

Remote Sensing of Suspended Particulate Matter in Turbid Waters: State of the Art and Future Perspectives

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1. INTRODUCTION

The objective of this study is to review the state of the art for remote sensing of suspended particulate matter (SPM) in turbid waters and to outline future perspectives. The main focus of the review is on medium resolution (typically 1 km) satellite applications in coastal waters, but much of the methodology is applicable also to inland waters and airborne applications (Dekker et al., 2001). The review is illustrated with results from recent and ongoing research from the BELCOLOUR-2 project.

Interest in remote sensing of SPM is motivated by the environmental and economic importance of sediment transport in coastal waters. Applications include the optimisation of dredging/dumping operations, assessing the environmental impact of offshore construction activities, understanding geomorphological change, evaluating fluxes of particulate organic carbon from rivers to the sea, etc.. These applications are generally addressed by model studies supported by *in situ* and/or remote sensing data (Vos et al., 2000), thus combining the advantage of each of these sources of information: the forecast ability and complete 4D coverage of modelling, the higher reliability of *in situ* data and the good spatio-temporal coverage of remote sensing. While progress is continuous also in modelling techniques and in *in situ* instrumentation, the attractiveness of remote sensing as an information source has increased greatly over the last ten years as the new generation of medium resolution satellite sensors (SeaWiFS, MERIS and particularly MODIS-AQUA) has become available.

Various parameters may be used for describing the concentration and characteristics of suspended particulate matter according to whether mass or optical properties are of interest and whether particulate matter is sorted into organic/inorganic fractions or not ("total"). In the present review the focus is on mapping of Total Suspended Matter (TSM). The precise definition of this parameter, by means of a unique measurement procedure, is surprisingly difficult because the definition of "particle" implies a threshold size cutting off the smallest particles from a continuous size distribution, e.g. see Figure 1 of (Stramski et al., 2004). For example, the International Standards Organisation defines "suspended solids" as "solids removed by filtration or centrifuging under specified conditions" (ISO, 1989) and has described a method for determination based on filtration through glass fibre filters (ISO, 1997), but the results of such a measurement may vary significantly according to the effective pore size of filters. Moreover the ISO method is not well adapted for TSM measurement in marine waters where concentrations comparable to the stated detection limit of 2 mg/l are important. For such low

concentration waters the method used to remove salt from filters becomes critical and is perhaps best addressed in the REVAMP protocol (Tilstone and Moore, 2002), used for validation of MERIS, although further improvements and more precise specification of this measurement method may be expected in the future.

In remote sensing studies TSM is estimated via the optical properties of suspended particles assuming, either directly or indirectly, a constant relationship between particle mass and particulate scattering or absorption. It is well-known that this relationship between particle mass and optical properties in reality varies as function of particle size and composition (refractive index) (Babin et al., 2003a), giving an important limit on the generality and accuracy of remote sensing algorithms for estimating TSM. TSM is the main focus here and is the parameter generally required for sediment transport applications. However, it is interesting to note that turbidity, defined from the measurement of 90° scattered light and more easily measurable *in situ*, may be a more relevant parameter for certain water quality applications where optical properties, such as water transparency, are directly important.

2. METHODS

Although ocean optics research has historically been oriented more towards estimation of chlorophyll *a* concentration, in turbid waters TSM is a much “easier” parameter to detect optically even with the crudest of instruments. While subtle changes of water colour relating to varying chlorophyll concentration may require high precision measurements, spatial variations of TSM can easily be seen in LANDSAT imagery from the 1970s, in Google Earth imagery or by a casual observer on a ship or plane. As an example Figure 1 shows spatial variations of TSM visible even through thin, patchy clouds.



Figure 1. Top-of-atmosphere Red-Green-Blue composite from MERIS data of 11th June 2006. While thin clouds and contrails cover much of the region it is still possible to see underlying water colour variations related to regions of high TSM (light green) contrasting with offshore regions of low TSM (dark blue).

Algorithms for quantification of TSM from water-leaving reflectance fall roughly into one of three families: single band, band ratio or multispectral as described in the following sections.

2.1 SINGLE BAND ALGORITHMS

The ease of detection of TSM features is related to the almost linear relationship between TSM and reflectance at any given wavelength, at least for low and moderate reflectances (Althuis and Shimwell, 1995). At higher reflectances this relationship becomes non-linear and the reflectance is usually considered to approach asymptotically a maximal “saturation” value (Bowers et al., 1998; Doxaran et al., 2002) where an increase in TSM concentration no longer affects reflectance. Many algorithms have been developed to estimate TSM from reflectance at a single wavelength. For example, based on the first order reflectance model of (Gordon et al., 1988) and assumptions that total backscatter and particulate absorption are proportional to TSM concentration, S , and that space-time (but not wavelength) variability of non-particulate absorption can be neglected, (Nechad et al., 2003; Nechad et al., 2008 (in preparation)) suggest the algorithm:

$$S = A \frac{R_{rs}}{1 - R_{rs}/C} \quad (1)$$

where R_{rs} is the remote sensing reflectance defined as water-leaving radiance divided by above-water downwelling irradiance, and A and C are wavelength-dependent calibration coefficients, with C representing the saturation reflectance. In this study A is determined by regression analysis of sea-borne measurements of R_{rs} and S , and is related theoretically to inherent optical properties. The relationship between S and R_{rs} defined by this family of one band algorithms is illustrated in Figure 2 for various wavelengths.

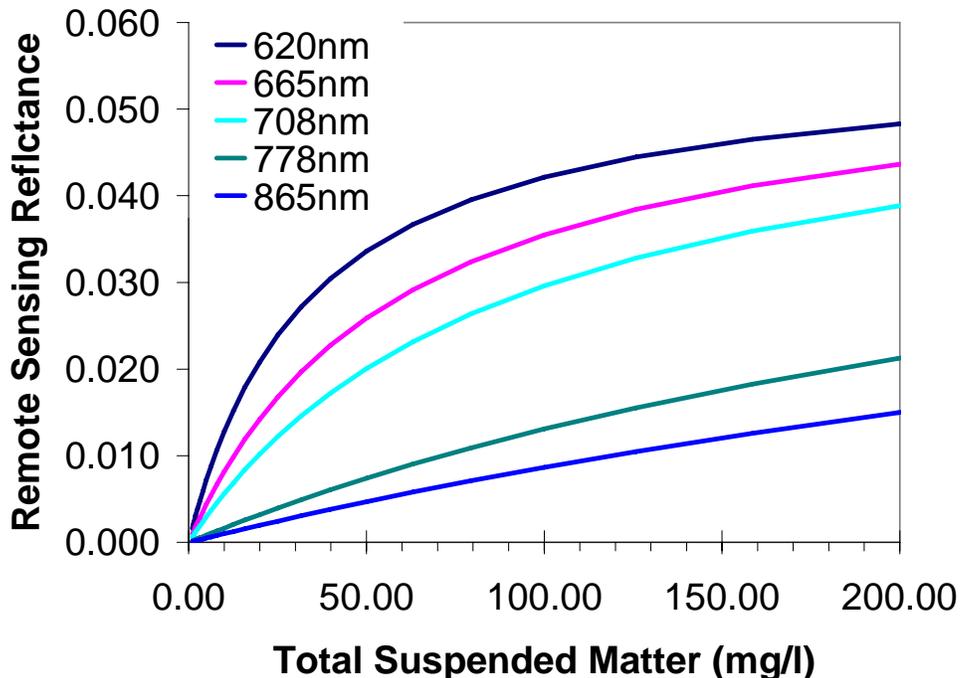


Figure 2. Variation of remote sensing reflectance with TSM according to the model (1) for various red and near infrared wavelengths. For low reflectances (<0.01) the relationship is approximately linear, becoming non-linear but still monotonic for moderate reflectances (0.01 to 0.03) before reaching an asymptotic value (near 0.05).

Alternative one band algorithms have been suggested in a number of studies with functional forms of $S(R_{rs})$ generally involving a linear, low reflectance, regime and a monotonic but non-linear high reflectance regime, although various functional forms have been suggested for the latter including logarithmic (Ouillon et al., 1997), power law (Ahn et al., 2001), etc. Calibration of such algorithms may be made from simultaneous measurements of S and R_{rs} (satellite or *in situ*) or from measurements of specific inherent optical properties (Van Der Woerd and Pasterkamp, 2004).

The performance of such single band algorithms is generally best for low to moderate reflectances (linear regime) and their accuracy depends on the validity of the underlying assumptions, particularly that total backscatter is proportional to TSM concentration and that space-time variability of non-particulate absorption can be neglected. The latter requirement suggests that the use of red or near infrared bands is preferred so that non-particulate absorption arises essentially from pure water absorption. The requirement of low to moderate reflectance suggests that the optimal wavelength will depend on concentration and fixed wavelength algorithms will typically be limited to a certain range of concentrations. Alternatively, if sufficient wavelengths of data are available, an adaptive algorithm could be envisaged using the basic one-band algorithm given by (1) but with the retrieval wavelength being chosen differently for each input reflectance spectrum.

An interesting variant on these algorithms is the use of algorithms based on the difference between two bands, generally red and near infrared. Such algorithms have similar properties to the single band algorithms but combine the TSM retrieval with a full aerosol correction (Stumpf and Pennock, 1989) or a residual correction for aerosols after atmospheric correction (Hu et al., 2004; Sterckx et al., 2007).

The appropriateness of single band algorithms for TSM estimation means that TSM mapping can be made not just with dedicated ocean colour sensors such as MODIS or MERIS but also with a very wide range of optical remote sensors, including SPOT, LANDSAT, ASTER, AVHRR, SEVIRI, etc.

2.2 BAND RATIO ALGORITHMS

As an alternative to single band algorithms, two-band ratio algorithms have been suggested for TSM estimation by (Doxaran et al., 2002). One band algorithms are highly sensitive to backscatter and hence are subject to uncertainties if the mass-specific backscatter coefficient has high natural variability. By contrast, band ratio algorithms can be designed to be less sensitive to this natural variability since spectrally flat backscatter effects largely cancel when a ratio is taken. Similarly band ratio algorithms will be less sensitive to illumination conditions (Doxaran et al., 2003). Band ratio algorithms may however be sensitive to the natural variability of sediment absorption properties since the use of a reflectance ratio shifts the relevant physics from backscattering properties to absorption properties (Moore et al., 1999).

2.3 MULTISPECTRAL ALGORITHMS

With dedicated ocean colour sensors, many more bands of data are available. Use of this extra information, provided it is reliable enough, could improve algorithm performance. The mathematical methods used in multispectral algorithms are quite diverse. However, this family of algorithms is generally based on a forward model defining reflectance as function of inherent optical properties, including particulate backscatter and absorption, and an inversion procedure to find the model

reflectance spectrum that best fits the measured reflectance (Doerffer and Fischer, 1994). The IOP set corresponding to this best-fitting model reflectance spectrum is then related to TSM concentration. One operational example of a multispectral TSM algorithm is the standard case 2 water algorithm for MERIS (Doerffer and Schiller, 1997) which uses a forward model based on radiative transfer simulations and a neural network inversion procedure.

One major advantage of the multispectral algorithms is the possibility of automatically adapting to a varying mixture of algal and non-algal particles and thus offering greater generality. Put simply, the analysis of multispectral data can provide an estimate of phytoplankton absorption and hence of the contribution of algal particles to total particulate backscatter. It is no longer necessary to assume, as in the one-band approach, constant TSM-specific particulate backscatter. Moreover the consistency between the measured reflectance spectrum and the best-fit modelled can provide indications on the quality of the water-leaving reflectance data and on the uncertainty of the retrieved TSM. However, such algorithms are still subject to uncertainties relating to conversion from optical properties to mass concentration.

2.4 VALIDATION

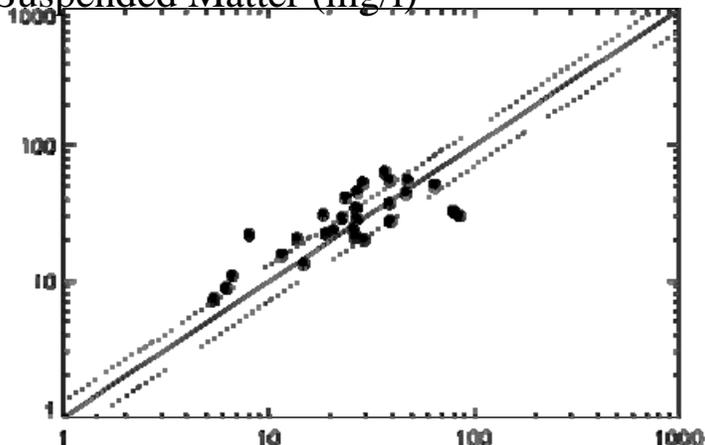
The primary approach to TSM product validation is by “match-up” validation, comparing the data value for a satellite pixel with an *in situ* measurement from a location within that pixel and acquired almost simultaneously (in coastal waters, within 1 hour according to the recommendations of the MERIS Validation Team). An example of such a comparison is shown in Figure 3. Differences between *in situ* and satellite measurements are typically many tens of per cent. Analysis of these differences is a challenging scientific exercise because of the large number of sources of uncertainty both on the satellite-side (TSM algorithm including variability of mass-specific properties, water-leaving reflectance input including atmospheric correction uncertainties, etc.) and on the measurement side (space-time mismatch with satellite pixel, mixing of sample, rinsing/weighing of filters, etc.). The lack of simultaneous *in situ* data is a serious drawback.

TSM algorithm validation using seaborne reflectance measurements is also important and removes at least some sources of difference (atmospheric correction) and improves the space-time match of the two datasets.

Depending on the application needs, it may be more relevant to validate at the level of multitemporal products such as monthly or climatological averages. Such an approach enables much more *in situ* data to be used. While appropriate for establishing the fitness for purpose of such multitemporal products it can be difficult to understand and trace the causes of satellite/*in situ* measurement differences because of the asynchronicity of data.

Although not generally considered as validation, *in situ* measurements of mass-specific inherent optical properties and study of their natural variability (Astoreca et al., 2006; Babin et al., 2003a; Babin et al., 2003b), provides important information on related product uncertainty.

Satellite, Total Suspended Matter (mg/l)



In situ, Total Suspended Matter (mg/l)

Figure 3. Validation of TSM derived from the MODIS 678nm band using algorithm (1) against simultaneous in situ measurements in Southern North Sea waters. [Points generally lie within 30% of the 1-1 line for a range of concentrations from 5 to 100 mg/l]

2.5 QUALITY CONTROL

In addition to *a posteriori* validation analysis, methods are emerging for automatic quality control of satellite data products. Processing flags indicating warning conditions relating to atmospheric correction such as negative water-leaving reflectances or out-of-bound aerosol products are a standard feature of operational ocean colour processing chains (Robinson et al., 2003). Multispectral inversion algorithms also allow (partial) assessment of product uncertainty by calculating the range of TSM values that could correspond to a reasonable spectral fit between the satellite measurement and the modelled reflectance that would result from the TSM algorithm output. This product uncertainty can be output in map form alongside the product itself as similar to those generated for chlorophyll products by (Peters et al., 2005).

3. RESULTS

Maps of instantaneous TSM distribution form the basis of all satellite TSM products and can be downloaded from various global or regional web sites – e.g. Figure 4.

Depending on the application requirements these products can be combined into multitemporal composite maps representing a variety of statistical parameters (mean, median, percentile 90, etc. in linear or logarithmic space) over any suitable time scale (daily, weekly, monthly, etc. at fixed intervals or as rolling average). Methods for multitemporal binning and caveats are discussed in detail in (IOCCG, 2004).

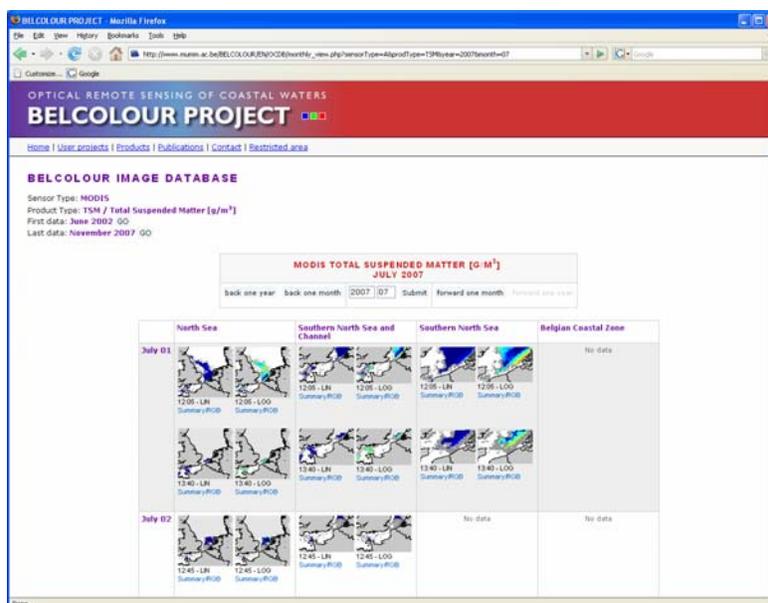


Figure 4. Screenshot from the TSM archive distributed by the BELCOLOUR project (<http://www.mumm.ac.be/BELCOLOUR>). [shows thumbnails of available imagery for each day at different spatial zooms from the whole North Sea down to the Belgian coastal zone]

Now that the medium resolution ocean colour sensors have been running for a few years it is also possible to analyse time series of TSM. One example is shown in Figure 5, where a clear annual cycle of TSM is seen that is related to the annual cycle of wind speed via the process of sediment resuspension.

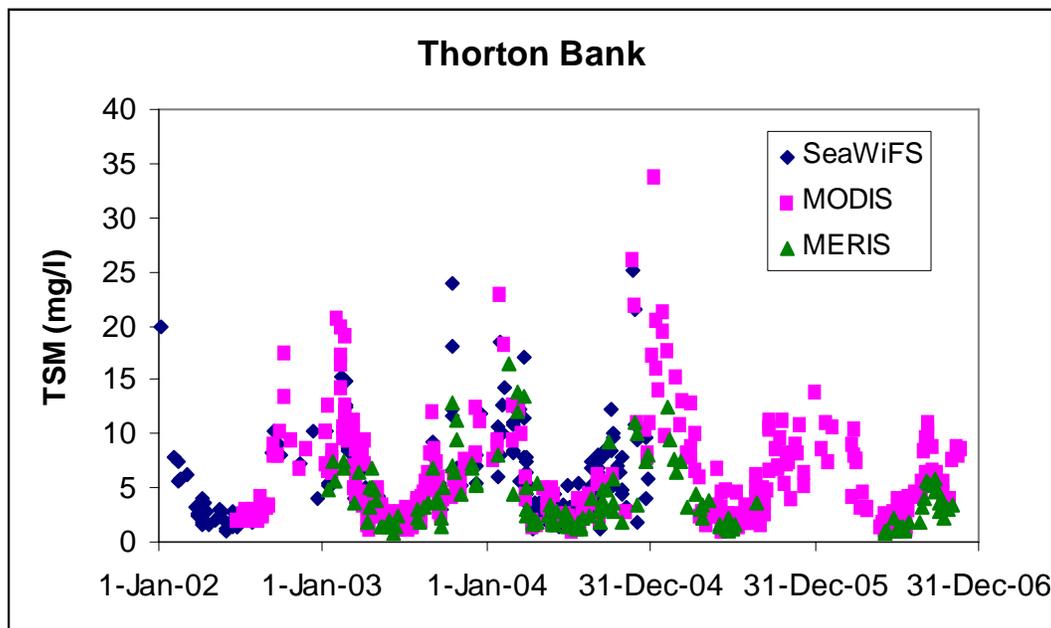


Figure 5. A 5-year time series of TSM for a location in Belgian waters ($51^{\circ} 33.14'N$, $2^{\circ} 59.55'E$) as derived from SeaWiFS and MODIS data using the algorithm (1) and from MERIS data using the standard MERIS product. Data from the 3 sensors is highly coherent. A strong seasonal cycle is seen which is related to sediment resuspension by the higher winds occurring in winter.

4. DISCUSSION

Mapping of TSM by optical remote sensors is now routine and existing algorithms, although quite diverse in nature, are quite robust. Product generation has matured from the basic “level 2” instantaneous images to now include time series for fixed locations, e.g. (Ifremer) and multitemporal composite images.

4.1 LIMITATIONS

However, a number of key limitations on TSM mapping exist

- Frequent cloudiness can be a severe obstacle to acquiring data in many regions.
- Only information on near-surface TSM can be provided by remote sensing.
- The absolute accuracy of TSM estimations can be poor if particle characteristics, particularly TSM-specific backscatter, are significantly different from the algorithm calibration dataset.
- The quality of TSM products is often poorly known.
- Atmospheric correction errors may impact on TSM estimation, particularly in nearshore or inland waters with strong adjacency effects.
- The temporal coverage of polar-orbiting satellite sensors such as AVHRR, MODIS and MERIS, although superior to ship-based TSM surveys, may be insufficient in coastal regions with tidal dynamics.

4.2 FUTURE PERSPECTIVES

Of course, these limitations provide the targets for researchers to do better and innovative methods are emerging to deal even with problems such as cloudiness. Promising directions for solutions to these problems are outlined below.

Geostationary sensors - For example, for situations of scattered clouds the once-per-day data from polar-orbiters is often highly unsatisfactory. However, the use of data from geostationary sensors (e.g. every 15 minutes!) may provide a nearly complete daily composite. A feasibility study, based on data from the SEVIRI sensor onboard METEOSAT Second Generation, is described by (Neukermans et al., 2008) and illustrated in Figure 6. The use of geostationary sensors can also overcome problems of high frequency variability of TSM. Although there are technical limitations to geostationary sensors (particularly for high latitudes where viewing zenith angle becomes prohibitive) as well as cost constraints related to the much higher orbit, the potential for geostationary remote sensing is enormous.

Statistical information - In nature TSM distributions in coastal waters are highly correlated in space and time because of the dominant large scale physical processes. Spatial distributions are often highly structured by bathymetric features and by river plumes. For example the high turbidity features seen in Figure 1 can be seen on the majority of satellite TSM maps of the Southern North Waters, albeit at different intensities. Temporal variability from day to day (or hour to hour) may be limited. Despite the strong constraints on spatial and temporal variability provided by nature, all operational TSM processing chains currently process data independently for each pixel for each image. The information contained in long time series of images could be exploited to provide both a synthesis of dominant spatio-temporal processes and to provide reasonable TSM estimates for cloudy pixels (Sirjacobs et al.,

2008). Moreover, exploitation of information contained in nearby pixels in space or time could be used to flag suspect or extreme data in cloud-free pixels.

Automated quality control - Now that TSM retrieval algorithms are becoming rather mature the focus for algorithmic research is shifting to the retrieval of TSM product *quality*. Approaches both for providing pixel-by-pixel quality estimates and detailed flags relating to special conditions or product confidence are emerging, e.g. the MERIS Product Confidence Flag. Grey areas are creeping into TSM maps where data providers/users prefer not to show data that might be suspect.

Mass-specific optical properties - Natural variability of mass-specific optical properties is likely to remain a significant problem for TSM mapping in a global context. *In situ* measurements of optical properties, particularly TSM-specific backscatter, may help constrain regional algorithms in this respect.

Vertical extrapolation – The need for below-surface information on TSM can clearly not be met by remote sensing alone and requires coupling of remote sensing information with sediment transport models. This has already been demonstrated in a number of studies (Fettweis et al., 2007; Vos et al., 2000).

Atmospheric correction – Atmospheric correction remains a significant problem for optical remote sensing, although TSM algorithms using red and near infrared wavelengths may suffer less from atmospheric correction uncertainties than chlorophyll *a* retrieval algorithms. Significant progress has been made over the last ten years to improve atmospheric correction problems relating to absorbing aerosols and turbid water effects, thus pulling the frontier of acceptable data closer to the coast. The critical limit is now often reached when adjacency effects become important. There is a good scientific understanding of this issue (Santer and Schmechtig, 2000) and a capacity to at least detect when problems may occur (Sterckx et al., 2008). Operational processing algorithms are under development but are not yet available.

Validation – Validation will remain a key issue because of the sparsity of *in situ* data. Continuously monitoring instruments on moored buoys (Mills et al., 2003) and ships of opportunity (Hydes et al., 2006) may contribute to filling this data gap, but only via optical proxies for TSM. There seems to be no “quick fix” to this problem, just a need for more seaborne measurements. Improved standardisation of measurement protocols and international sharing of data could optimise the exploitation of these seaborne resources.

4.3 CONCLUSION

In conclusion, mapping of TSM has progressed enormously over the last 10 years as witnessed by the maturing of products and applications. 10 years ago research focussed mainly on TSM algorithm design and exploitation concentrated on inspection of a few instantaneous TSM maps. Now TSM products are standard output from ocean colour sensors and may carry quality estimates or product confidence indications. Exploitation has progressed to use of higher level products (e.g. multitemporal composites) and/or time series analysis. Research challenges remain, but exciting new prospects have been identified, particularly the use of geostationary sensors (Neukermans et al., 2008) and the exploitation of geostatistical correlations in space and time (Sirjacobs et al., 2008).

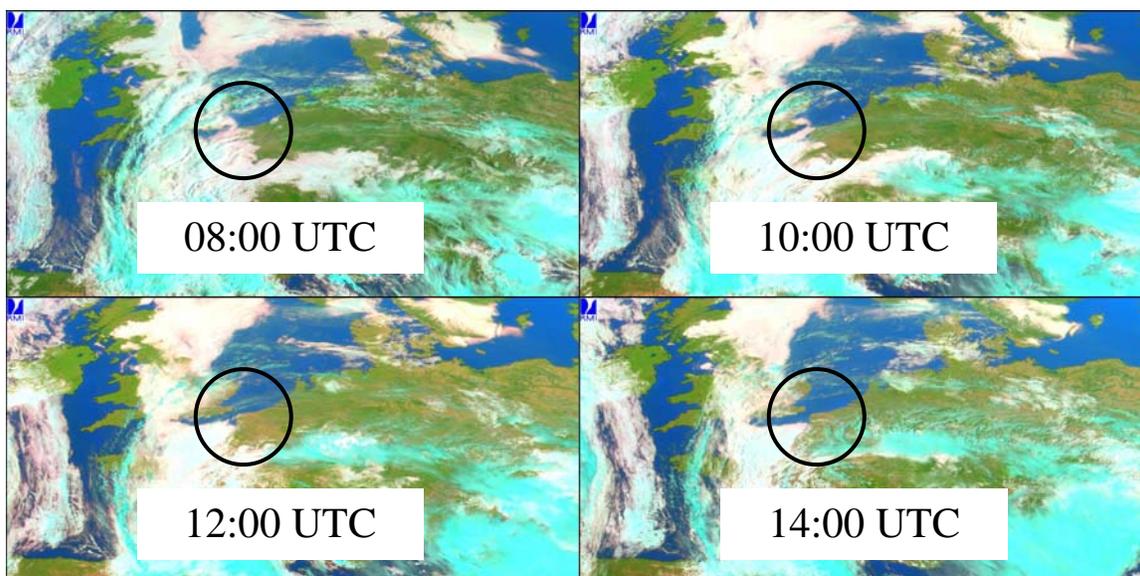


Figure 6. RGB composite imagery from the SEVIRI sensor for selected times during 16th September 2008. MODIS imagery is available for this day at 12:05 UTC but is severely cloud-contaminated for the Southern North Sea (shown here as black circle). Since the cloud conditions are highly variable over the day a composite of SEVIRI imagery could give full coverage where MODIS gives only very partial coverage. Data courtesy of the Belgian Royal Meteorological Institute.

Of course, now that TSM products are becoming more reliable scientists and users want more information on the suspended particulate matter. What is the particle size distribution? What is the particle composition? These questions will push algorithm development in new directions and stimulate the need for more data to be used as algorithm input both from optical remote sensing itself (hyperspectral, multi-look? polarisation?) and from other sources (geostatistical, sediment transport modelling).

5. ACKNOWLEDGEMENTS

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