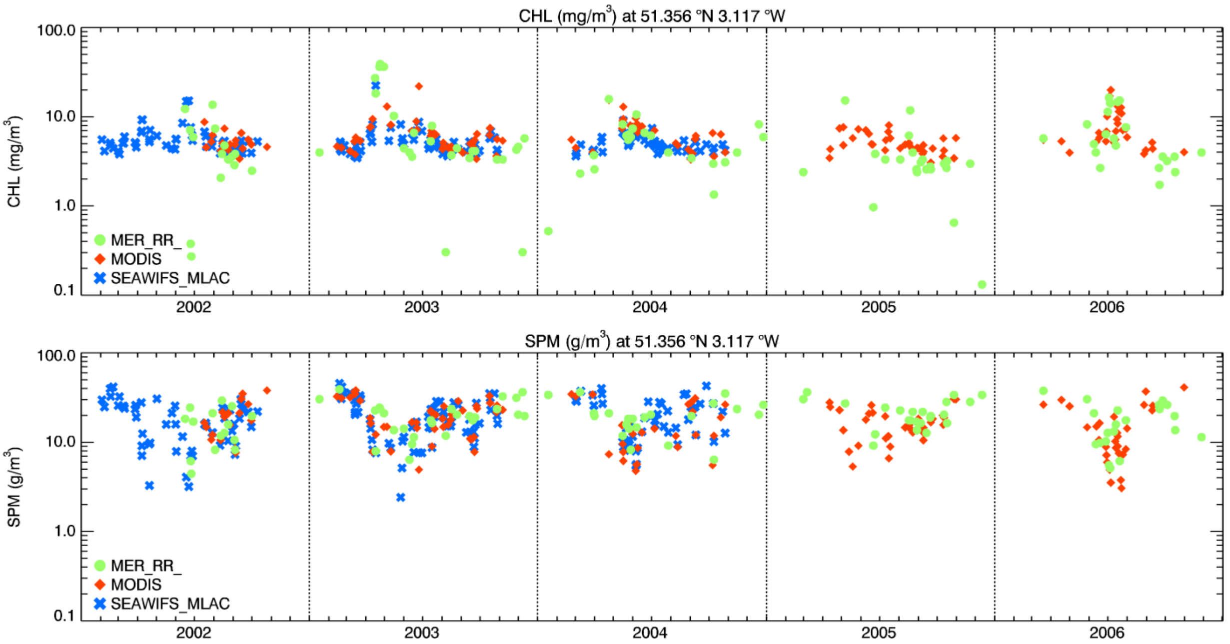

Figure 3 Time series of CHL (top) and SPM (bottom) at the Zeebrugge/MOW1 location from MERIS, MODIS and SeaWiFS over the period 2002-6.

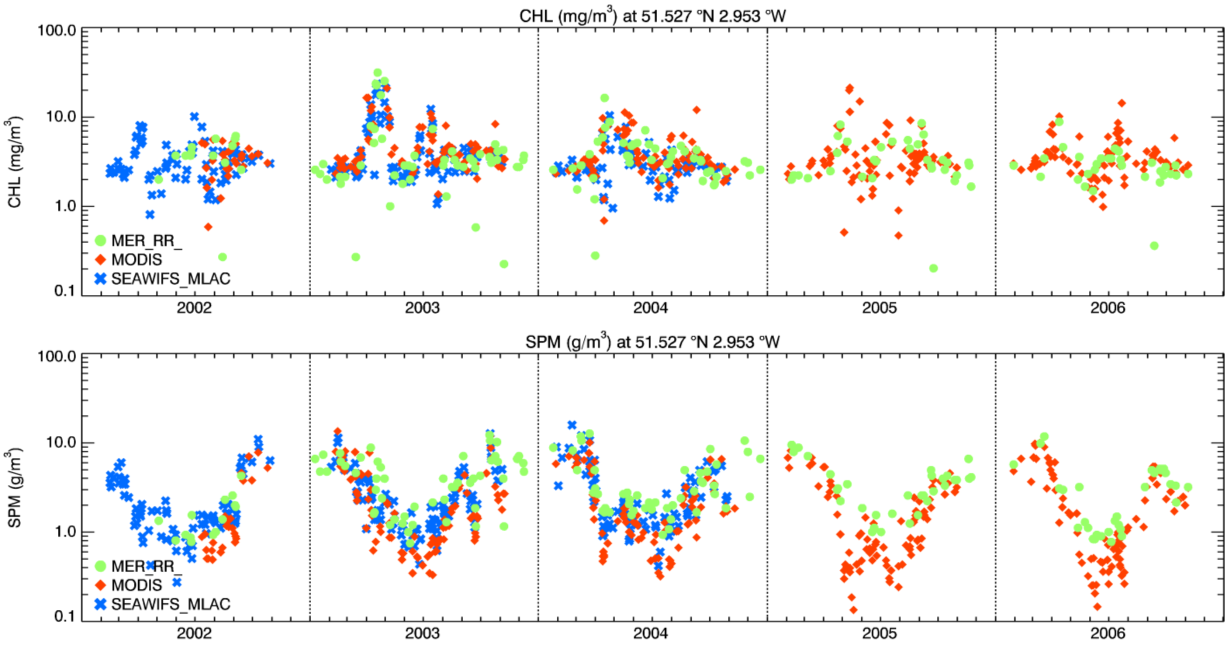

Figure 4 Time series of CHL (top) and SPM (bottom) at the Thornton/C-Power location from MERIS, MODIS and SeaWiFS over the period 2002-6.

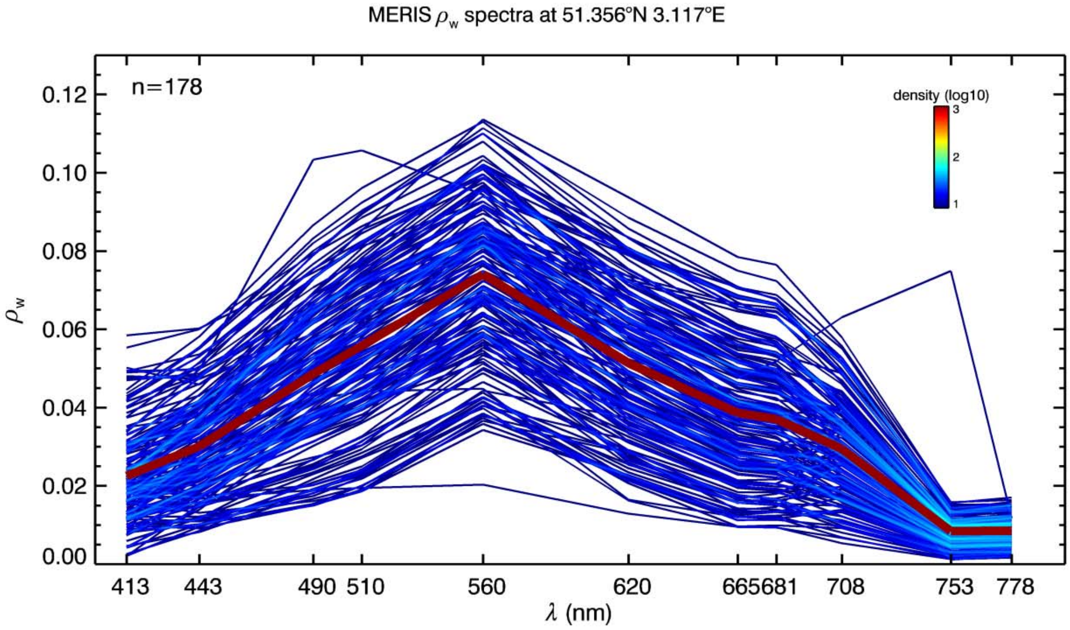

Figure 5 Water reflectance spectra from MERIS at the Zeebrugge/MOW1 location. MERIS Reduced Resolution second reprocessing data is used, giving n valid spectra over the full mission (2002-2012). The median spectrum from a 5x5 kernel over the location is represented when >12/25 are valid pixels according to the product confidence flag. The median of all spectra is shown as a red line.

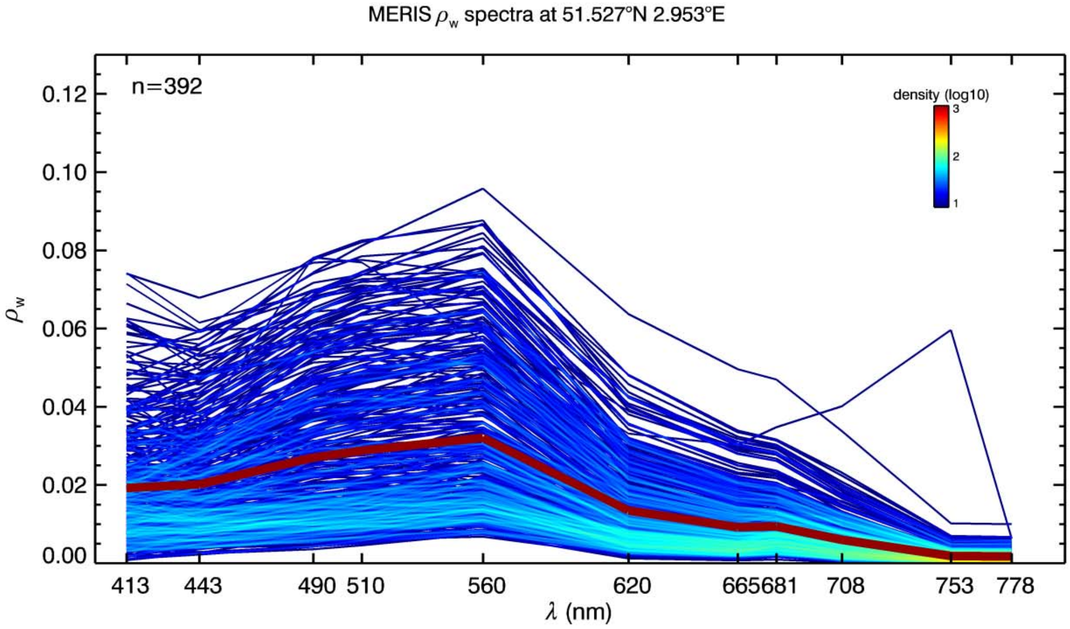

Figure 6 Water reflectance spectra from MERIS at the Thornton/C-Power location. MERIS Reduced Resolution second reprocessing data is used, giving n valid spectra over the full mission (2002-2012). The median spectrum from a 5x5 kernel over the location is represented when >12/25 are valid pixels according to the product confidence flag. The median of all spectra is shown as a red line.

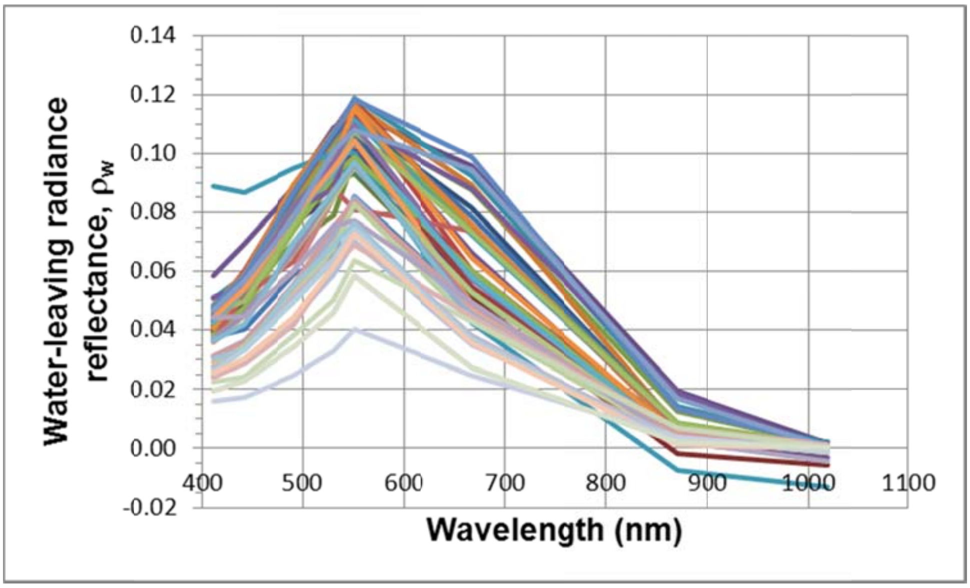

Figure 7 Water reflectance spectra (without f/Q correction) acquired by the AERONET-OC/Zeebrugge site over the period 5.3.2014-1.5.2014.

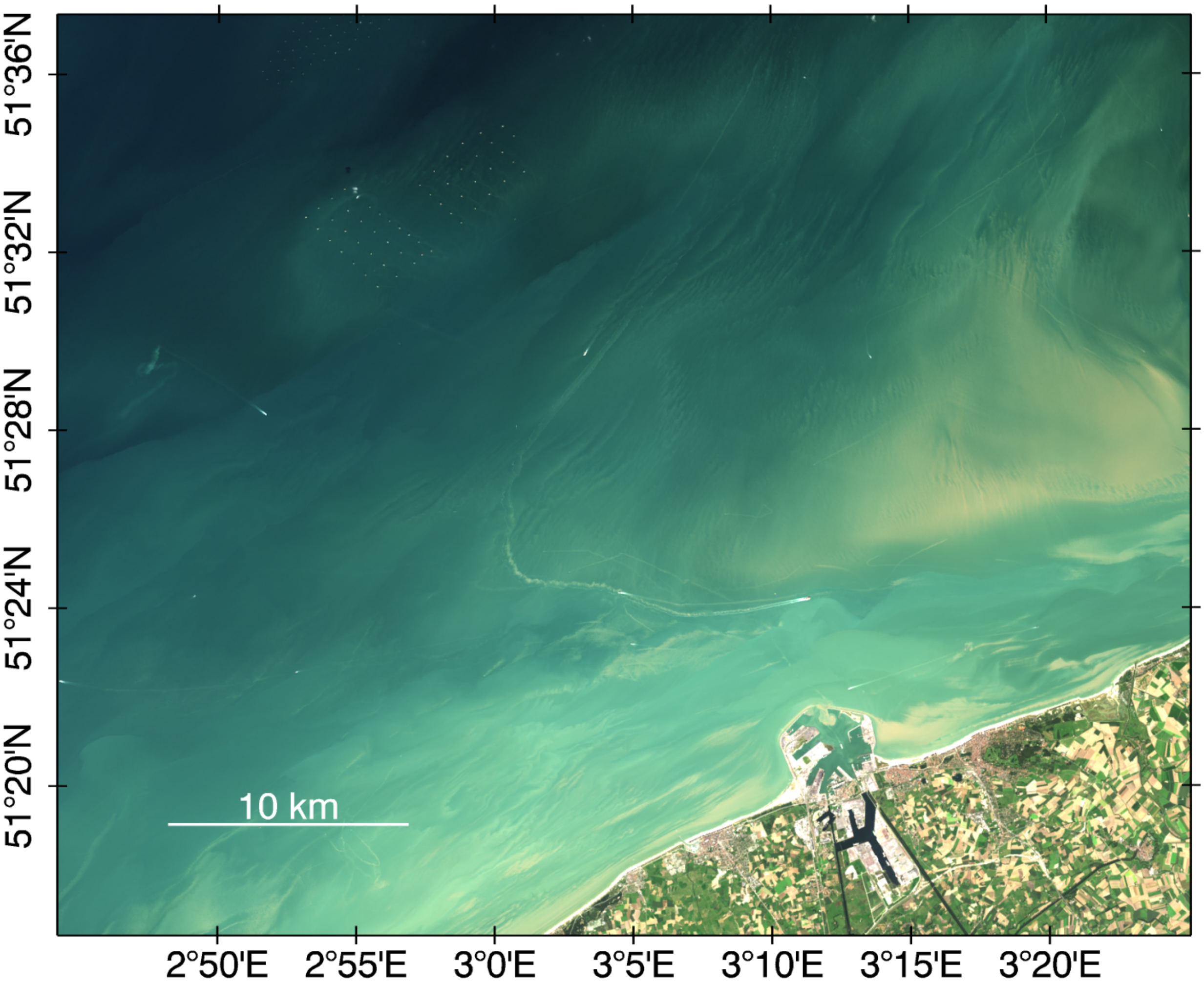

Figure 8a Data from Landsat-8/OLI acquired on 8.9.2014 at 10:40 UTC at full 30m resolution. RGB composite using Rayleigh-corrected reflectance at bands 4 (630-680nm), 3 (525-600nm) and 2 (450-515nm).

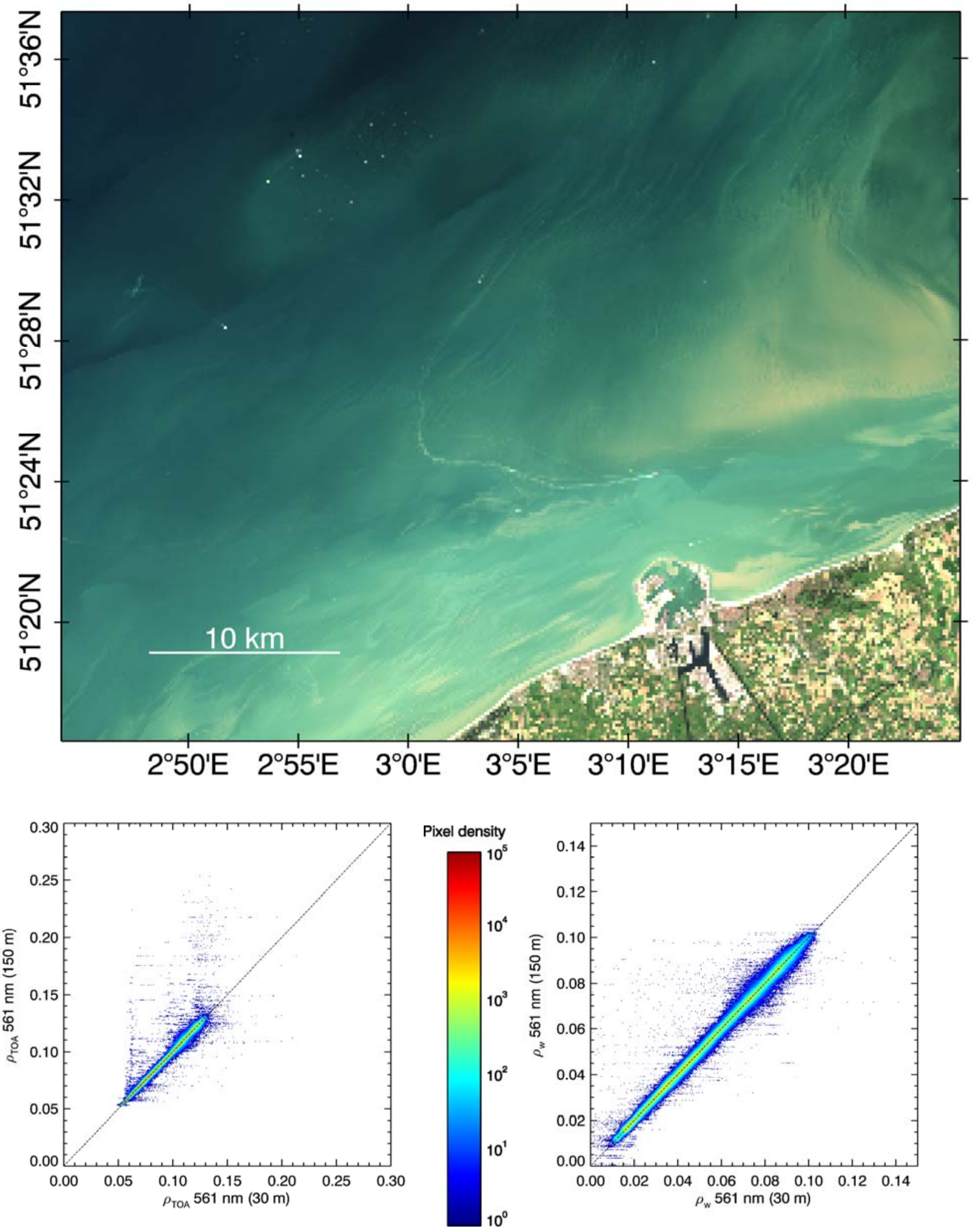

Figure 8b Data from Landsat-8/OLI acquired on 8.9.2014 at 10:40 UTC degraded by mean averaging to 150m: (top) RGB composite as Figure 8a (bottom-left) Top of atmosphere reflectance at 561nm at 150m compared to 30m and (bottom-right) water reflectance at 561nm at 150m compared to 30m.

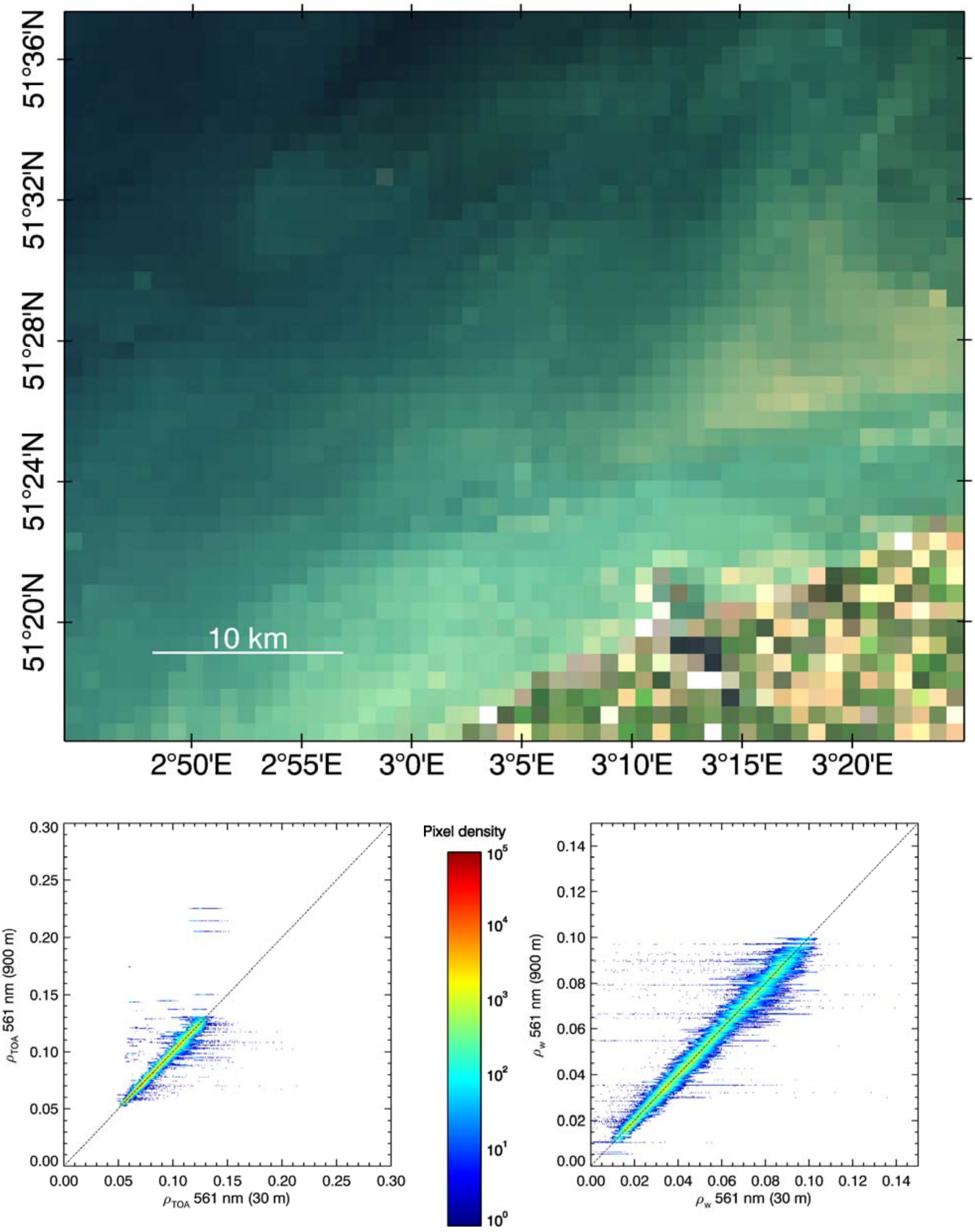

Figure 8c Data from Landsat-8/OLI acquired on 8.9.2014 at 10:40 UTC degraded by mean averaging to 900m: (top) RGB composite as Figure 8a (bottom-left) Top of atmosphere reflectance at 561nm at 900m compared to 30m and (bottom-right) water reflectance at 561nm at 900m compared to 30m.

Figure 9a Data from Pléiades acquired on 8.9.2014 at 11:10 UTC. Red (600-720 nm)-Green (490-610 nm)-Blue (430-550 nm) composite of Rayleigh-corrected top of atmosphere data at native 2.8m spatial resolution, resampled by the satellite data provider to 2m. The region shown is a 1950m*1500m subimage of the full image and includes the MOW1 platform and its turbid wake extending to the North East.

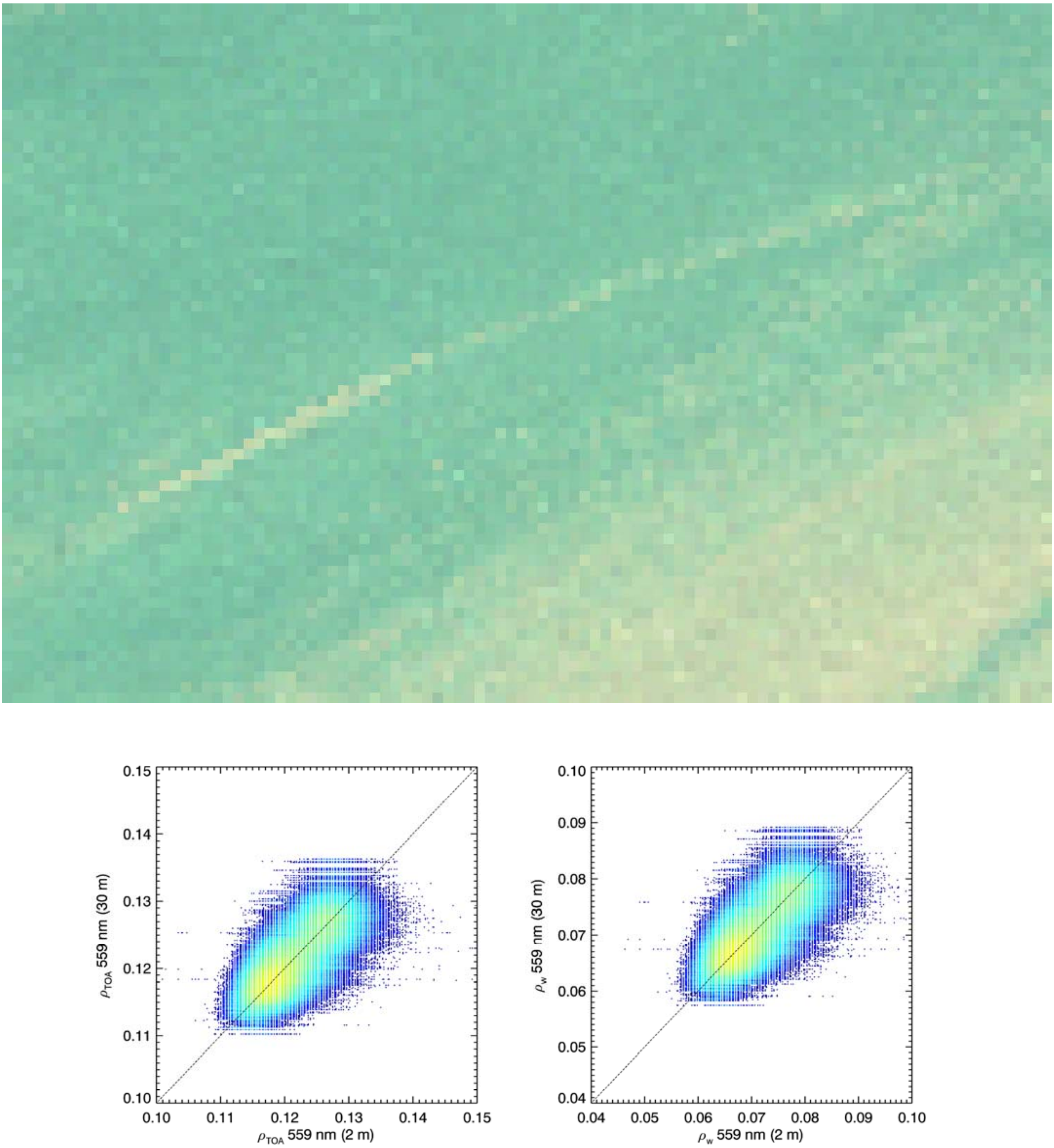

Figure 9b Data from Pléiades acquired on 8.9.2014 at 11:10 UTC. (top) RGB top of atmosphere composite as Figure 9a but degraded to 30m resolution (bottom-left) Top of atmosphere reflectance at 559nm at 30m compared to 2m and (bottom-right) water reflectance at 559nm at 30m compared to 2m.

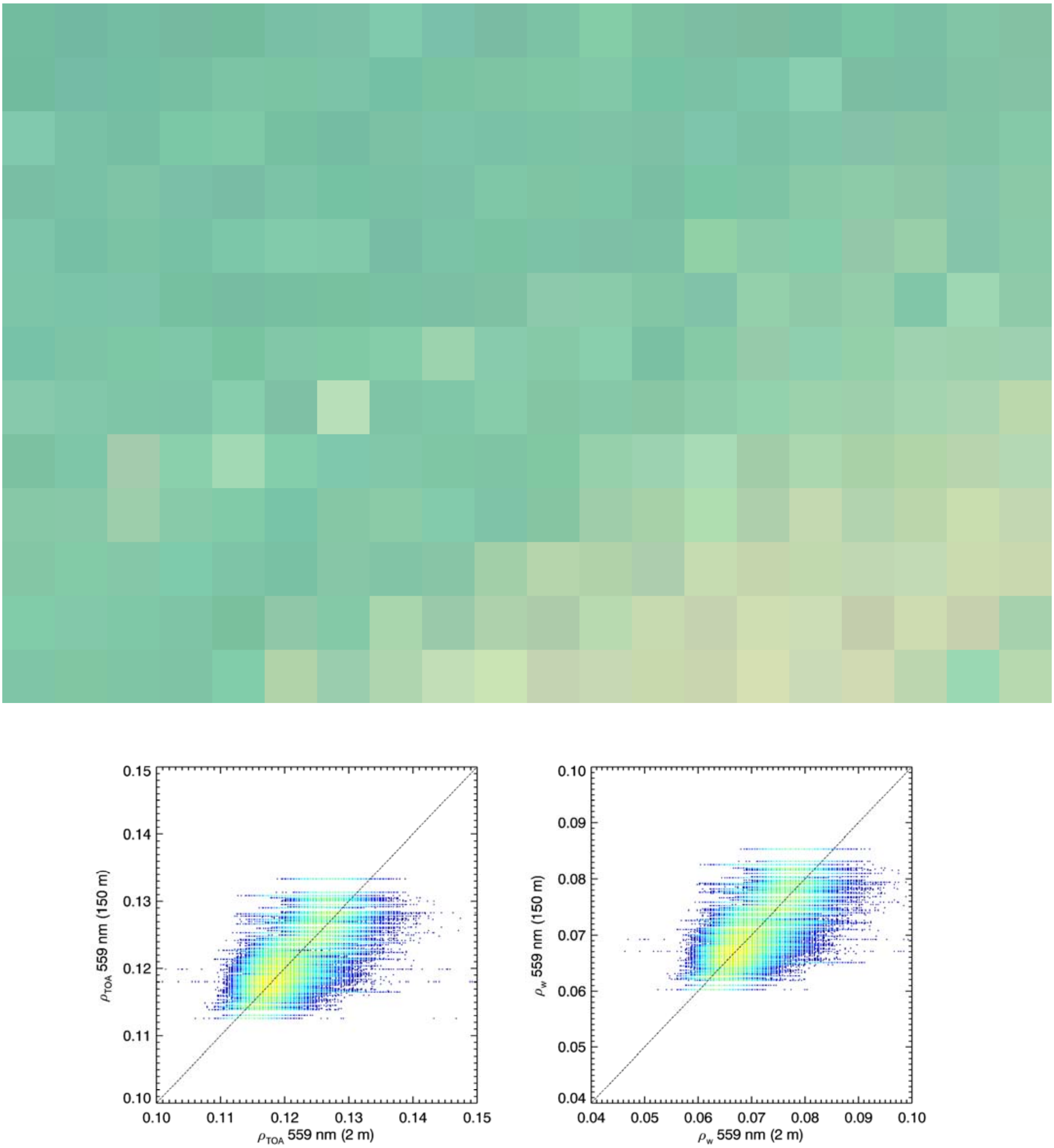

Figure 9c Data from Pléiades acquired on 8.9.2014 at 11:10 UTC. (top) RGB top of atmosphere composite as Figure 9a but degraded to 150m resolution (bottom-left) Top of atmosphere reflectance at 559nm at 150m compared to 2m and (bottom-right) water reflectance at 559nm at 150m compared to 2m.