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Diurnal variability of turbidity and light attenuation in the southern North Sea from the SEVIRI geostationary sensor

G. Neukermans [a,b,c,d,*], K.G. Ruddick [a], N. Greenwood [e]

[a] Management Unit of the North Sea Mathematical Models (MUMM), Royal Belgian Institute for Natural Sciences (RBINS), Gulledelle 100, B-1200 Brussels, Belgium
[b] Université Lille Nord de France, F-59000 Lille, France
[c] Université du Littoral Côte d'Opale (ULCO), Laboratoire d'Océanologie et Géosciences (LOG), F-62930 Wimereux, France
[d] Centre National de la Recherche Scientifique (CNRS), UMR 8187, F-62930 Wimereux, France
[e] Centre for Environment, Fisheries and Aquaculture Science (Cefas), Pakefield Road, Lowestoft, Suffolk, NR33 0HT, UK

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ABSTRACT

This study follows up on the successful feasibility study of Neukermans et al. (2009) for mapping suspended matter in turbid waters from the SEVIRI sensor on board the METEOSAT geostationary weather satellite platform. Previous methodology is extended to the mapping of turbidity, *T*, and vertical attenuation of photosynthetically active radiation (PAR), K_{PAR}. The spatial resolution of the SEVIRI products is improved from 3 km × 6.5 km to 1 km × 2 km using the broad high resolution visual band. The previous atmospheric correction is further improved and the uncertainties on marine reflectance due to digitization are considered. Based on a two year archive of SEVIRI imagery, available every 15 min, the diurnal variability of *T* and K_{PAR} is investigated during cloud free periods and validated using half-hourly *T* and K_{PAR} data obtained from a system of moored buoys (SmartBuoys) in the southern North Sea. Based on numerous match-ups, 80% of SEVIRI derived *T* and K_{PAR} are within 53% and 39% of SmartBuoy *T* and K_{PAR}, respectively. Results further show that on cloud free days, the SEVIRI *T* and K_{PAR} signals are in phase with the SmartBuoy data, with an average difference in the timing of the maximum *T* and K_{PAR} of 11 min and 23 min, respectively. It is concluded that diurnal variability of *T* and K_{PAR} can now be mapped by remote sensing offering new opportunities for improving ecosystem models and monitoring of turbidity. Limitations of the current SEVIRI sensor and perspectives for design of future geostationary sensors and synergy with polar orbiting satellites are discussed.

1. Introduction

Polar-orbiting multispectral ocean colour sensors such as the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), the Moderate Resolution Imaging Spectroradiometer (MODIS), and Medium Resolution Imaging Spectrometer (MERIS) provide 2-day coverage of the global ocean and coastal zones since their respective launches in 1997 and 2002. These sensors have become well-established sources (McClain, 2009) of concentration of chlorophyll *a*, [Chl *a*] (see Table 1 for notation), and suspended particulate matter, [SPM], and there has been considerable progress towards many new products including particulate and dissolved organic and inorganic carbon (Stramski et al., 1999; Vantrepotte et al., 2011), particle size distribution (Loisel et al., 2006), phytoplankton species composition (Alvain et al., 2008), vertical light attenuation (Stumpf et al., 1999), turbidity (Nechad et al., 2009; Stumpf et al., 1999; Woodruff et al., 1999) etc. During the last decades the spectral and spatial resolution of space-borne ocean colour sensors has improved, from multispectral to hyperspectral (e.g., Hyperspectral Imager for the Coastal Ocean, launched in September 2009), and from 1 km nadir pixel resolution down to less than 100 m in coastal areas. The quality and quantity of atmospheric corrections and bio-optical algorithms has also significantly progressed.

Even though further progress can still be expected for polar-orbiting sensors in terms of sensor design and processing algorithms, their sampling frequency, typically once per day, is insufficient for many studies and applications. Many physical and biogeochemical processes in coastal regions show variability at time scales shorter than the daily sampling frequency of polar-orbiting sensors. For example, in situ measurements have shown that [SPM] can vary by a factor two or more during the day due to horizontal advection and/or vertical resuspension forced by tides or wind events (Eisma & Irion, 1988; Thompson et al., 2011). Hence, long term data series from polar-orbiting sensors are affected by aliasing that can only be treated indirectly (e.g., Stumpf et al., 1993). Furthermore, cloudiness and/or sun glint reduce data availability from typically once per day (e.g. mid-latitude MODIS imagery) to significantly less. Remote sensing applications, such as harmful algae bloom detection (Stumpf et al., 2003; Tomlinson et al., 2004), have critical vulnerability to such data gaps.

* Corresponding author at: Marine Physical Laboratory, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093-0238, USA. Tel.: +1 858 534 7841. Fax: +1 858 534 7641.
E-mail addresses: gneukermans@ucsd.edu (G. Neukermans), k.ruddick@mumm.ac.be (KG. Ruddick), naomi.greenwood@cefas.co.uk (N. Greenwood).

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Table 1
Notation.

Symbol	Parameter definition, units
A_0	SEVIRI solar channel calibration correction factor, dimensionless
A_S, A_T	[SPM] and turbidity retrieval algorithm calibration constants, mg L^{-1} or FNU
B_S, B_T	[SPM] and turbidity retrieval algorithm offsets, mg L^{-1} or FNU
b_b, b_{bp}, b_{bw}	Total, particulate, and pure water backscattering coefficient, m^{-1}
b_{bp}^m	b_{bp}:[SPM], mass-specific backscattering coefficient, m^2 g^{-1}
[Chl *a*]	Chlorophyll *a* pigment concentration, μg L^{-1}
c_f	Calibration gain factor for SEVIRI bands, mW m^{-2} sr^{-1} cm
Δ	Uncertainty of a measurement
Δ_a	Aerosol correction uncertainty, dimensionless
Δ_d	Digitization uncertainty, dimensionless
Δ_w	Turbid water uncertainty, dimensionless
ε	VIS06:VIS08 band ratio of aerosol reflectances, dimensionless
E_d	Downwelling spectral irradiance, W m^{-2} nm^{-1}
E_0^{TOA}	Extraterrestrial solar irradiance at TOA, W m^{-2} μm^{-1}
ϕ, ϕ_v, ϕ_0	Azimuth angle, sensor and sun azimuth angle
γ	VIS06:VIS08 ratio of two-way aerosol transmittances, dimensionless
K_d	Spectral diffuse attenuation coefficient for downwelling irradiance, m^{-1}
K_{PAR}^{SB}	Vertical attenuation of PAR derived from SmartBuoy PAR data, m^{-1}
$K_{PAR,\otimes}$	Vertical attenuation of PAR derived from SEVIRI on the HRV grid, m^{-1}
K_{PAR}	Diffuse attenuation coefficient of PAR, m^{-1}
$\bar{K}_{PAR}$	Vertically averaged diffuse attenuation coefficient of PAR, m^{-1}
λ	Wavelength of light, nm or μm
λ_0	Waveband central wavelength, nm or μm
L_a^{TOA}	Aerosol radiance at TOA, W m^{-2} sr^{-1} μm^{-1}
L_g^{TOA}	Sun glint radiance at TOA, W m^{-2} sr^{-1} μm^{-1}
L_r^{TOA}	Rayleigh (air molecule) radiance at TOA, W m^{-2} sr^{-1} μm^{-1}
L_{ra}^{TOA}	Aerosol–Rayleigh multiple scattering radiance at TOA, W m^{-2} sr^{-1} μm^{-1}
L_{tot}^{TOA}	Total radiance at TOA, W m^{-2} sr^{-1} μm^{-1}
L_w^{TOA}, L_w^{0+}	Water-leaving radiance at TOA or above-water, W m^{-2} sr^{-1} μm^{-1}
L_{wc}^{TOA}	White-cap radiance at TOA, W m^{-2} sr^{-1} μm^{-1}
m	Two-way air mass, dimensionless
n_o	Total number of observations
n_x	Number of outliers
$\omega(\lambda)$	Sensor spectral response function, dimensionless
PAR	Photosynthetically active radiation, photons s^{-1} m^{-2}
r	Correlation coefficient, dimensionless
r_0	Calibration offset factor for SEVIRI bands, mW m^{-2} sr^{-1} cm
ρ	Reflectance, dimensionless
$\bar{\rho}$	Spatial average of the HRV reflectance on the VIS06 grid, dimensionless
$\hat{\rho}$	Spatial anomaly of the HRV reflectance within the VIS06 grid, dimensionless
ρ_a^{TOA}	Aerosol reflectance at TOA, dimensionless
ρ_c	Rayleigh and gas corrected reflectance at TOA, dimensionless
ρ_g^{TOA}	Sun glint reflectance at TOA, dimensionless
ρ_{ra}^{TOA}	Rayleigh–aerosol interaction reflectance at TOA, dimensionless
ρ_{tot}^{TOA}	Total reflectance at TOA, dimensionless
ρ_w^{TOA}	Marine reflectance at TOA, dimensionless
ρ_w^{0+}	Above-water marine reflectance, dimensionless
$\rho_{w,\otimes}^{0+}$	Above-water marine reflectance on HRV grid, dimensionless
ρ_{wc}^{TOA}	White cap reflectance at TOA, dimensionless
σ	VIS06:VIS08 band ratio of marine reflectance (dimensionless), or standard deviation, depending on the context
[SPM]	Suspended particulate matter concentration, g m^{-3}
$t_o^a, t_v^a, t_{o,v}^a$	Sun–sea, sea-sensor, and two-way aerosol transmittance, dimensionless
$t_o^g, t_v^g, t_{o,v}^g$	Sun–sea, sea-sensor, and two-way atmospheric gas transmittance, dimensionless
$t_o^r, t_v^r, t_{o,v}^r$	Sun–sea, sea-sensor, and two-way Rayleigh transmittance, dimensionless
T	Turbidity, FNU
T_0, T_v, $T_{o,v}$	Total sun–sea, sea-sensor, and two-way atmospheric transmittance, dimensionless
T^{SB}	Turbidity recorded by SmartBuoy, m^{-1}
$T_\otimes$	Turbidity retrieved by SEVIRI on the HRV grid, FNU
θ_v	Viewing zenith angle, degrees
θ_0	Solar zenith angle, degrees

Ocean colour remote sensing from geostationary sensors has the potential to overcome or mitigate these limitations: the availability of ocean colour data would significantly increase during periods of scattered clouds (Mazeran & Meskini, 2008) and the much higher sampling frequency, typically 1 per hour or higher, allows to observe the diurnal or tidal cycles of optical and biogeochemical processes of the open ocean and coastal waters. Geostationary ocean colour data offers possibilities to study the coupling between physics and biogeochemistry, to quantify fluxes and study transport of carbon and sediment. Assimilation of geostationary ocean colour data into ecosystem models may improve modelling results and eutrophication studies. For example, the availability of light to marine organisms may vary rapidly in coastal environments due to rapid changes in water turbidity. In light-limited ecosystems such as the Channel and Southern Bight of the North Sea, this unrepresented high frequency variability of underwater light may be a cause of discrepancy between the modelled and observed timing of the phytoplankton spring bloom (Lacroix et al., 2007).

The Geostationary Ocean Colour Imager (GOCI, Faure et al., 2008), launched by the Korean Space Agency (KORDI) in June 2010, is the first ocean colour sensor in geostationary orbit. It provides hourly multispectral imagery of waters surrounding the Korean peninsula at a spatial resolution of 500 m. Other national and international space agencies have plans to launch geostationary ocean colour sensors. The European Space Agency (ESA) has commissioned studies on user requirements and some concept design in the framework of Geo-Oculus. A proposal to host a GOCI-like sensor on a geostationary telecommunication satellite has been submitted to ESA (Antoine et al., 2011). The Hosted Ocean Colour Imager, HOCI, would provide hourly multi-spectral imagery of the European seas and adjacent open ocean from late 2014. NASA is preparing the Geostationary Coastal Ocean and Air Pollution Events (GEO-CAPE) mission, planned to be operational by 2020 (NRC, 2007).

Even though the Spinning Enhanced Visible and Infrared Imager (SEVIRI) radiometer onboard the METEOSAT Second Generation (MSG) satellite platform is not capable of ocean colour remote sensing because of its limited spectral resolution, SEVIRI has sufficient bands for the mapping of [SPM] in turbid waters (Neukermans et al., 2009). SEVIRI imagery, available since 2004 at 15 minute temporal resolution, offers the possibility to address the problems (reduced signal at high orbit and high viewing zenith) and advantages (high temporal resolution, stable viewing geometry) specific to the geostationary orbit. The feasibility study for mapping [SPM] with SEVIRI (Neukermans et al., 2009) was a first attempt to exploit the potential of a geostationary platform for marine optics. This study, based on a one month SEVIRI dataset of the southern North Sea, has shown that [SPM] can be reliably detected in turbid waters, but with considerable uncertainties in clear waters due to SEVIRI's low radiometric resolution. Even though at a much lower spatial resolution (3 km × 6.5 km), SEVIRI [SPM] products were shown to correlate well with MODIS-AQUA 667 nm [SPM] products, and SEVIRI's marine reflectance correlated well with marine reflectance from the spectrally similar MODIS-AQUA 645 nm band (Neukermans, 2012).

The present study follows up on the successful feasibility study of Neukermans et al. (2009). The specific objectives of this study are to (i) improve the spatial resolution of SEVIRI products using its High Resolution Visual (HRV) band, (ii) improve the quality of the existing atmospheric correction and extend its uncertainty estimation to include digitization effects, (iii) extend the methodology to the mapping of turbidity, *T*, and vertical attenuation of photosynthetically active radiation (PAR), K_{PAR}, with uncertainty estimates, (iv) investigate diurnal variability of *T* and K_{PAR} during cloud free periods based on a two year SEVIRI archive, and (v) validate SEVIRI *T* and K_{PAR} products and their temporal dynamics using *T* and K_{PAR} data obtained from a system of moored buoys in the southern North Sea.