An investigation of the potential use of ocean colour remote sensing to assess the influence of variations in freshwater inputs to coastal ecosystems: Phytoplankton and Sediment Dynamics of the Natal Bight.

Report to the
Water Research Commission

by

Stewart Bernard[1] and Marie Smith[2]
1. Ecosystems Earth Observation, CSIR-NRE
2. Department of Oceanography, University of Cape Town

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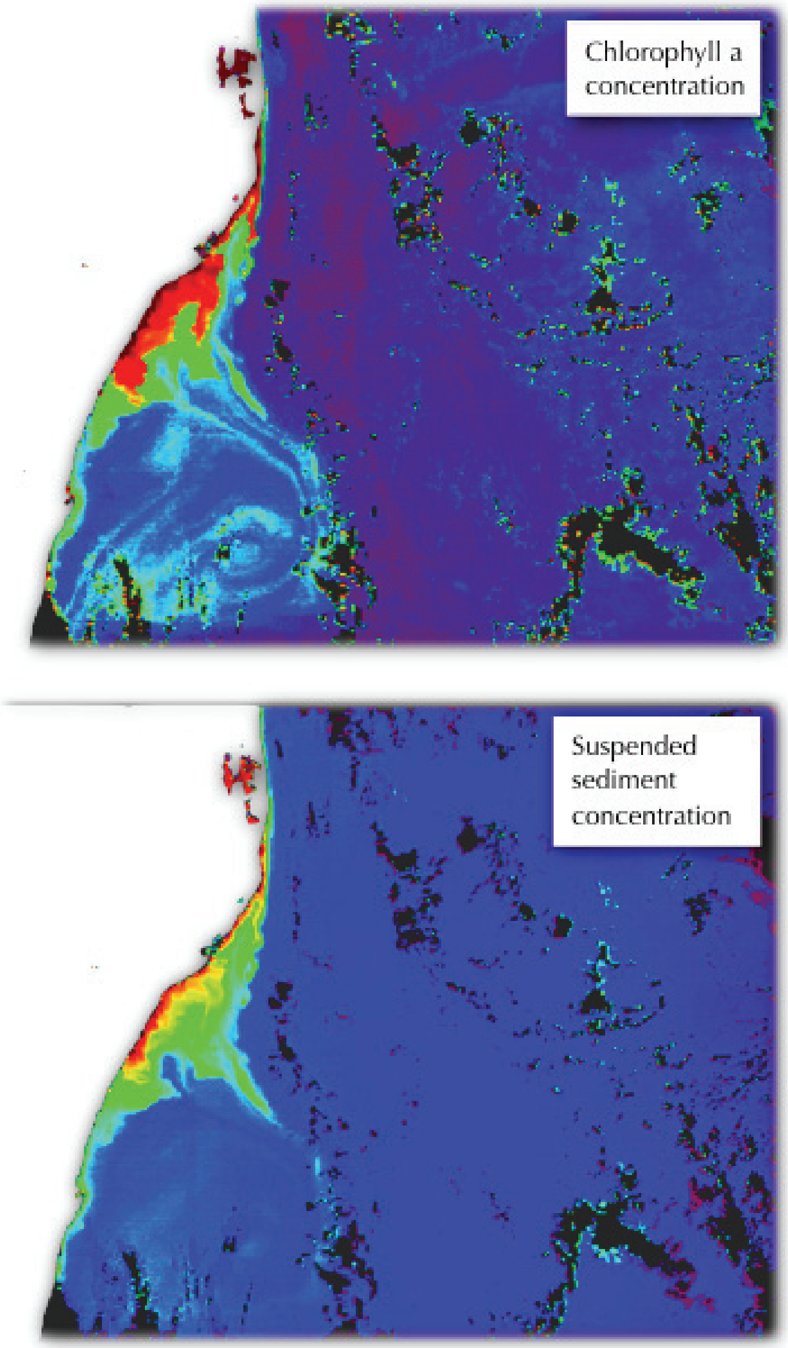

Chlorophyll a and suspended sediment concentration from the European Space Agency's Medium Resolution Imaging Spectrometer (MERIS) using the Case 2 Regional Processor: a Natal Pulse event on 3rd March 2004

Executive Summary

New Regional Ocean Colour Products: New Case 2 ocean colour products from the Medium Resolution Imaging Sensor (MERIS) have been analysed for the first time in South Africa, providing a preliminary qualitative ability to synoptically map phytoplankton biomass, suspended sediment and dissolved organic material in the Natal Bight. Preliminary findings indicate that the default MERIS "Algal 1" and "Algal 2" products are not effective in the Case 2 waters of the Natal Bight; that the Case 2 Regional (C2R) processor is more accurate and robust in these inshore water types, but appears to function less well in mesotrophic and oligotrophic offshore waters; that the fluorescence line height products are extremely useful in distinguishing between phytoplankton and sediment dominated synoptic features; and that ultimately an optimal regional product may consist of a "switching" algorithm, e.g. using the C2R processor for inshore Case 2 waters, and the default "Algal 1" product for offshore waters.

New Insights into System Function: The new C2R ocean colour products provide new insight into event scale drivers in the Natal Bight/Agulhas system, by allowing simultaneous estimates of phytoplankton biomass, suspended sediment concentration and dissolved organic material. Relatively high suspended sediment concentrations do not appear to significantly depress production in the inshore zone, indicating that additional nutrient loading from the dissolved phase in riverine influenced waters outweigh the potential light limiting effects on production resulting from sediment-associated reduced light availability. Consistent with this, it also appears that riverine influences may enhance offshore productivity, as a function of offshore transport and recirculation associated with the entrainment effects of the Agulhas current acting on the offshore boundary of the Bight. Additionally, using the new ocean colour products as synoptic indicators of the distribution of riverine influenced waters, it appears that the Agulhas Current is an important driver of the circulation in the Bight on the event scale through upwelling and entrainment mechanisms.

Regional Ocean Colour Validation: The project has acquired the first radiometric ocean colour validation measurements in the Natal Bight, as a collaboration between the University of Cape Town, the University of KwaZulu-Natal and the Council for Scientific and Industrial Research. Whilst these data are still being processed, preliminary findings support the first point above, i.e. the MERIS C2R algorithm provides optimal products in Case 2 waters, but the default atmospheric correction and "Algal 1" in-water products will serve users better in offshore Case 1 waters. Validation data have been gathered during two field expeditions in 2009 and 2010, and are to be expanded to form the basis of one of the project-associated publications due end 2010. These validation data will form the basis for providing error products along with geophysical products routinely in the region – an important step in the effective utilisation of the ocean colour data in climate-related time series analyses.

User Consultation: The project has carried out broad consultation with earth observation and marine stake-holders including the University of Cape Town, the University of KwaZulu-Natal, the Council for Scientific and Industrial Research, the Oceanographic Research Institute, and the Department of Environmental Affairs. One outcome of this consultation/community building has been the joint UCT/UKZN/CSIR validation field exercises, which have resulted in the submission of a conference paper and should produce a peer-reviewed publication submission end 2010.

Placing Project Outputs in Public Space: Subject to the agreement of the WRC, this report (or the relevant sections) will be made available on the Marine Remote Sensing Unit's web site to provide users with information regarding regionally optimised ocean colour products. Publications emerging from the project will also be placed on the web site when they are available. Trial operational ocean colour products are currently available through the same site – www.chlorogin-africa.org.za. Whilst these are currently restricted to the regionally sub-optimal MERIS and MODIS default products, processing for the new regionally optimised products discussed will be implemented by end 2010. A conference paper has been submitted to the All African Remote Sensing of the Environment conference in October 2010, and a paper will be submitted to a peer reviewed journal (probably Remote Sensing of the Environment) end 2010.

Capacity Building: High level capacity building has been achieved, given the scope of the project, through Marie Smith's MSc, expected to conclude end 2010. Ms Smith has independently planned and executed two field expeditions, attended an international ocean colour training course in October 2009, has demonstrated new processing and analysis capabilities, and will expect two publications as detailed above.

Acknowledgements

Roy van Ballegooyen (CSIR) for promoting the original research; Dr Sean O'Donoghue (UKZN) for assisting with the planning of fieldwork, data collection and analysis. Dr AJ Smit (UKZN) for the use of his lab and equipment; Dr Trevor Probyn and Dr Grant Pitcher (DAFF) for the use of their equipment and lab space; Dr Isabelle Ansorge and Dr Howard Waldron (UCT) for the use of their equipment; Christo Whittle (UCT) for providing MODIS data; John and Ryan Harding for skippering the boat and assisting with data collection; Rod Smith for repairing equipment and assisting in transporting equipment

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Table of Symbols/Acronyms

Symbol	Definition	Unit
a	absorption coefficient	m^{-1}
a_g	gelsbtoff absorption coefficient	m^{-1}
a_dg	combined gelsbtoff and detrital absorption coefficient	m^{-1}
a_ph	Phytoplankton absorption coefficient	m^{-1}
b_b	backscattering coefficient	m^{-1}
C2R	Case 2 Regional Processor	
CDOM	Coloured Dissolved Organic Matter or gelbstoff	
Chl-a	total algal chlorophyll *a* concentration	$mg\ m^{-3}$
CSIR	Council for Scientific and Industrial Research	
ESA	European Space Agency	
FLH	Fluorescence Line Height	
GF/F	Glass Fibre Filter (Whatman)	
MERIS	Medium Resolution Imaging Spectrometer (ESA)	
MODIS	Moderate Resolution Imaging Spectrometer (NASA)	
OCR	Ocean Colour Radiometry	
QAA	Quasi Analytical Algorithm	
NASA	North American Space Agency	
Rrs	remote sensing reflectance	sr^{-1}
SeaWiFS	Sea viewing Wide Field of View Sensor	
SPM	Suspended Particulate Matter	$g\ m^{-3}$
SST	Sea Surface Temperature	
TSM	Total Suspended Matter	$g\ m^{-3}$
TSRB	Tethered Spectral Radiometer Buoy (Satlantic)	
UCT	University of Cape Town	
UKZN	University of KwaZulu-Natal	
λ	in vacuo wavelength	nm

1. Introduction

Studies linked to the Thukela catchment, have recently drawn attention to the significance of freshwater influxes into the marine environment beyond the limits of estuaries. Van Ballegooyen *et al.* (2006) have emphasised the necessity for cost-effective routine assessment of the productivity of riverine influenced coastal ecosystems, and the associated influence of variations in freshwater flows.

Ecosystem response to freshwater influxes into the marine environment is poorly understood and requires the consideration of individual abiotic drivers and their associated responses in the marine systems. Van Ballegooyen *et al.* (2007) highlight the need to assess these impacts differently in a variety of ecosystems ranging from oligotrophic east coast systems to more naturally eutrophic south and west coast systems. A requirement would be realistic and cost-effective methods of assessing the reduction of freshwater influx on the marine environment. Ocean colour has the potential to provide valuable information in this regard.

Ocean colour remote sensing provides a unique means of assessing the effects that variation in freshwater influxes have on the coastal marine environment, as it provides a cost-effective ability to routinely provide quantifiable synoptic data of phytoplankton biomass and production, as well as fluctuations of sediment and dissolved organic material from riverine input.

Remotely-sensed ocean colour offers the routine quantification of phytoplankton biomass, sediment concentration, coloured dissolved organics and other water quality parameters by equivalent products from different sensors. It also allows for robust long term monitoring of the oceanic boundary conditions and the effects of mesoscale variability on the coastal zone. This ability to operationally use ocean colour products could help evolve environmental indices, improving our understanding of how the variations in freshwater inflows affects the coastal ecosystems on a temporal scale.

This study has focused on the heavily riverine influenced marine system of the Natal Bight where a preliminary assessment and validation of ocean colour algorithms and methods will be completed. This will subsequently provide the future ability to quantitatively use ocean colour to assess freshwater impacts on similar marine systems.

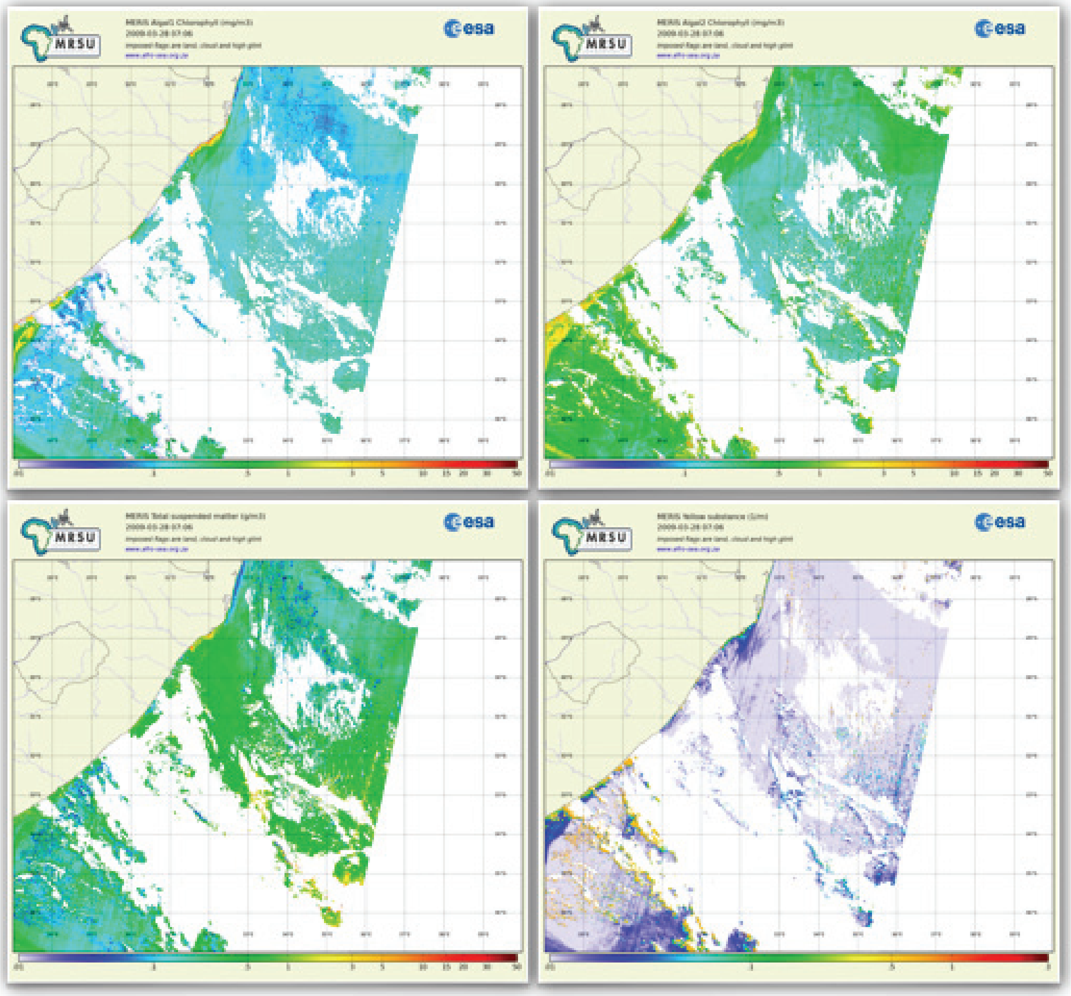

Figure 1. Default products from ESA's MERIS sensor, 28th March 2009, as currently processed by the Marine Remote Sensing Unit. From top left, clockwise: A) Algal 1 Chl a, B) Algal 2 Chl a, C) Yellow Substance (Gelbstoff), D) Suspended Particulate Matter. Note the Case 2 products ascribe much of the inner shelf mid bight "chlorophyll" of the Algal 1 product to SPM and gelbstoff.

2. Literature Review

2.1 Background Oceanography of the Natal Bight

The Natal Bight is an extremely dynamic area – whilst predominantly influenced by the fast-flowing oligotrophic waters from the Agulhas current, this unique environment of riverine influxes, retention mechanisms and topographically induced upwelling makes it highly optically variable and a fascinating and challenging environment for ocean colour applications. The waters of the Natal Bight are generally well mixed (Lutjeharms *et al.,* 2000). Short term fluctuations in temperature and salinity due to various upwelling processes and upper layer water movement correlated to winds (Pearce *et al.,* 1978) leading to sudden current reversals.

The east coast of South Africa tends to be very smooth, with a generally narrow continental shelf and steep slope (Lutjeharms *et al.,* 2000). It is this regular shelf morphology that allows the adjacent fast flowing Agulhas current to maintain a very stable trajectory (De Ruijter *et al.,* 1999). The only distinct offset along the coastline is the Natal Bight which is an area with a broader continental shelf between Durban and Richards Bay.

The Natal Bight is 160 km long and about 50 km wide at its broadest point at the Thukela River mouth (Lutjeharms *et al.,* 2000). The continental slope gradient is also very slight compared to other areas along the southeast African coast making it a favorable area for the growth of meanders (De Ruijter *et al.,* 1999). These large solitary meanders that have a propensity to originate in the Natal Bight are known as "Natal pulses".

The waters that are encountered on the Natal Bight are very different to the oligotrophic waters from the Agulhas current that are generally found next to the coast. This fast moving current tends to follow the shelf break, represented by the 200 m isobath, and thus encloses the waters of the Bight (Lutjeharms *et al.,* 2000). The circulation of these semi-trapped shelf waters are however still strongly influenced by the Agulhas current which gives the water masses its tropical and subtropical characteristics (from Schumann, 1988 cited in Lutjeharms *et al.,* 2000). Shear edge plumes from the upper waters of the Agulhas Current are responsible for the Tropical surface water that gets brought onto the shelf (from Grundlingh and Pearce, 1990 cited in Lutjeharms *et al.,* 2000). A quasi-permanent lee eddy can be found off Durban due to the sudden narrowing of the continental shelf in that area; as a result, occasional cyclonic movement near Durban advects Indian Tropical Surface Waters from the upper part of the Agulhas Current onto the shelf (Lutjeharms *et al.,* 2000).

The Agulhas current controls the nutrient distribution over the largest part of the Bight (Meyer *et al.,* 2002), whether it is by increasing or decreasing the amounts present in the waters. Colder, deeper water may be introduced onto the shelf via various upwelling processes. Firstly, by bottom Ekman veering at the edge of the current along the full length of the shelf slope (from Schumann, 1986 cited in Lutjeharms *et al.,* 2000). And secondly by a topographically induced upwelling cell at Richards Bay (Lutjeharms *et al.,* 2000). This upwelling cell is largely wind-independent and the main source of nutrients for the whole Bight (Meyer *et al.,* 2002). It is responsible for bringing colder, saltier and nutrient-rich South Indian Subtropical Surface Water onto the shelf, from where it gets transported southwards over the Bight at all depths (Lutjeharms *et al.,* 2000). High nutrient concentrations may occasionally even be advected downstream at the shoreward edge of the current (Meyer *et al.,* 2002). The Agulhas current also controls the nutrient concentrations at southern part of the Bight by the creation of a lee eddy that forces nutrient poor surface water from AC onto shelf (Meyer *et al.,* 2002).

It has been reported that nutrients from terrestrial run-off play only a small role in the nutrient distribution of the Natal Bight (from Carter and D'Aubrey, 1988 cited in Van Ballegooyen *et al.,* 2007), but it is possible that they might have a significant role in the center of the Bight where high phytoplankton concentrations have been observed periodically (from Carter and Schleyer, 1998 cited in Van Ballegooyen, 2007). This could be connected to the Thukela outflow; although its effects on the nutrient distributions of the Natal Bight are generally small, large flood events have the potential to influence the shelf waters substantially (Meyer *et al.,* 2002).

As previously discussed, the shelf waters between Durban and Richards Bay are relatively insulated from the direct effects of the generally strong offshore currents in this region. As a result there are significant retention and concentration mechanisms that operate in the nearshore and shelf regions which, together with the upwelling node just north of Richards Bay, have resulted in the Natal Bight being one of the four southern African spawning grounds of importance (from Hutchings *et al.,* 2002 cited in Van Ballegooyen *et al.,* 2006). With the great number of estuarine inputs of freshwater, nutrients and sediments into this area, these retention mechanisms would have a vast effect on the constituents of the Bight waters and could likely have a substantial influence on the nearshore marine ecosystems (Van Ballegooyen *et al.,* 2007).

2.2 The Natal Bight and Ocean Colour

As discussed earlier there is significant retention of water both in the nearshore and shelf regions, which lead to sediments and other particulate matter having longer resident time in the Bight waters than would be expected for other more exposed shelf environments (Van Ballegooyen *et al.,* 2007). The area is therefore highly amenable to the advanced use of remotely sensed ocean colour as the three major constituents that need to be distinguished are theoretically available from current ocean colour algorithms: sediment and dissolved organic matter from riverine inputs, and phytoplankton that respond to nutrient input from upwelling and terrestrial run-off.

Generally the sediments that are discharged onto the shelf are thought to be carried away to deeper waters and that the only accretions tend to occur in relatively quiescent areas or areas of recirculation (Van Ballegooyen *et al.,* 2007). A prime example of this is at the Thukela River mouth where a combination of the wider continental shelf together with the southwest sloping coastline relative to the southward-flowing Agulhas Current leads to the generation of a semi-permanent cyclonic gyre over the continental shelf (Bosman *et al.,* 2007). Sediments loads that feed this gyre could come from the Thukela River outflow (6 790 000 m^3/year) or also from a northward moving longshore drift caused by the dominant south-easterly swell which moves about 850 000 m^3/year of sediment (Bosman *et al.,* 2007). Other annual sediment loads from some of the major sources along the Natal Bight are the Mfolozi river which delivers about 1 500 000 m^3/year and the Mhlatuze with only 237 000 m^3/year (Van Ballegooyen *et al.,* 2007).

The upwelling of nutrient-rich water onto the Bight has had a substantial influence on phytoplankton productivity over the whole Bight (from Carter and Schleyer, 1988 cited in Meyer *et al.,* 2002). Upwelling in the Richards Bay cell can increase surface nitrate-nitrogen from 1.0 to 7.0 μmol/l (from Oliff, 1973 cited in Meyer *et al.,* 2002) although the levels usually reached are about 4.0 μmol/l (from Pearce, 1977 cited in Meyer *et al.,* 2002). Peak nitrate-nitrogen levels in the Richards Bay estuary attained 20 μmol/l (from Begg, 1978 cited in Meyer *et al.,* 2002) and can cause a maximum increase of around 1 μmol/l in the near-shore surface water during periods of strong outflow (from Carter and D'Aubrey, 1988 cited in Meyer *et al.,* 2002). Table 1 shows some of the possible nutrient concentrations that could be expected in the Natal Bight as shown in Meyer *et al.* (2002).

Table 1. Nutrient concentrations in μmol/l at 10 m depth for the three major areas of the Natal Bight (Meyer *et al.,* 2002)

	Nitrate	**Silicate**	**Phosphate**
North	0.15-15.30	2.52-9.41	0.35-1.64
Centre	1.01-1.86	3.50-4.69	0.48-0.72
South	0.15-1.65	2.66-4.05	0.35-0.65

It can be clearly seen that the nutrient distribution of the Natal Bight shows an enhanced northern section with an intermediate central region and a deprived southern area (Meyer *et al.,* 2002), which would be reflected by the phytoplankton assemblages and chlorophyll-a (Chl-a) concentrations that are found in these regions. Meyer *et al.* (2002) found the Chl-a concentrations at Richards Bay to be in excess of 1.5 mg/m^3 which decreased to 0.5 mg/m^3 just north of the Thukela River; the southern parts of the Bight were very much depleted with values of less than 0.1 mg/m^3, whilst the central parts had intermediate concentrations of 0.1-0.5 mg/m^3.

A previous study undertaken by Barlow *et al.* (2008) has found that small flagellates generally dominate the Natal Bight and that the overall trophic status could be classified as mesotrophic. They also found that the northern sector (total Chl-a 1.5-3.2 mg/m^3) and a small section of the southwest were dominated by diatoms and could thus be classified as eutrophic. These areas were most probably due to eddy driven upwelling processes onto the shelf as was reflected by the cooler temperatures in these regions (Barlow *et al.,* 2008). In their study small flagellates were generally dominant in waters where total Chl-a was 0.1-1 mg/m^3, while diatoms occurred in waters where Chl-a concentrations were 1-3.2 mg/m^3. Prokaryotes were also detected, but since their populations only represented less than 20% of the whole they were never dominant, and it could be concluded that there were no oligotrophic waters on the Bight (Barlow *et al.,* 2008).

Whilst the Delagoa Bight is obviously a very different system oceanographically, it has many similarities with regard to ocean colour applications – a mixture of riverine, coastal and oligotrophic influences. A preliminary validation study in the region (Kyewalyanga *et al.,* 2007) found a generally good agreement between field measured and satellite derived Chl-a concentrations for a cruise in August 2004, although with considerable scatter, i.e. potential error, and some bias at low Chl-a concentrations. It also appears that the cruise took place at a time of low riverine input from the Limpopo, and this preliminary validation therefore represents a best-case scenario.

2.3 Scientific Introduction to Ocean Colour Coastal Applications

When oceanic and coastal waters are examined through ocean colour radiometry, the water masses can be classified into two categories. Case I waters are less complex and the optical properties are mainly influenced by phytoplankton (IOCCG, 2000). More optically-complex waters found in coastal regions and lakes are classified as Case II waters and can include phytoplankton, inorganic particles and gelbstoff (ibid.).

The radiance measured by the satellite-based sensor originates from sunlight that firstly passes through the atmosphere, is then reflected, absorbed, and scattered by the all the components in the ocean; and is then finally transmitted back through the atmosphere to sensor (IOCCG, 2006). The colour of water is thus determined by not only the scattering but also the absorption of visible light by the water itself as well as constituents that might be present in the water (as seen in Figure 2), be it organic or inorganic, particulate or dissolved or all of the above (IOCCG, 2000).

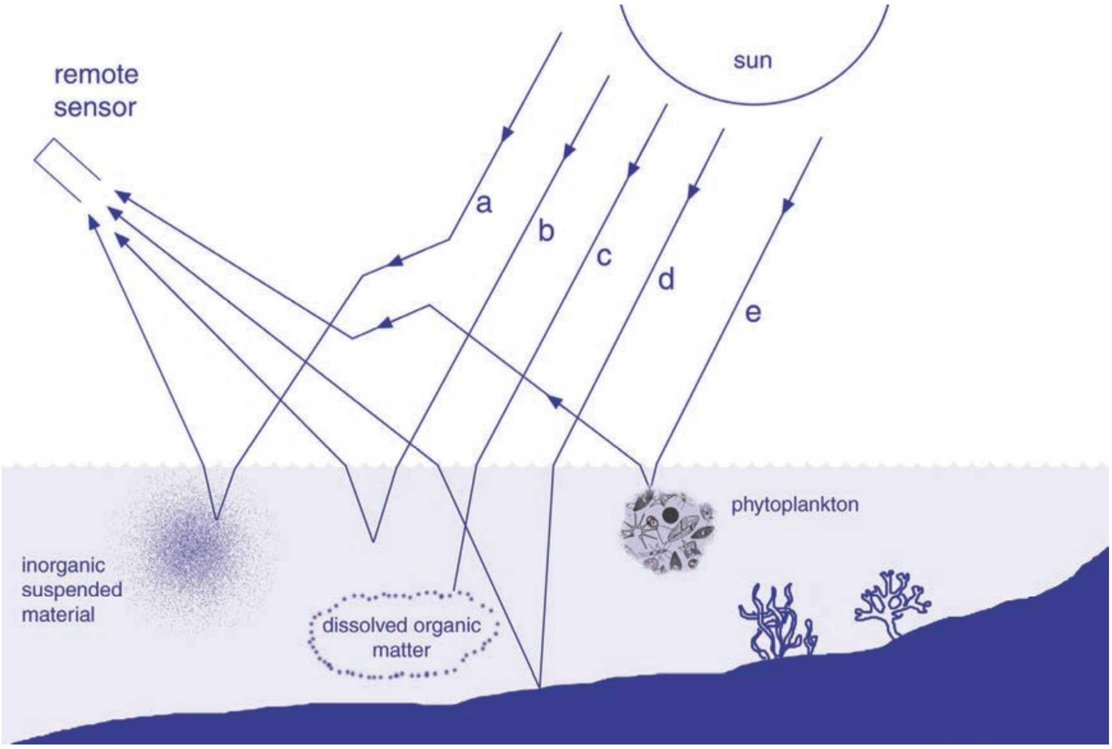

Figure 2. Factors that influence upwelling light leaving the sea surface. (a) upward scattering by inorganic suspended material; (b) upward scattering from water molecules; (c) absorption by the yellow-substances component (gelbstoff, per se, are not considered to be important scatterers. However, in this report we have included the detrital component with the yellow-substance component, and detritus may scatter.); (d) reflection off the bottom; and (e) upward scattering from the phytoplankton component. Note that absorption by any of these components or by the bottom will serve to decrease the water-leaving signal. Light from the sun may be scattered by atmospheric constituents before it reaches the sea surface. Similarly, light leaving the water may be scattered away from, or towards the remote sensor by the atmosphere. (from IOCCG, 2000)

All optical properties of ocean waters are wavelength dependent and it is important that these constituents be considered individually, since they will often fluctuate independently of each other in Case II waters and could also require regional-specific atmospheric correction procedures (IOCCG, 2000). When determining phytoplankton pigments in Case I waters it is possible to use relatively simple empirical algorithms that are based on colour ratios, but these are not applicable to Case II waters since suspended matter influences the whole blue to red spectral range (Doerffer and Schiller, 1997). The remote-sensing reflectance spectra from different types of waters can be seen below in Figure 3.

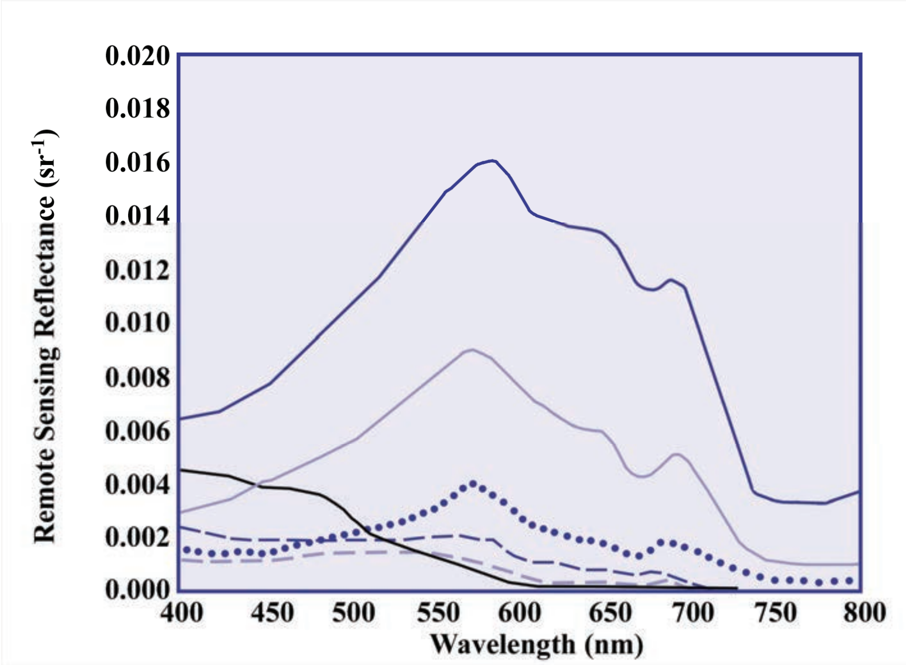

Figure 3. Some examples of remote-sensing reflectance spectra from different types of waters. The figure shows (a) waters with very high sediment and gelbstoff concentrations, (b) high sediment and gelbstoff concentrations, (c) moderate sediment and gelbstoff with some phytoplankton, (d) clear water, (e) waters with moderate chlorophyll and sediment concentrations, (f) waters with moderate chlorophyll concentration. a, b, c and e are Case 2 waters; d and f are Case 1 waters. Data courtesy of Robert Arnone. (from IOCCG, 2000)

In ocean-colour remote sensing, the forward radiative transfer problem is to predict the spectral distribution of water-leaving radiance based on a quantitative description of all the absorption and scattering characteristics of the optical components in the ocean (IOCCG, 2006). When viewing chlorophyll concentrations in Case II waters for example, the presence of high concentrations of gelbstoff and/or SPM has significant implications when applying simple empirical algorithms and generally do not provide accurate results (Kratzer *et al.,* 2008). The gelbstoff (also termed coloured dissolved organic matter or CDOM) and suspended particulate matter (SPM) could have a very important influence on the light attenuation, in addition to that of the water and phytoplankton pigments (Kratzer *et al.,* 2008), making it difficult to separate the effect of each substance. Some of the values that would constitute Case II waters would include gelbstoff absorption above 0.1 m^{-1} at 380 nm (corresponding to a gelbstoff absorption of about 0.03 m^{-1} at 440 nm) and SPM concentrations above 0.5 g/m^3 (Kratzer *et al.,* 2008).

At high concentrations of all three constituents, model simulations have shown that the correct determination of one constituent was only possible if the other constituents that determine the water leaving radiance are determined correctly (Doerffer and Schiller, 1997). It has also been shown that the optimum spectral range for the retrieval of a substance, as well as the error, depends on the concentrations of the other constituents (from Doerffer, 1979; Doerffer & Schiller, 1994). Since the Natal Bight is known to be a region with variable and significant presence of these constituents, it is an important location that is in need of algorithms that could accurately be applied on a regional scale.

2.4 Case 2 Operational Ocean Colour Products & Previous Studies

Potential ocean colour data for Natal Bight application are presented below, with a summary of their immediate and potential use, and ease of acquisition and processing. The high resolution (300 m) data from both MERIS and OCM II, whilst being of great potential value, would (currently) require both X-band receiving facilities, political motivation for reception, and investment in processing infrastructure. The MODIS sensor has two bands at 250 m resolution, and 2 bands at 500 m resolution in addition to more complete multi-spectral capability at 1 km resolution. These higher resolution bands might be useful for coarse change detection empirical algorithms (which will need considerable derivation work), but are unlikely to be sufficient for the constituent discrimination algorithms required here.

Table 2: Current ocean colour sensors and potential for regional application

Sensor & Agency	**Spatial Resolution**	**Sensor life time**	**Case 2 Products**	**Ease of Acquisition**	**Processing Infrastructure**
MERIS/ESA	1 km	2002-2011	Current	Good	Available
MERIS/ESA	300 m	2002-2011	Current	Difficult	Input needed
MODIS/NASA	1 km	2002-2011	Input needed	Good	Available
MODIS/NASA	250/500 m	2002-2011	Input needed	Good	Available
SeaWiFS/NASA	1 km	1997-2011	Input needed	Good	Available
OCM II/ISRO	4 km	2009-	Input needed	Good	Input needed
OCM II/ISRO	300 m	2009-	Input needed	Difficult	Input needed

MERIS = Medium Resolution Imaging Spectrometer; MODIS = Moderate Resolution Imaging Spectrometer; SeaWiFS = Sea Viewing Wide Field of View Sensor; OCM II = Ocean Colour Monitor Second Generation.

The most immediately useful data are the MERIS Case 2 products : the data are being received and processed locally through C-Band reception facilities at the University of Cape Town, and there are operational products available for Chl-a in Case 2 waters (algal_2), suspended particulate matter (SPM) and gelbstoff. These products are derived from a neural network based algorithm utilising primarily synthetic data sets (Doerffer and Schiller, 1997) – whilst they still need considerable validation for the Natal Bight region, they would appear to offer the best default starting point for ocean colour application in the region. Recent sample imagery can be seen in Figure 1 – it is interesting to note the differences between the Case 1 (Algal 1) and various Case 2 products. The latter ascribe much of the inner shelf mid bight “chlorophyll” of the Algal 1 product to SPM and gelbstoff.

Doerffer and Schiller (1997) have developed an inverse radiative transfer modelling technique (IRTM) which takes into account the problems of the separation of the three groups of substances as well as the atmospheric correction over turbid waters. The model describes the flux of sunlight that travels into the ocean and back to the sensor, and whilst varying the concentrations and other parameter it uses an optimisation procedure to minimise the deviation between the calculated and measured spectra (Doerffer and Schiller, 1997). The scope of this algorithm for turbid estuarine water is defined by the composition of the substances present in the water, and comprises the following concentration ranges:
Chl-a: 1-50 µg l^{-1}
gelbstoff absorption a(440): 0.1-2 m^{-1}
mineralic suspended matter: 1-50 mg l^{-1}

The MERIS “Algal pigment index 2” product (or algal_2) is a product that is specifically defined to represent the concentration of chlorophyll-a in mg m^{-3} in Case II waters. This product was however designed to be globally valid, and improved results could be attained by including measurements and concentrations of inherent optical properties from the specific area of study (Ruddick *et al.,* 2003). MERIS processing incorporates a type of warning device (known as flags) which takes into account different sources of possible error including high turbidity in water, glint from the sun and atmospheric correction failure. It computes the reliability of a pixel by regarding these different possible error sources and raises a flag for the specific error if the uncertainty value exceeds a certain threshold. This would give the user the option of accepting or rejecting the pixel for further computations (IOCCG, 2006).

A preliminary study by Siegel *et al.* (2004) in the open Western Baltic Sea, where the Chl-a, suspended matter concentration as well as gelbstoff absorption at 442 nm normally fall in the ranges between 0.2-8 mg m^{-3}, 1-6 mg dm^{-3}, and 0.2-0.5 m^{-1} respectively found that the MERIS algal_2 values of different areas in the Baltic Sea where within the *in-situ* variation ranges. An algal_2 conversion factor that was specifically derived for the Baltic Sea significantly improved these results. (Siegel *et al.,* 2004)

Similar results were obtained by Sorensen and Hokendal (2006) in the Skagerrak, an area which includes a mixture of water masses consisting of low salinity with high amounts of gelbstoff, high salinity waters with low content of gelbstoff and high salinity with high gelbstoff content. They found a good agreement between the *in situ* data and the MERIS products of algal_2 and total suspended matter.

For these algorithms and models to work properly it is essential to have enough knowledge of the optical properties of the water as well as the atmospheric aerosols. For improved results the focus should be on obtaining regional and temporal data sets of the specific optical properties of the water constituents with their related spectral high resolution radiance spectra (Doerffer and Schiller, 1997).

2.5 Emerging Alternative Case 2 Algorithms

There have been a very wide range of other Case 2 algorithms for phytoplankton biomass, suspended sediment concentration and gelbstoff, developed and applied for a range of sensors and ecosystems. Further systematic review of these studies will be made more constructively in comparison to preliminary results from this study, but the most important broad conclusion is the success of regionally specific algorithms, developed for specific ecosystems using a combination of *in situ* and satellite data.

Quasi-Analytical Algorithm (QAA)

The Quasi-Analytical Algorithm (QAA) was developed by Lee *et al.* (2002) to derive inherent optical properties (IOPs) of optically deep waters, which are directly linked to the constituents of the water. It is used to retrieve the total backscattering and absorption coefficients from remote sensing reflectance, and also spectrally decomposes the total absorption coefficient into its key contributors (Lee *et al.*, 2002). The benefit of this algorithm is that it is easily adaptable to a variety of sensors, fairly simple, and efficient enough to process large amounts of data such as satellite images (IOCCG, 2006).

Fluorescence Line Height (FLH)

The chlorophyll-a contained within phytoplankton is the only substance in case 2 waters that has the ability to fluoresce in the red region (±685 nm) when stimulated by sunlight. This fluorescence signal can be measured from space by both the MERIS and MODIS sensors (and planned sensors such as Sentinel-3) – the MERIS Bands 7, 8 and 9 were specifically designed for the purpose – and the most commonly use semi-quantitative product is the fluorescence line height (FLH) This signal is specific to phytoplankton, and makes the remote sensing of sun-induced chlorophyll fluorescence a useful and unambiguous method of identifying phytoplankton-dominated synoptic features in surface waters. However, whilst the FLH is unambiguous with regard to its source, it can be complex to quantify and analyse, and has yet to be routinely used for quantitative Chl-a algorithms. Nevertheless, studies by Gons *et al.* (2008) have found a strong linear relationship between Chl-a concentration and FLH.

The high sediment and gelbstoff concentrations in some areas of the Natal Bight tend to decrease the accuracy of the atmospheric correction and thus the accuracy of the standard algorithms for retrieving Chl-a values over those areas. The FLH product (Gower *et al.*, 1999) is therefore extremely useful in qualitative image analysis, i.e. determining whether specific synoptic features are phytoplankton dominated.

MERIS Case 2 Regional Processor (C2R)

The MERIS case 2 regional processor (C2R) employs a coupled ocean-atmosphere neural network for the atmospheric correction of the sensor received signal measured over case 2 coastal and inland waters (Doerffer & Schiller, 2008). It has the ability to take into consideration the effect of cirrus clouds, sun glint and the water leaving radiance reflectances produced by the in-water constituents (*ibid*), and tends to produce more robust atmospheric corrections and clearer images than the standard case 2 water products.

The standard MERIS atmospheric correction procedure for case 2 waters was designed for waters with only limited concentrations of SPM and gelbstoff (Doerffer & Schiller, 2008). In waters with high concentrations of these constituents there is a tendency to produce negative reflectances and other artefacts, particularly in the blue bands (*ibid*). Schroeder *et al.* (2007) has shown that when compared to the standard MERIS Level 2 reflectance products, the C2R reveals a significant increase in accuracy particularly in the blue part of the spectrum, where the MERIS Level 2 reflectances resulted in errors of up to 122% compared to only 19% with the C2R.

Other Empirical and Analytical Algorithms

There are several studies using simple empirical models. Eleveld *et al.,* 2008 used simple single band empirical models to estimate SPM concentrations in the North Sea using SeaWiFS data. Chen *et al.,* 2007 successfully used 250 m MODIS data with simple single band empirical algorithms with a variety of atmospheric correction models in the Gulf of Mexico to detect sediment variations. D'Sa *et al.,* 2007 used two band empirical SeaWiFS algorithm to successfully distinguish between absorbing phytoplankton and backscattering sediments in Mississippi River outflow waters. Nezlin *et al.,* 2005 used single band SeaWiFS algorithms to analyse the relationship between precipitation, run-off, sediment plume size and freshwater fluxes in the Southern Californian system. Shutler *et al.,* 2007 present new atmospheric correction schemes and empirical algorithms to utilise 500 m MODIS data in coastal waters.

Analytical models offer the ability to detect several constituents simultaneously.
Kratzer *et al.*, 2007, variety of neural network based algorithms with 300 m (FR) MERIS data to estimate Chl a, SPM and gelbstoff in the Baltic, highlighting the importance of understanding the atmospheric correction. Brodie *et al* (in press) used MERIS data in combination with inversion models to assess sediment discharge effects in the Great Barrier reef system.

Such studies highlight the importance of characterising the variability of the Natal Bight with regard to the primary optical constituents, undertaking both radiometric and geophysical validation programmes, and developing regional algorithms based on these data.

3. Outline of Data Requirements

Ocean colour radiometry (OCR) has several fundamental steps. Radiance is measured at the top of the atmosphere; to get the oceanic signal the atmospheric signal has to be removed (typically accounting for more than 80% of the total signal). The derivation of geophysical parameters such as Chl-a concentrations from this corrected signal uses various empirical or analytical algorithms. Atmospheric correction schemes considered suitable for the open ocean often perform poorly in turbid, atmospherically complex coastal waters where a lack of suitable validation data hampers our ability to analyse and improve these vital procedures.

Ocean colour validation is effectively an analysis of algorithm performance – comparing satellite derived products from available algorithms with *in situ* data (with known confidence limits). This can be achieved on a point-by-point basis, i.e. comparisons of in situ data at specific stations to those derived from the satellite as it passes overhead within a close enough time period to be considered concurrent. There is also value in a longer term, more statistical approach – if sufficient regional in situ data exists over a variety of space and time scales, the variability of these data can be compared with satellite-derived products. A third approach can be adopted in data-poor environments – the inter-comparison of different satellite algorithms to assess the spatial coherency of products, using existing knowledge of system behaviour and oceanography to provide a more qualitative assessment of algorithm performance.

The project therefore requires two primary forms of data: the in situ bio-optical data needed to directly compare with satellite products, and to characterise the bio-optical and biogeochemical variability of the region; and the satellite measured ocean colour data needed for the in situ comparison, the assessment of algorithm performance on the event scale, and the time-series analyses needed to characterise riverine influence from an ecosystem perspective. Optimal data requirements, and a more pragmatic assessment of the data that are likely to be available to the project, are discussed below.

3.1 In Situ Data Requirements

Ideally, data would be available to validate all steps in the ocean colour processing chain: aerosol optical thickness and water leaving radiance data to validate the atmospheric correction; water leaving radiance and inherent optical property data to perform radiometric and bio-optical validation; inherent optical property and biogeochemical data such as Chl-a to perform biogeochemical validation. Such data should ideally be available throughout the region at the event and seasonal time scales. In practice this is impossible without a massive resource injection, particularly given the current paucity of any of these data for the region.
The project (and ongoing efforts beyond the project lifetime) has therefore focused on obtaining in situ data for radiometric and biogeochemical validation. These data have been obtained in collaboration with the University of KwaZulu-Natal, using small boat based sampling and available borrowed instrumentation from Marine & Coastal Management and the University of Cape Town. The focus has been on obtaining radiometric data to assess the accuracy of the atmospheric correction; and data pertaining to the three most important constituents in Case 2 waters – phytoplankton biomass, sediment concentration, and the concentration of gelbstoff. Data consist of:

- Aerosol optical thickness: MicroTops sun photometer
- Water leaving reflectance: Satlantic Hyperspectral Tethered Radiometer Buoy
- Phytoplankton, detrital and gelbstoff absorption: Shimadzu UV-2501 spectrophotometer
- Total and particulate backscattering: HobiLabs Hydroscat-2
- Extracted chlorophyll a concentration: Turner 10-AU fluorometer
- Suspended sediment concentration: gravimetric technique

- Ancillary data such as CTD profiles and metocean data

3.2 Satellite Ocean Colour Data Requirements

Requirements for the ocean colour data are discussed in detail in Section 2.4. In practical terms, there is a requirement for a cohesive data archive, i.e. access to an uninterrupted archive of regional data, and obviously ongoing access to the data. Available data on an ongoing basis are from the MERIS and MODIS sensors, and merged data sets such as the European Space Agency's GlobColour data set which merges SeaWiFS, MODIS and MERIS data. Whilst MERIS is in some regards a more optimal sensor for project purposes, there is not currently a cohesive MERIS regional archive, although data can be accessed on the event scale, i.e. small multi-week time series of images for particular events. There is a cohesive regional MODIS archive from 2003 onwards that can be used for time series analyses – with the proviso that only relatively simple Case 1 products can be utilised. The GlobColour data is relatively low resolution (maximum 4 km spatial resolution), which makes it less attractive. The project has therefore used a combination of approaches: assessing GlobColour viability, using MERIS predominantly on the event scale, and using MODIS to demonstrate a time-series approach.

4. Methods

4.1 Methods: Ocean Colour and Other Remote Sensing

GlobColour data were used as a first approach, since an extensive global archive was readily available. The CHL1 and CDM merged GSM 8 day composites of 25 km resolution were used to look at the mean chlorophyll and coloured dissolved matter respectively. The data were imported into Matlab, plotted and compared to the high flow events from the Thukela. The spatial and temporal resolution was however too coarse to focus on the event scale.

The main data source were the 1 km resolution MERIS level 1 and 2 data, with particular focus on the operational Case 2 water products of algal_2, SPM and gelbstoff. The product files were examined using the Envisat software package BEAM, which is a toolbox for viewing, analysing and processing of remote sensing data. This data produced almost daily images corresponding to varying levels of flow rates, and enable a much clearer representation of the changes in the concentrations of the in-water constituents. A variety of BEAM processors and algorithms were applied to the original data in order to compare it to the standard products. These included running the MERIS level 2 data through the Fluorescence Line Height (FLH) processor and the Quasi-Analytical Algorithm (QAA) and also running MERIS level1 data through the Case 2 Regional Processor, all of which are freely available plug-ins for BEAM (see Section 2.4)

4.2 Methods: In situ Data

4.2.1 Thukela River Flow Data

As the primary contributor of fresh water to the waters of the Natal Bight, the Thukela River was chosen as an indicator of the level of riverine input. Flow rates from 2003-2009 for the Thukela River at the Mandini station, as the most downstream station from which data are available, were obtained from the Department of Water Affairs and Forestry website. These data, in the absence of historical data regarding Thukela or coastal discharged sediment concentrations, were used as indicators of riverine discharge and by implication sediment and dissolved organic input to near-coastal waters.

4.2.2 Bio-Optical and Supporting Field Data

The first in situ data acquisition was planned for the synoptic leg of the August 2009 Natal Bight ACEP cruise on the RV Algoa. Unfortunately the cruise was delayed for several weeks due to necessary ship repairs, and this resulted in cancellation of acquisition exercise. A small boat based field validation exercise was conducted in collaboration with UKZN from 9^{th} to 30^{th} November 2009, with the aim of acquiring validation data for both MERIS and MODIS during the wet season in KwaZulu-Natal. The exercise was followed by a second data acquisition exercise in April 2010. Sampling grid location was chosen at the Mgeni River mouth, since it complied with the following criteria:

- sufficiently deep water to avoid bottom reflectance
- far enough from shore to avoid land-pixel flagging
- possible to launch out of Durban harbour which is in close proximity to UKZN lab

The sampling grid included 4 stations, with 2 inshore stations that were at least 4 km offshore and another 2 stations another 2 km further out to sea (Figure 4)

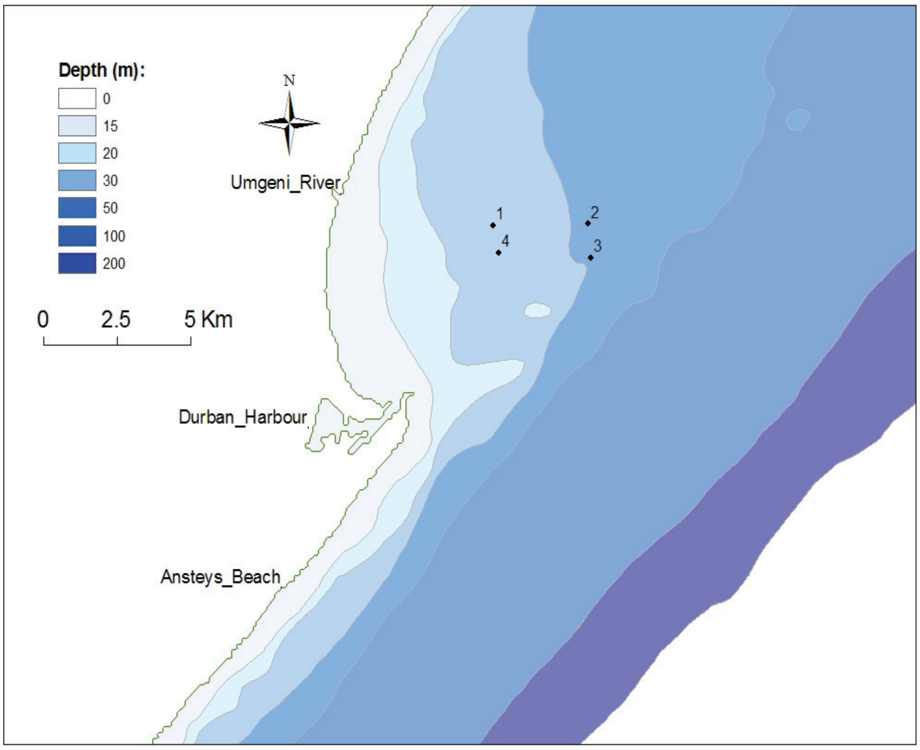

Figure 4. The sampling grid and stations off Durban Harbour and the Mgeni River mouth

The methods for data collection and analysis during the fieldwork were, as much as possible, based upon the Applied Optics Protocols for Satellite Ocean Colour Validation by Mueller *et al.* (2003). All measurements were taken within 2 hours of the satellite overpass times. Aerosol optical thickness measurements were taken with the Microtops sunphotometer from a jetty in Durban harbour before and after heading out to the sampling grid location. The measurements conducted at each station included:

- Radiometric measurements from the TRSB spectroradiometer
- Two backscattering and fluorometric profiles from the HobiLabs Hydroscat 2
- Secchi depth taken at every station in order to determine the depth at which deeper water samples should be taken. A rough estimate was used according to type of water present at the station: clear water = secchi depth >15 m (collect water at 10 m), normal water = 10 m (5 m); riverine water = <5 m (2 m)
- Discrete water sample collection was performed using a 3L Niskin bottle to be lowered down to the desired depth. 5L surface and 5L deeper water collected at each station.
- Conductivity (salinity), temperature, depth (CTD) and dissolved O_2 measurements using a RBR Data logger Model XR-620. Two of these CTD profiles were completed at each station to a depth deeper than the secchi depth.
- Other ancillary measurements included:
  - A recording of wind speed and direction taken at each station
  - Percentage cloud cover and type recorded at beginning of day's fieldwork. Any subsequent changes in conditions noted in the logbook

- Sea state and swell height noted at start of day's work. Any subsequent changes in conditions noted in the logbook

Radiometric Measurements

In-water hyperspectral radiometric measurements were made with a Hyperspectral Tethered Surface Radiometer Buoy (HyperTSRB S/N 018), manufactured by Satlantic, Inc. (Halifax, Canada), and is designed to obtain upwelling near surface spectral radiance Lu(z) and above surface downwelling irradiance Ed (0+), away from vessel perturbations in the submarine light field. Upwelling radiance is measured at a nominal depth of z = 0.66 m. The instrument consists of two 256 channel spectrographs linked by fiber optic bundles to an upward looking cosine corrected irradiance sensor, and a downward looking 8.5º field of view radiance sensor. Adaptive gain allows a variable integration time to be chosen independently for each sensor head based on the current light field. Actual acquisition rates are therefore variable and dependent upon instrument response to the light field, and typically range from 0.7 Hz to 1.6 Hz. The 256 channel spectrographs provide a spectral range of 400 nm to 800nm, at a spectral resolution of 3.3 nm and accuracy of 0.3 nm. Radiometric measurements were typically made for a duration of 2 to 5 minutes, with median values from the whole sampling period used to derive single spectra for both sensors, re-sampled to a wavelength resolution of 5 nm. Further processing of radiometric data, namely propagation of radiance data through the water column and air-sea interface, were carried out using the reflectance algorithm of Bernard (2005).

Particulate Absorption Measurements

Particulate absorption data were measured with the quantitative filter pad technique (Yentsch, 1962; Roesler, 1998) using a Shimadzu UV-2501 spectrophotometer equipped with a ISR-2200 internal integrating sphere. Discrete seawater samples were filtered under less than 10 mm mercury pressure using Whatman GF/F filter pads, which were placed at the entrance port of the sphere, and scanned from 350 nm to 750 nm using an air reference and baseline. In cases where filters could not be read immediately they were stored frozen in liquid nitrogen. Blank filter pads were prepared by filtering several hundred ml of Milli-Q water through fresh GF/F filters, which were then read in the same manner as the samples. Filtration volumes were adjusted to maintain a large amount of material on the filter while avoiding excessive clogging, and varied between 2 l and 0.1 l. Absorption coefficients were calculated using the pathlength amplification factor of Roesler (1998) assuming a null point correction at 750 nm. Detrital measurements were made using methanol extraction on the filter, followed by re-reading in the spectrophotometer (Kishino *et al.*, 1985). Phytoplankton absorption data were then obtained by subtraction of detrital absorption from total particulate absorption

Gelbstoff Absorption Measurements

Samples were prepared by filtering discrete water samples through GF/F filter papers under less than 10 mm mercury pressure, using stainless steel filter frits. Absorbance measurements were made using a Shimadzu UV-2501 spectrophotometer equipped with 10 cm pathlength matched quartz cuvettes. Milli-Q water was used as a pure water reference. Absorption coefficients were calculated as by Mueller & Austin (1995), with a null absorption point set to 750 nm.

Chlorophyll *a* and Suspended Matter Measurements

Variable sample volumes were filtered through 25 mm Whatman glass microfibre filter (GF/F) subject to 13 mm mercury pressure. Filtered samples were placed in polypropylene tubes with 10 ml acetone and then frozen for 6-48 h, ground in 90% acetone using a glass rod to extract the pigments, and analysed in a Turner Trilogy Fluorometer (Parsons *et al.*, 1984). For SPM measurements, 300 ml sample water was filtered through pre-weighed ashed filter, which were then frozen until desiccation and reweighing.

5. Results and Discussions

5.1 Preliminary Ocean Colour Validation

preliminary radiometric validation data are presented here. The field exercise suffered from much bad weather and many overcast days, negatively affecting acquisition of high quality MERIS match up data. Two match-ups with MERIS were realised during the three week exercise; preliminary radiometric comparison are presented below. Whilst this is not a sufficient quantity of data with which to analyse regional sensor performance, it is the first ocean colour validation data acquired in the Bight, and will be complemented by data from the April 2010 field experiment.

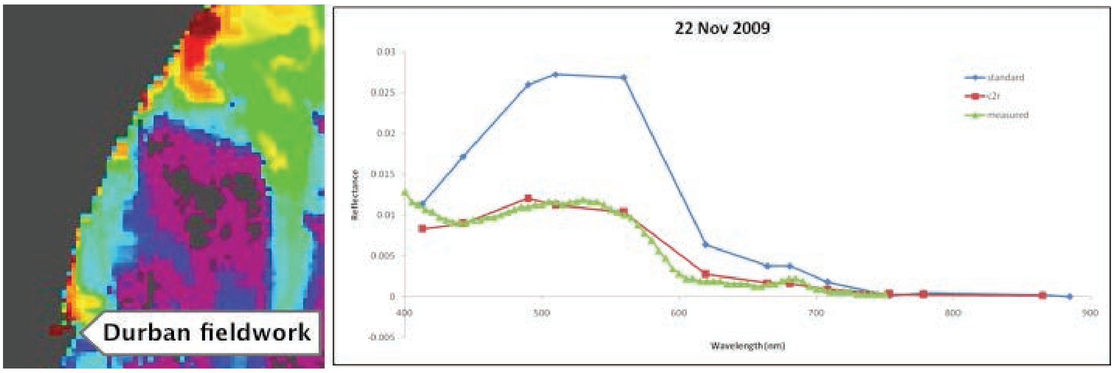

Figure 5. Preliminary radiometric validation data for the Mgeni river mouth station from a match-up on 22 November 2009. Data are MERIS C2R Chl-a concentration (left), and comparison between measured remotely-sensed reflectance Rrs [green], "standard" MERIS Rrs [blue]; and C2R calculated MERIS Rrs [red] (right). Note the large differences between the "standard" and the C2R derived reflectance data, and the good match between the measured and the C2R data.

The two radiometric match-ups with MERIS acquired during the 2009 field exercise obviously do not represent enough data to undertake a meaningful quantitative validation exercise, but nevertheless offer interesting insight into algorithm performance in the region. The radiometric data, presented in various formats in Figures 5 and 6, show large differences between the "standard" and the C2R MERIS water leaving reflectance data; and variable performance of the atmospheric correction associated with these two algorithms in comparison to the measured *in situ* data.

Comparison between different event scale MERIS products also show large discrepancies between the "standard" and C2R products, and suggest that the C2R algorithm is more robust and performs better within the region (see Section 5.2). This is consistent with the match-up from 22nd November shown in Figure 5. The reasons for this are not entirely clear, given the few data available, but are expected to be due to high regional atmospheric variability with regard to aerosol loading and type; highly variable water turbidity which will affect the atmospheric correction; and the response of the different atmospheric correction algorithms to this variability. The second match up from 25 November (Figure 6) again highlights the poor performance of the "standard" products, which displays physically implausible negative water leaving reflectance. In this case, while the C2R reflectance data is at least positive, it is not appreciably different from the "standard" product, and is not particularly well matched with the measured in situ data.

More validation data is required to proceed with a quantitative regional validation, but the preliminary validation data are in agreement with the event scale comparisons presented in Section 5.2 – the “standard” MERIS products frequently suffer from poor, and synoptically variable, performance of the atmospheric correction.

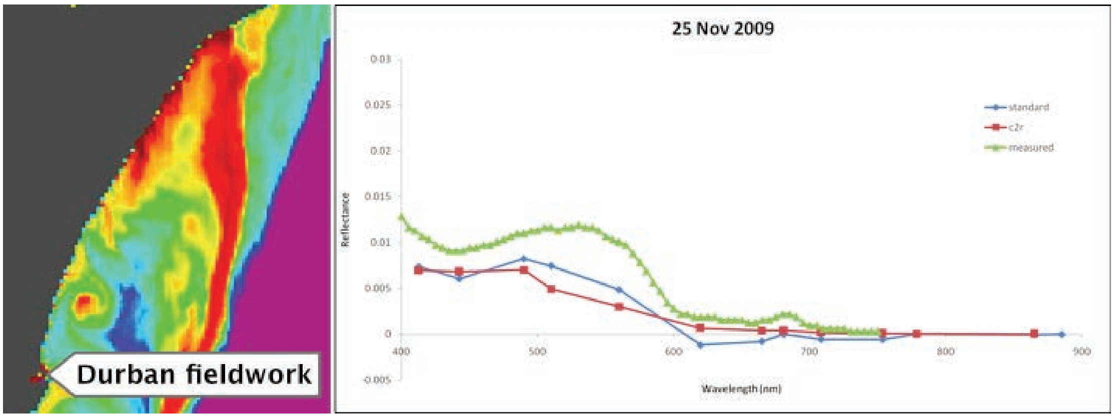

Figure 6. Preliminary radiometric validation data for the Mgeni river mouth station from a match-up on 25 November 2009. Data are MERIS C2R Chl-a concentration (left), and comparison between measured remotely-sensed reflectance Rrs [green], “standard” MERIS Rrs [blue]; and C2R calculated MERIS Rrs [red] (right). Note the negative values in the “standard” MERIS reflectance data, the more robust C2R data, i.e. non negative, resulting from the coupled neural network algorithm, and the poor match between both MERIS products and the measured reflectance data.

5.2 Event Scale Ocean Colour Algorithm Evaluation

The event scale data presented, all using data from the MERIS sensor, are single images, processed in a variety of ways, acquired under a variety of river discharge states, atmospheric conditions, and oceanographic scenarios as given by the influence of the Agulhas current. It is the inter-comparison between the different products, and specifically the spatial coherency between products that have known performance and/or ambiguity issues, that allows a greatly improved (if somewhat qualitative) understanding of algorithm performance.

Algorithm Assessment
Figures 7 -13, with the exception of Figure 9, all show comparisons between four different in-water algorithms, derived using two distinct atmospheric correction procedures. The figures are arranged consistently, and show (by descending rows):

- Chlorophyll *a* (Chl, mg m^{-3}), gelbstoff absorption (a_g, m^{-1}), and total suspended matter concentration (TSM, g m^{-3}) from the “standard” MERIS Case 2 neural network algorithm (Doerffer and Schiller, 1997). The atmospheric correction applied to these data are identical to those applied to all other products, excluding the C2R algorithm, and are part of the default MERIS ocean processing chain (Antoine & Morel, 1997; Aiken & Moore, 1997)

- Chlorophyll *a* (Chl, mg m^{-3}), gelbstoff absorption (a_g, m^{-1}), and total suspended matter concentration (TSM, g m^{-3}) from the MERIS Case 2 Regional Processor (C2R, Doerffer & Schiller, 2008). This is a coupled ocean-atmosphere neural network based algorithm, specifically designed to provide both the atmospheric correction and in-water algorithm for turbid and atmospherically complex coastal waters.

- Phytoplankton absorption (a_ph, m^{-1}), gelbstoff absorption (a_g, m^{-1}), and total backscattering (bb, m^{-1}) from the Quasi-Analytical Algorithm (QAA, Lee *et al.*, 2002). This algorithm is included as the simplest available implementation of an analytical-type inversion algorithm. It is important to note that whilst the QAA algorithm returns different parameters (inherent optical properties) to the above algorithms, the QAA returns are first order proxies for Chl,a_g and TSM, and considerable spatial coherency between the columns in the figure matrices should be expected (if algorithm performance is equivalent).

- Fluorescence line height product (FLH, Gower *et al.*, 1999). The FLH product is unambiguous with regard to association with phytoplankton dominated features – fluorescence at these wavelengths cannot originate from sediment or dissolved organic material. Whilst being quantitatively hard to interpret, it is extremely useful as a comparative product in Case 2 waters. It is used here to assess whether synoptic features are phytoplankton associated, e.g. a synoptic feature with high Chl-a concentrations that also displays high FLH value is very likely to be "real", whilst a synoptic feature with high sediment or gelbstoff concentrations that also displays high FLH values is very likely to be an algorithm artefact.

MERIS Artefacts

The MERIS sensor is composed of five cameras across the swath; there are some slight spectral discontinuities between cameras which can be seen as vertical striping in the imagery. This striping, known as the SMILE effect, can be variably amplified in certain products, e.g. Figure 8. It should be understood that the C2R algorithm – the only algorithm presented here explicitly processed from top-of-atmosphere Level 1 data – has a SMILE correction incorporated within the processing. The C2R products are thus visibly less affected by SMILE striping. All other products are processed from Level 2, without the benefit of the SMILE correction, and are thus more likely to display SMILE effects.

Atmospheric Correction Effects

Previous discussion has highlighted the critical importance of the atmospheric correction: given the lack of available validation data it is difficult to separate the apparent effects of the atmospheric and in-water algorithms, which have a mutual dependency – especially in turbid waters. However, there are some conditions of high atmospheric variability, i.e. where strong atmospheric fronts can be seen, where there are obvious algorithm artefacts in the imagery. Figure 10 shows such a front, and also displays typical artefacts – noisy data across different products and incoherency amongst synoptic oceanographic features around the frontal region.

5.2.1 In-Water Algorithm Performance & Ecosystem Characterisation

Two important aspects of ecosystem function are focused on here with regard to algorithm inter-comparison: riverine effects on the production of inshore waters; and riverine and oceanographic effects on production in the outer bight. The data presented in Figures 7-13 demonstrate, even with only semi-quantitative validation, that ocean colour offers considerable insight into the forcing mechanisms and functioning of the Natal Bight ecosystem.

Riverine Effects on Inshore Production

Riverine influence on the productivity of coastal ecosystems is highly variable. A simple first order approach is to consider two potentially competing influences: the effects of sediment as the particulate component, and the effect of the dissolved component, which can be expected to display different synoptic effects associated with selective mixing and dispersion post-discharge. Several very high discharge river-influenced systems show these competing effects: an inshore zone of depressed productivity related to the increased attenuation and thus light-limited nature of very high sediment concentrations; and an offshore zone of increased productivity caused by increased nutrient availability from the dissolved phase –

once sufficient sediment has settled from surface waters to relax the light-limitation. The Yangtze discharge in the East China Sea (Chen *et al*., 2003) and Amazon discharge into the Amazon basin (Gustavo *et al*., 2010) are good examples of this phenomenon.

Figures 7, 10, 11, and 12 all display apparently depressed Chl-a concentrations in near-coastal waters during moderate to high river flow in the “standard” Case 2 products. However, in all cases the C2R product displays elevated Chl-a concentrations in these high sediment inshore waters, with elevated FLH values for the same inshore synoptic features. This coherency between the C2R and FLH products, across a wide range of scenarios, would indicate that the elevated inshore Chl-a values observed during moderate to high riverine discharge are real. The depressed inshore Chl-a values in the “standard” products would therefore appear to be artifactual, most likely due to the sub-optimal performance of the atmospheric correction in these turbid waters (as seen in the preliminary validation match-up data). Much further interpretation than this becomes speculative, but it would appear to indicate that the potential light-limitation from the relatively small sediment input from the Thukela and other KwaZulu-Natal rivers is outweighed by the excessive nutrient loading from the same source. It is also possible (see discussion below) that the dynamic retention features discussed below play a role in enhanced inshore productivity through the formation of northward alongshore currents, acting as inshore retention mechanisms, associated with formation of cyclonic outer bight eddies.

Riverine and Oceanographic Effects on Outer Bight Production

Figure 7 shows, across all products, highly enhanced productivity in the outer waters of the Bight during a Natal Pulse event – when the inner edge of the Agulhas Current is anomalously far offshore. The same feature, to a lesser extent, can be seen Figure 11 during another Natal Pulse event. Both sets of images clearly show the formation of a cyclonic recirculation feature in the outer bight waters as the inshore edge of the Agulhas Current moves offshore. There are several potential reasons for this enhanced outer bight productivity: a) offshore transport of high nutrient riverine water from the inner shelf, b) offshore transport of high nutrient upwelled water from the St Lucia upwelling cell, and c) dynamic upwelling associated with eddy formation.

Sea surface temperature (SST) data (not displayed) around the period of the 2008 event displayed in Figure 7 show the appearance of cool 20ºC at the St Lucia cell in the northern bight approximately a week before the 5th June images displayed. This cool water appears as the Natal Pulse event begins to manifest as a southward moving offshore meander; consistent with this upwelling cell being topographically driven by the Agulhas (Lutjeharms *et al.*, 2000). These SST data then show the movement of this cool water southwards and offshore as the pulse develops and the Agulhas Current moves eastwards. It would thus appear that this enhanced offshore productivity is driven primarily by entrained upwelled water from the St Lucia cell. However, Figure 7 also shows moderately enhanced gelbstoff and sediment concentrations associated with the same feature: indicating that there is some entrainment and therefore influence of riverine water. Figure 11, representing higher river flow conditions during a Natal Pulse event, demonstrates the same phenomenon. It therefore appears that the offshore recirculation underlying enhanced productivity is driven by the pulsed Agulhas Current; this pulsing also results in upwelling and offshore transport from the St Lucia cell; and riverine influenced inshore waters are similarly transported and recirculated, with a variable biogeochemical influence.

Southern Bight Recirculation and Productivity

The Durban Eddy is an occasional recirculation feature in the southern Bight (Lutjeharms *et al.*, 2000) that is potentially responsible for elevated productivity. Figures 10 and 13 display this feature clearly – also clearly showing entrainment of riverine waters along the inner edge of the Agulhas during non Natal Pulse events.

Finally, it would also appear that the C2R data offer interesting perspectives on the dynamics offshore of the primary current (Figure 9). Both Chl-a and gelbstoff products display several eddies and jets. Given the regional and even global importance of Agulhas Current variability, the role of pulsed events, and the potential driving nature of eddy transport down the Mozambique channel, it would appear that new ocean colour products can offer new insights into broader scale regional ocean dynamics.

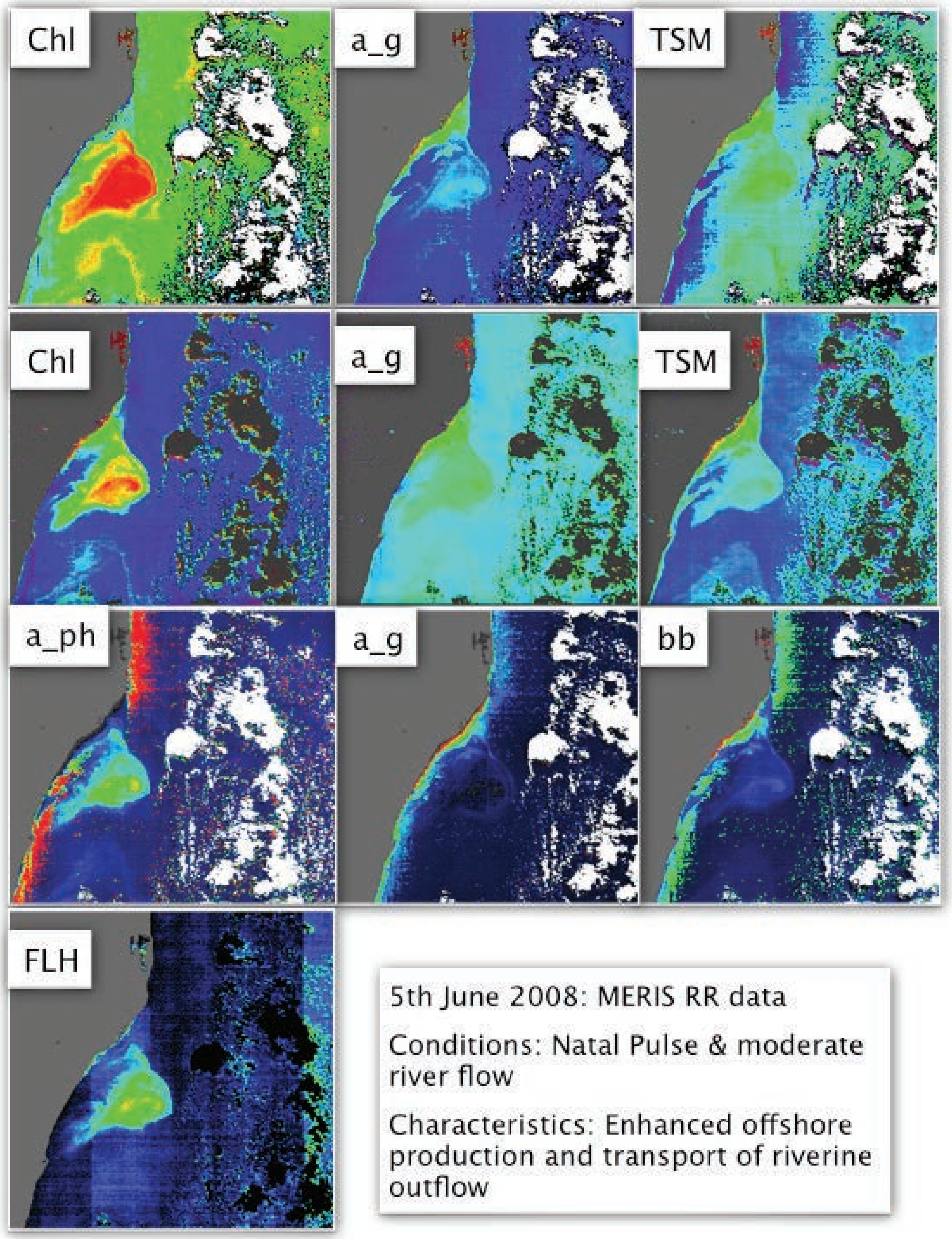

Figure 7. Example of MERIS products for 5th June 2008, during an event characterised by moderate river flow and a Natal Pulse (typified by the offshore movement of the Agulhas Current). Products displayed are those from the standard Case 2 algorithm (C2, upper row), the Case 2 Regional Processor (C2R, 2nd row), the Quasi Analytical Algorithm (QAA, 3rd row), and the Fluorescence Line Height (FLH, 4th row, in relative units). Colour bars are for standard Case 2, C2R and QAA products are shown in Figure 7a.

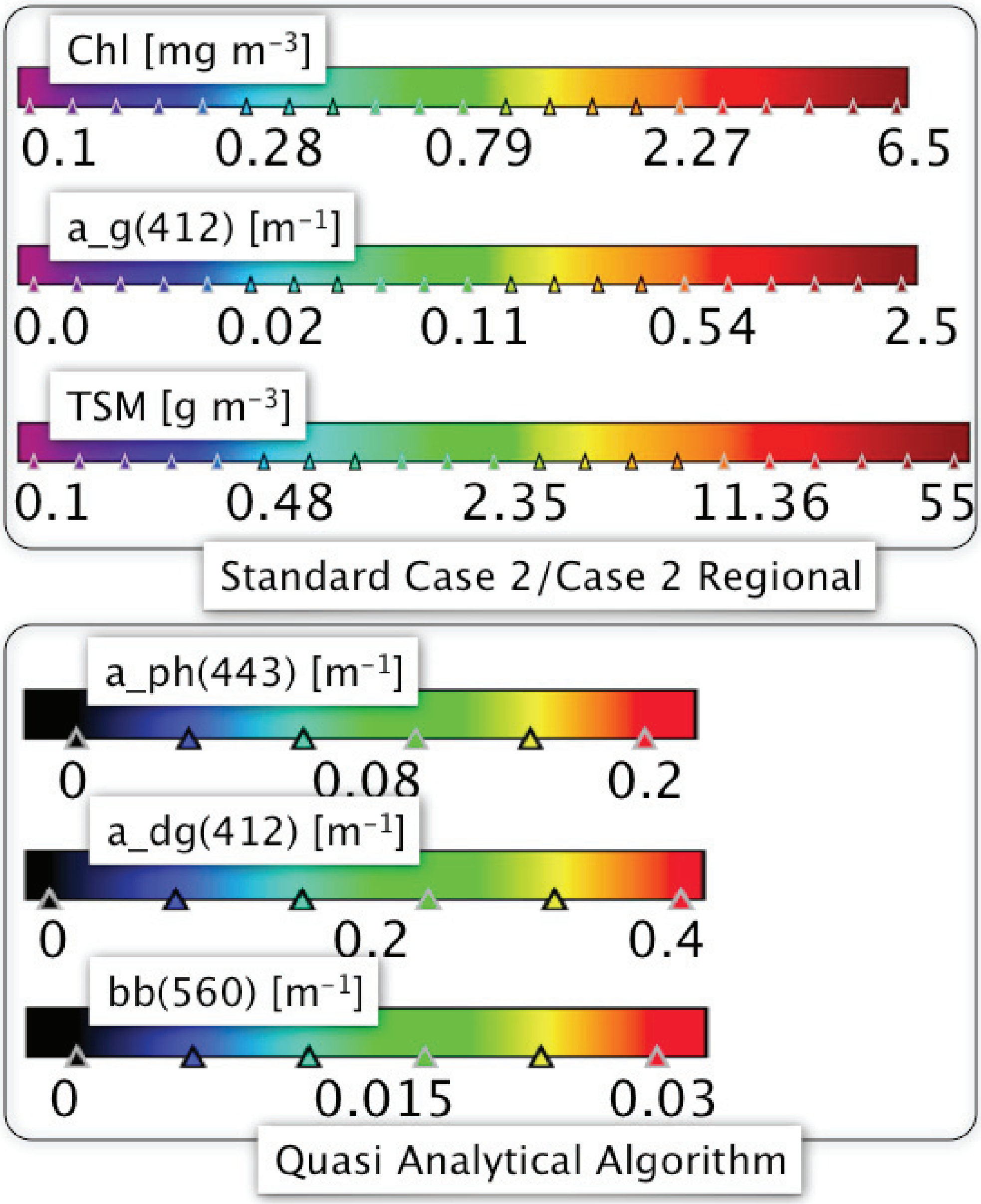

Figure 7a. Colour bar scales for products shown in Figures 7 to 13.

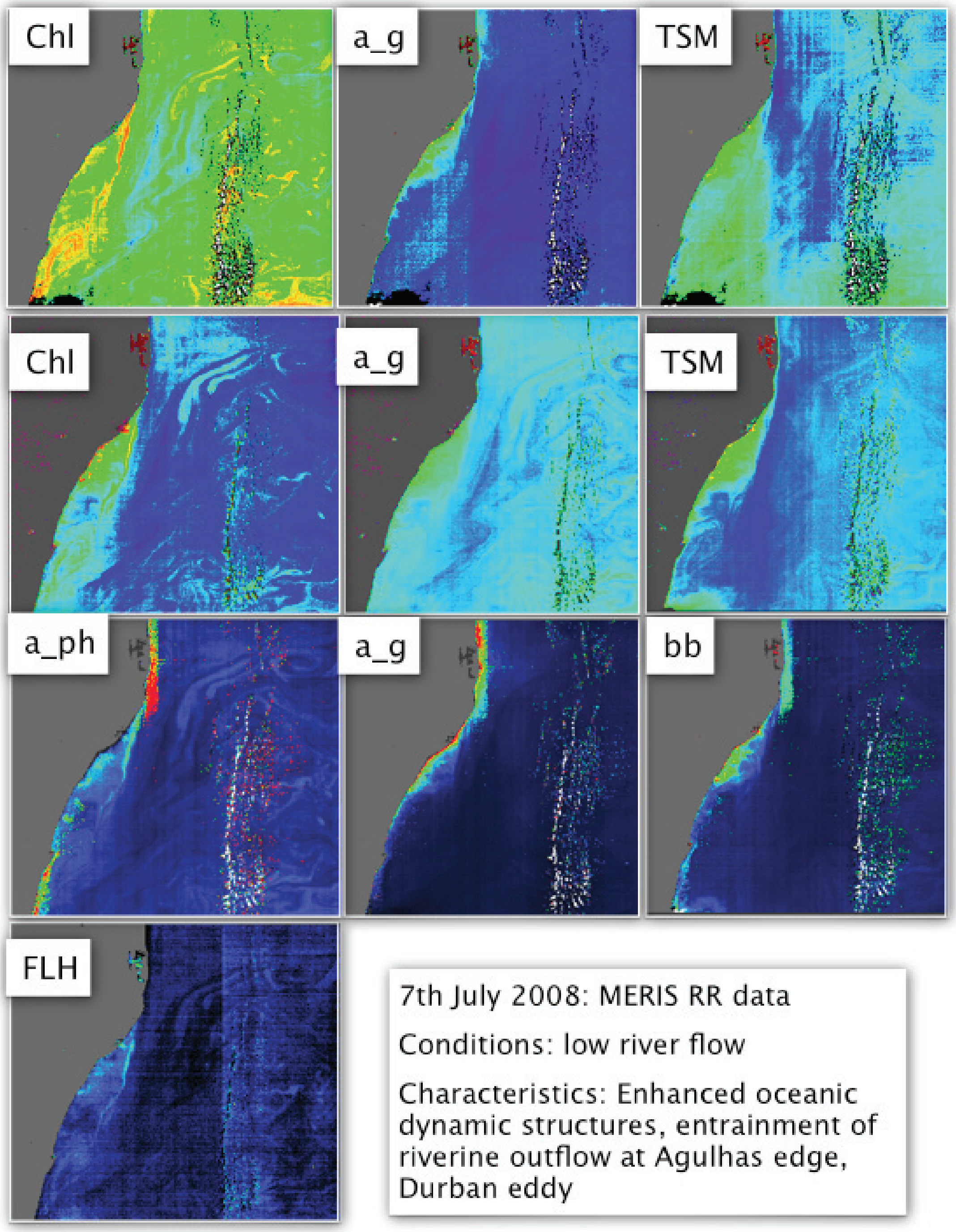

Figure 8. Example of MERIS products for 7th July 2008, during an event characterised by low river flow. Products displayed are those from the standard Case 2 algorithm (C2, upper row), the Case 2 Regional Processor (C2R, 2nd row), the Quasi Analytical Algorithm (QAA, 3rd row), and the Fluorescence Line Height (FLH, 4th row, relative units). See Figure 7a for colour bar legends.

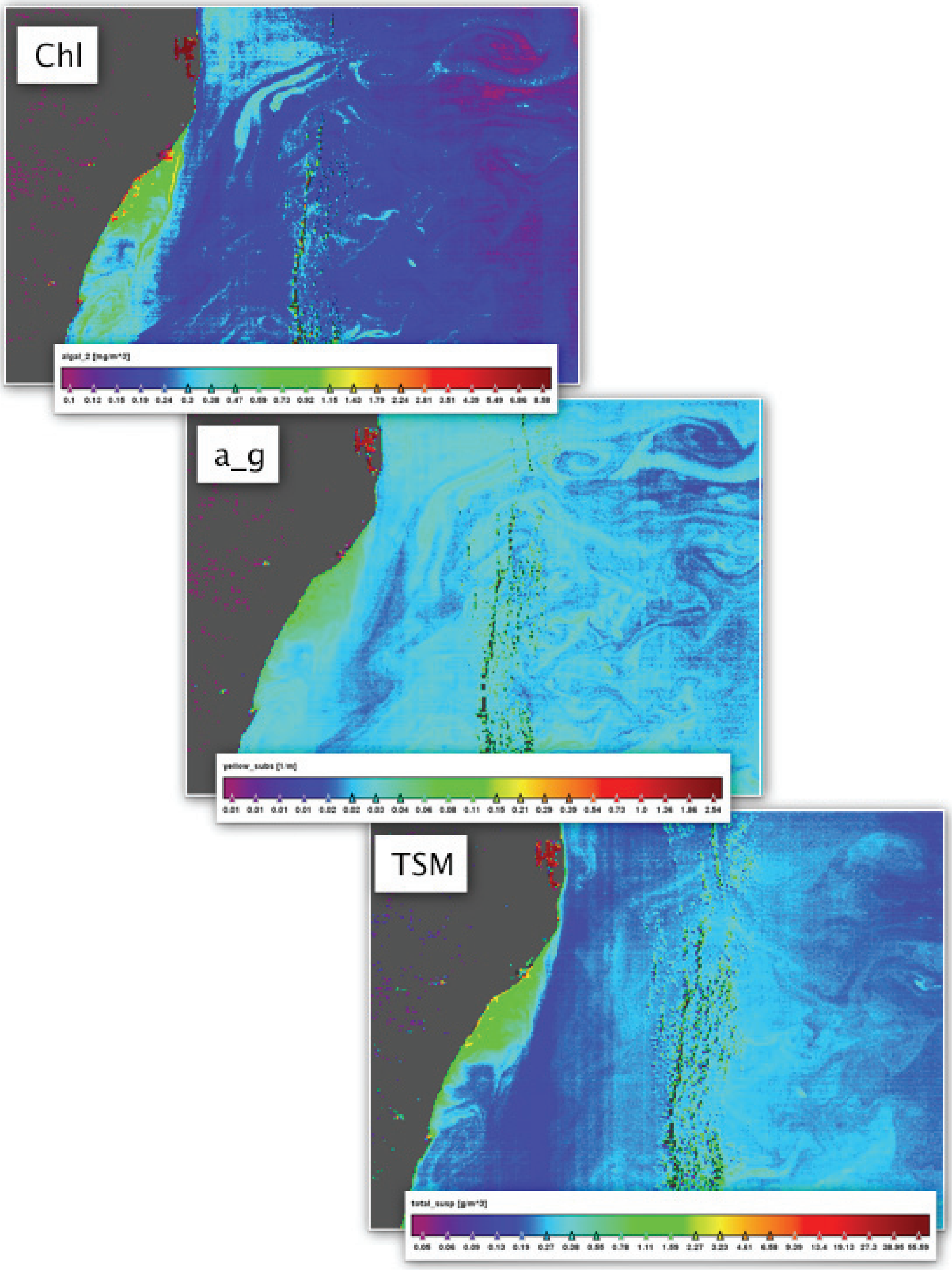

Figure 9. Enlarged images of the three Case 2 Regional products for 7th July 2008, detailing the eddy structures offshore of the Natal Bight

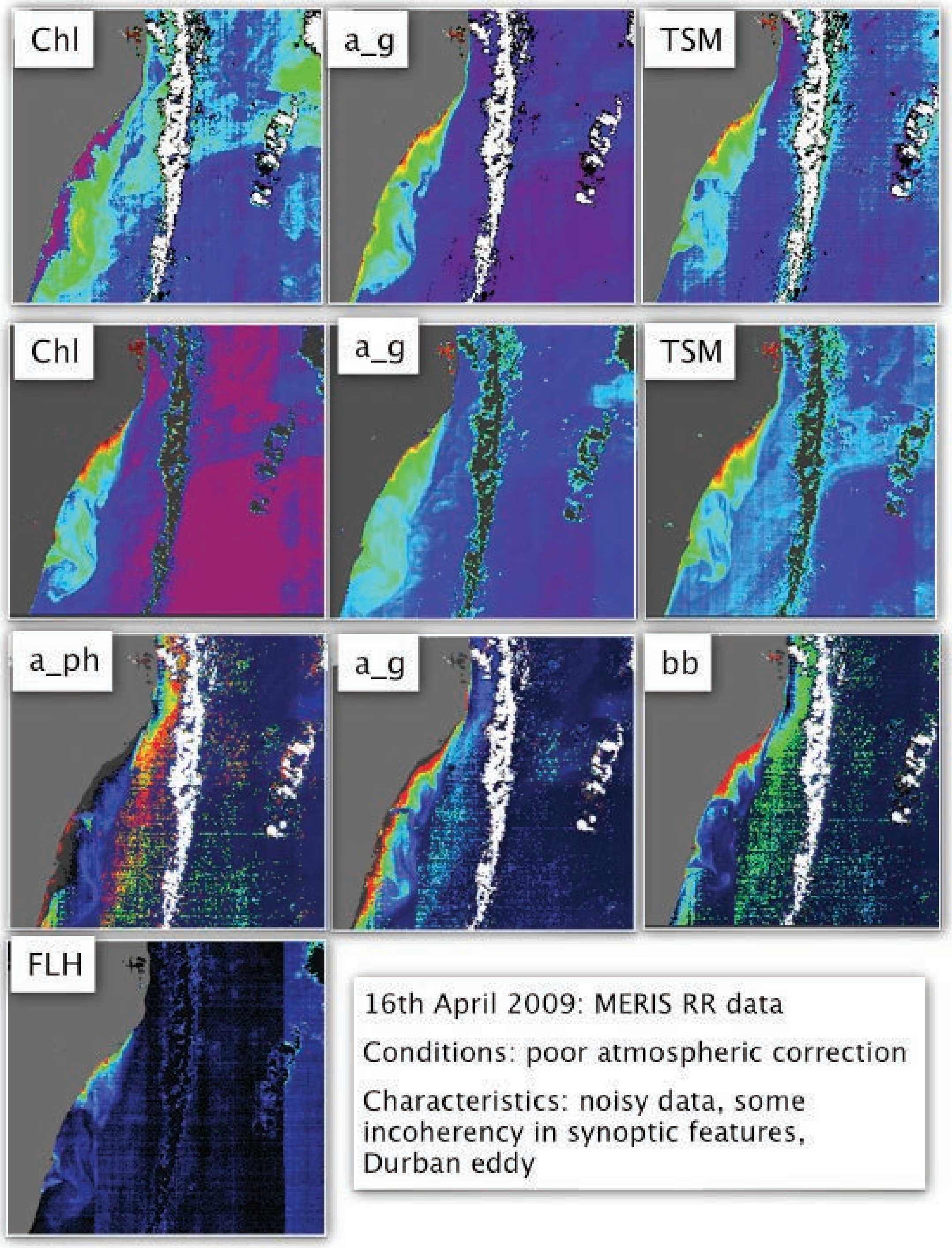

Figure 10. Example of MERIS products for 16th April 2009, during an event characterised by atmospheric frontal conditions and poor atmospheric corrections. Products displayed are those from the standard Case 2 algorithm (C2, upper row), the Case 2 Regional Processor (C2R, 2nd row), the Quasi Analytical Algorithm (QAA, 3rd row), and the Fluorescence Line Height (FLH, 4th row, relative units). See Figure 7a for colour bar legends.

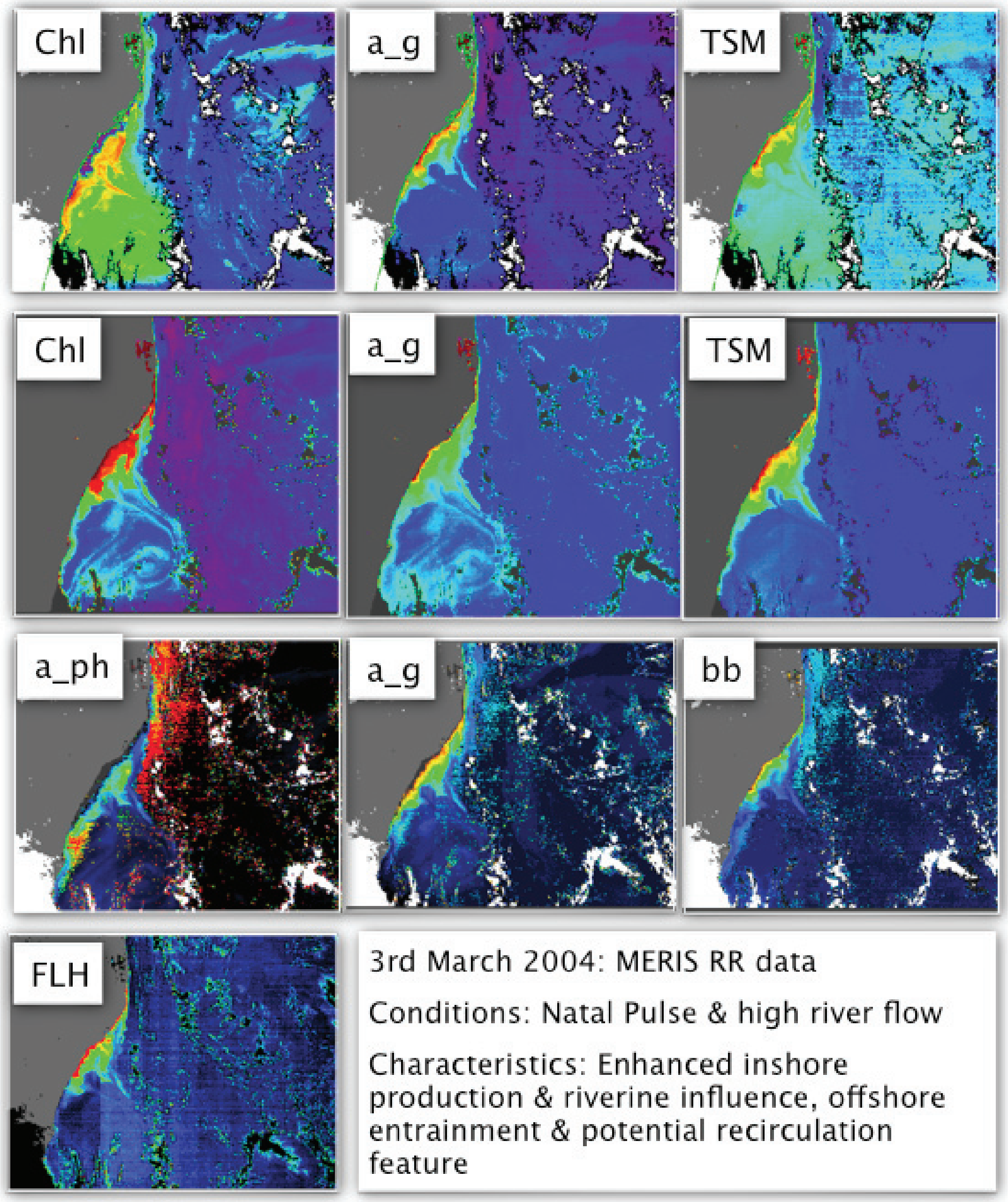

Figure 11. Example of MERIS products for 3rd March 2004, during an event characterised by high river flow and a Natal Pulse event. Products displayed are those from the standard Case 2 algorithm (C2, upper row), the Case 2 Regional Processor (C2R, 2nd row), the Quasi Analytical Algorithm (QAA, 3rd row), and the Fluorescence Line Height (FLH, 4th row, relative units). See Figure 7a for colour bar legends.

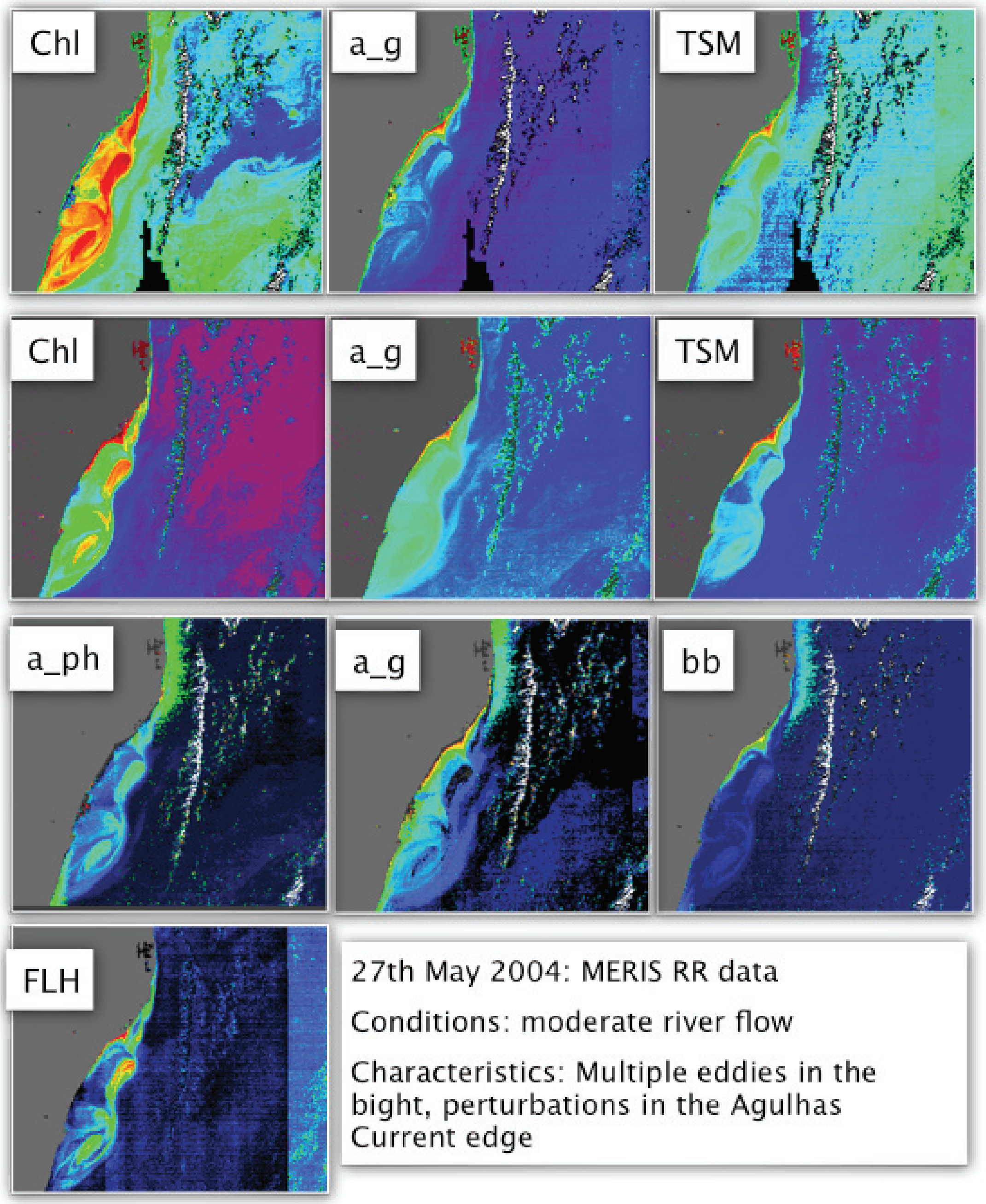

Figure 12. Example of MERIS products for 27th May 2004, during an event characterised by moderate river flow. Products displayed are those from the standard Case 2 algorithm (C2, upper row), the Case 2 Regional Processor (C2R, 2nd row), the Quasi Analytical Algorithm (QAA, 3rd row), and the Fluorescence Line Height (FLH, 4th row, relative units). See Figure 7a for colour bar legends.

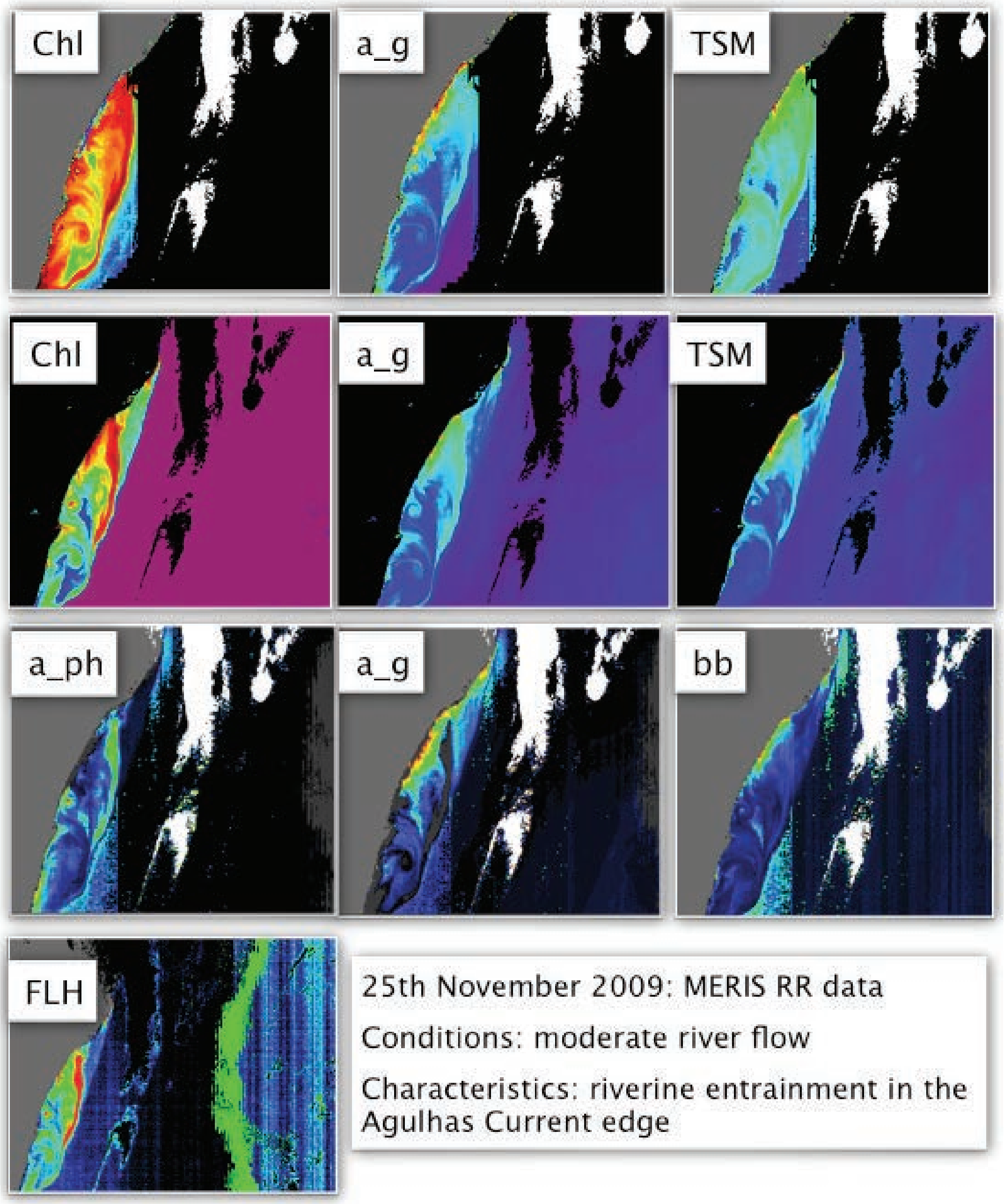

Figure 13. Example of MERIS products for 25th November 2009, during an event characterised by moderate river flow. Products displayed are those from the standard Case 2 algorithm (C2, upper row), the Case 2 Regional Processor (C2R, 2nd row), the Quasi Analytical Algorithm (QAA, 3rd row), and the Fluorescence Line Height (FLH, 4th row, relative units). See Figure 7a for colour bar legends.

5.3 Ocean Colour Time Series Analyses: MODIS

As discussed in Section 3, the locally held MERIS archive is not cohesive enough to allow even a demonstration time series analysis. It is analyses of this type that will ultimately realise the full value of ocean colour remote sensing with regard to ecosystem characterisation, and ecosystem variability over decadal time scales.

An example time series analysis was conducted using MODIS data for 2003, as a demonstration of the approach to lay the foundations for further research. Unfortunately, it was only possible to use standard Case 1 MODIS products: however effective use of the turbidity flag for this product (indicating moderate sediment concentration) allows at least a first order rejection of sediment compromised Chl-a data, and an estimate of synoptic sediment presence.

Three spatial blocks of data were analysed:

1) Tugela block: -29.1719 to -29.3506 S and 31.4535 to 31.6718 E
2) Richards bay block: -28.8195 to -29.1003 and 31.6636 to 31.9515 E
3) Standard: block: -29.1719 to -29.3506 S and 31.6718 to 31.8906 E

These were taken to represent inshore waters in the Thukela discharge zone, inshore waters representative of the St Lucia upwelling cell areas, and waters on the outer edge of the bight, respectively. Data presented in Figures 14-16 (by descending row) are 1) Chl-a from the MODIS OC3v3 algorithm with no turbidity flag applied; 2) Chl-a from the MODIS OC3v3 algorithm with turbidity flag applied; 3) the difference between these which is effectively the quantity of artifactual Chl-a incorrectly ascribed to sediment; 4) the number of pixels identified as turbid within each block; and 5) the flow rates from the Thukela Mandini station.

All blocks display the same gross characteristics:

- Flagged Chl-a values of up to ± 3 mg m^{-3}, considered reasonable given the available historical data (Section 2.2)
- A high and variable proportion of the unflagged Chl-a is actually due to sediment, particularly for the inshore blocks
- Good agreement between plots 3) and 4) above, indicating the turbidity flag approach is at least a robust indicator of synoptic sediment distribution
- Lack of seasonal trends in the “correct” flagged Chl-a concentrations
- A winter maximum in the synoptic sediment distribution, peaking in June-August.

Of particular interest is the last point – it seems somewhat counter-intuitive that the apparent maximum in areal sediment concentration is during low river flow. However, there is some evidence that this may be due to stronger wind mixing during winter months (Lutjeharms *et al.*, 2000). This may also be at least partially due to the nature of the sediment metric used, which is determined by the type of MODIS data available. Effectively these metrics, e.g. the number of “turbid” pixels in a block is an estimate of what areal extent of water has a moderate sediment concentration – this is appreciably different to a metric that indicates the mean concentration of sediment within an area. It is therefore quite possible that the turbidity metrics use here are more responsive to oceanographic dispersion and recirculation mechanisms than volume of riverine input. As seen from the previous discussion these oceanographic mechanisms have a profound impact upon the biogeochemistry of the Bight. Further analyses are needed, using more quantitative sediment indices from validated Case 2 algorithms.

Inter-comparisons between the blocks are also of interest, particularly the much higher areal sediment distributions observed in the Richard's Bay block. Qualitative interpretation of the event scale imagery indicates that the Richard's Bay areas often appears turbid, and the time-series analysis appears to support this observation. This may be due to a combination of factors: the area is extremely dynamic owing to the proximity of the Agulhas Current and there may be much sediment resuspension; and the input of the Mhlathuze River, one of the largest in the KwaZulu-Natal area. It also may be possible that there are at least parts of the block which are optically shallow, i.e. the satellite is seeing the effects of the bottom in the water leaving radiance, which is misinterpreted as sediment effects. Again, more effective analysis can be made once sufficient volumes of validated data are available to assess confidence limits in both MODIS and MERIS products across the different regions of the Bight.

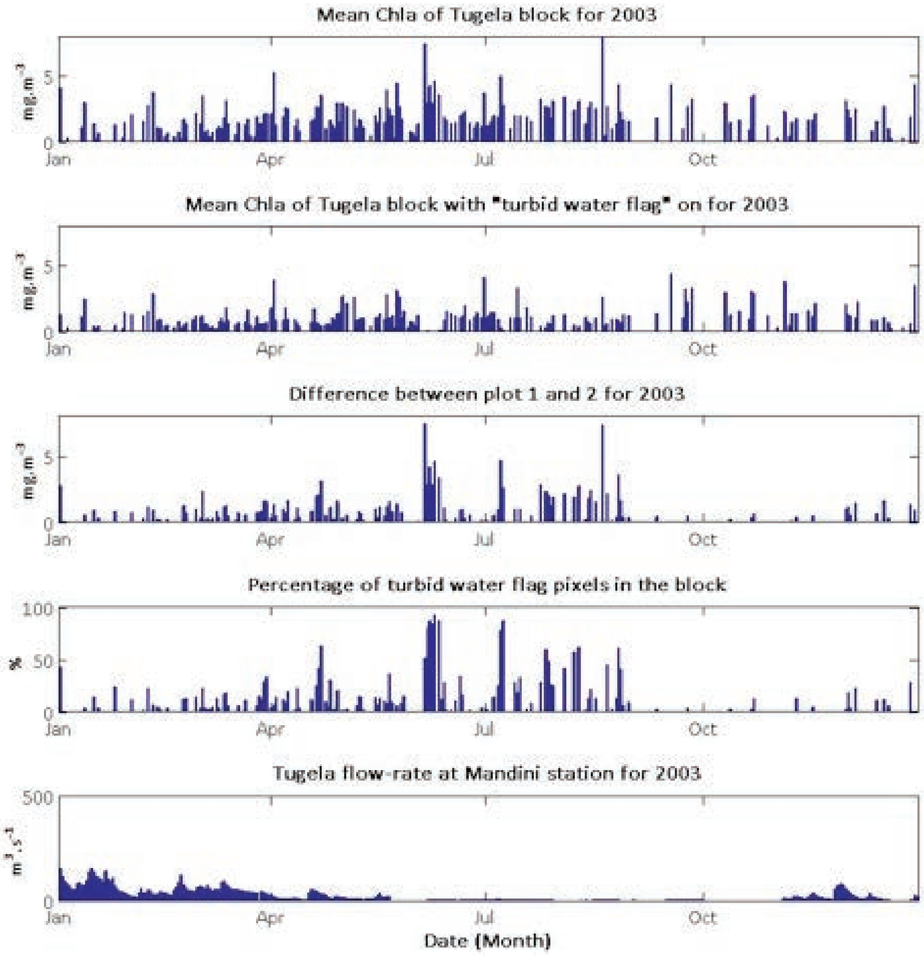

Figure 14. MODIS time series analyses for 2003, for the Thukela block, using the standard Case 1 OC3v3 Chl-a algorithm in combination with the turbidity flag to indicate sediment compromised Chl-a data and the presence of moderate sediment concentrations. Graphs from top are a) unflagged OC3v3 Chl-a concentrations in mg m-3, b) OC3v3 Chl-a concentrations in mg m-3 with the turbid water flag applied, c) the difference between a) and b) – effectively the amount of Chl-a spuriously ascribed to sediment, d) the total number of turbid water flagged pixels in the block, and e) flow rates from the Thukela Mandini station.

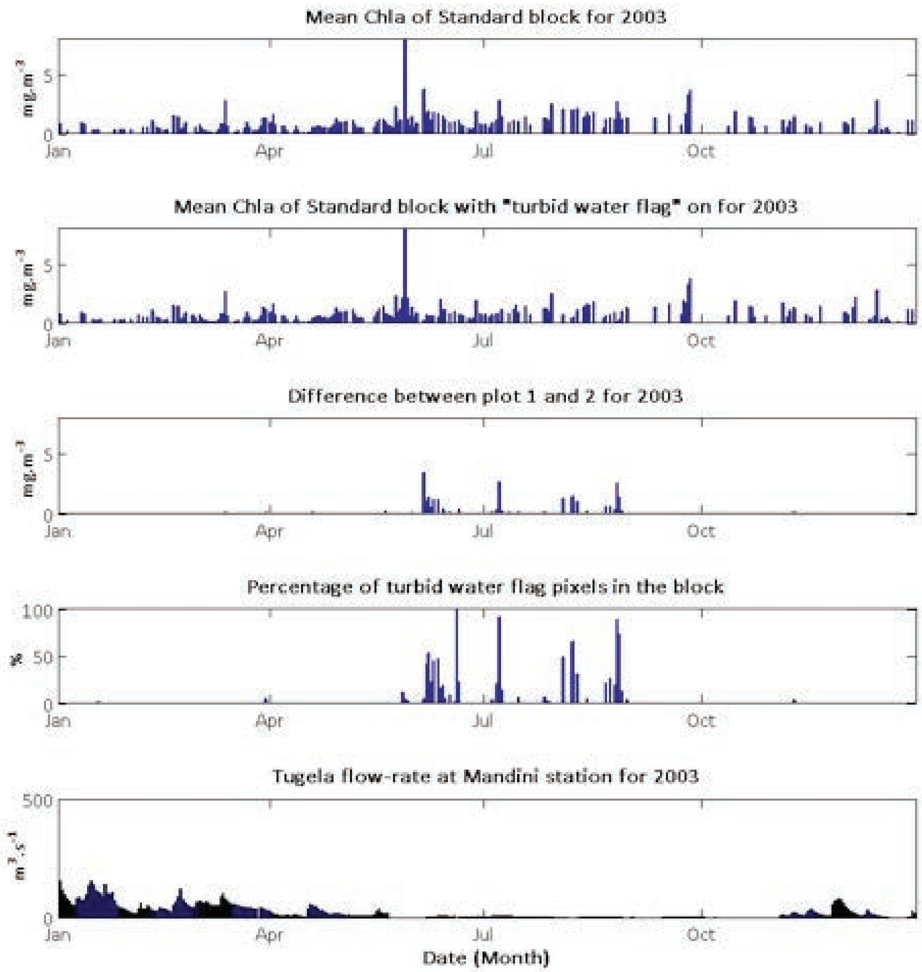

Figure 15. MODIS time series analyses for 2003, for the standard (offshore) block, using the standard Case 1 OC3v3 Chl-a algorithm in combination with the turbidity flag to indicate sediment compromised Chl-a data and the presence of moderate sediment concentrations. Graphs from top are a) unflagged OC3v3 Chl-a concentrations in mg m-3, b) OC3v3 Chl-a concentrations in mg m-3 with the turbid water flag applied, c) the difference between a) and b) – effectively the amount of Chl-a spuriously ascribed to sediment, d) the total number of turbid water flagged pixels in the block, and e) flow rates from the Thukela Mandini station.

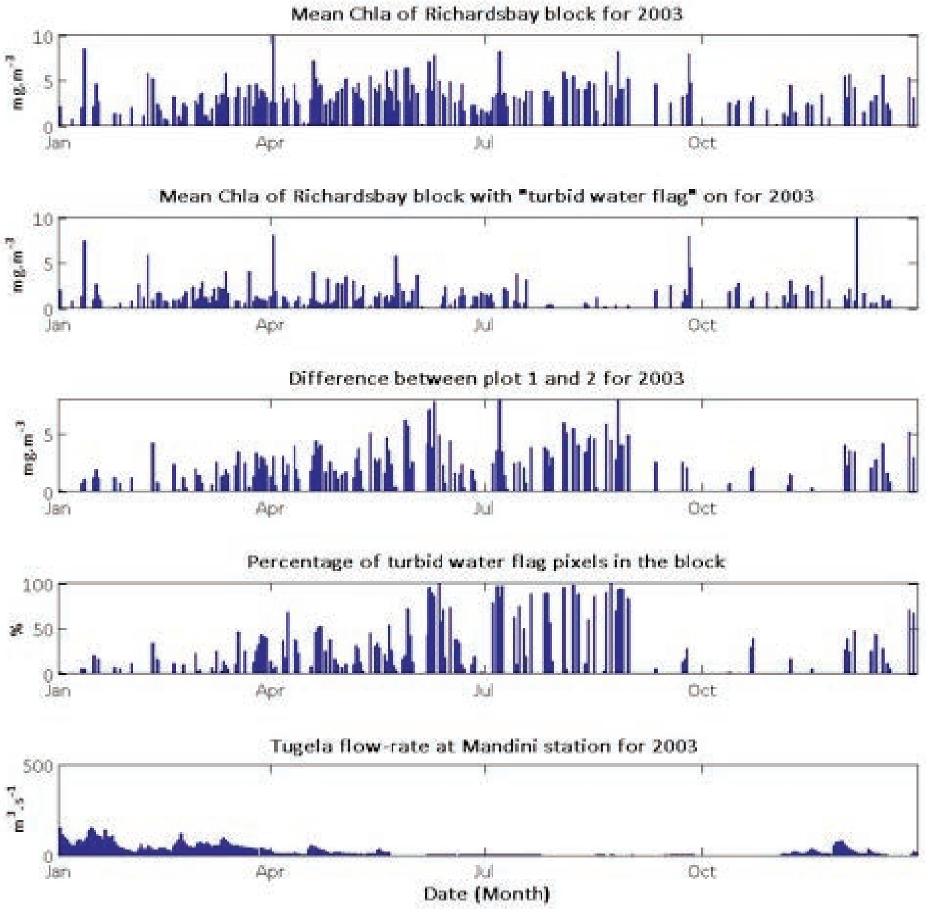

Figure 16. MODIS time series analyses for 2003, for the Richard's Bay block, using the standard Case 1 OC3v3 Chl-a algorithm in combination with the turbidity flag to indicate sediment compromised Chl-a data and the presence of moderate sediment concentrations. Graphs from top are a) unflagged OC3v3 Chl-a concentrations in mg m-3, b) OC3v3 Chl-a concentrations in mg m-3 with the turbid water flag applied, c) the difference between a) and b) – effectively the amount of Chl-a spuriously ascribed to sediment, d) the total number of turbid water flagged pixels in the block, and e) flow rates from the Thukela Mandini station.

6. Conclusions & Recommendations

6.1 Assessment of the Effect of Freshwater Inputs to Coastal Waters

Preliminary conclusions have been discussed in the previous section, with the proviso that only very precursory validation has been conducted for the ocean colour products. Nevertheless the following primary conclusions can be drawn:

- It appears that riverine input enhances primary production in both inshore and (less frequently and directly) offshore waters of the Natal Bight, based upon analysis of the MERIS Case 2 Regional Processor and Fluorescence Line Height products. This would appear to indicate that light limitation by suspended sediments is a secondary limiting factor relative to riverine nutrient input.
- It appears that oceanographic processes, largely driven by variability in the Agulhas Current, exert a profound influence on the biogeochemistry of the Natal Bight, controlling upwelling in the St Lucia cell, offshore transport of high nutrient waters, and recirculation patterns. Whilst none of these findings are new or unexpected, the project has emphasised the scale of the physical control over the Bight's biogeochemistry.

6.2 Validation and Algorithm Development

The poor performance of the standard MERIS Case 2 algorithm, and the variable performance of the other selected algorithms (even from a necessarily qualitative perspective) underlines the need to gather and analyse greater volumes of in situ validation data. As outlined in Sections 3 and 5.1, these data must address validation of the atmospheric correction, radiometry and the water leaving reflectance/radiance data, and in-water algorithm through characterisation of the regional inherent optical properties and key biogeochemical parameters. These parameters must include chlorophyll a concentrations, suspended sediment concentrations, and gelbstoff absorption. Should the resources be available, the use of autonomous validation platforms is very strongly encouraged: bio-optical buoys in combination with shore-based AERONET or AERONET-OC sun photometer systems (Zibordi *et al.*, 2009).

Further validation must be conducted of available MERIS algorithms, the wide variety of MODIS algorithms available, and non sensor-specific algorithms such as empirical Case 2 algorithms (e.g. Gitelson *et al.*, 2009), spectral classification algorithms (e.g. Moore *et al.*, 2001) and local analytical algorithms (Bernard, 2005).

6.3 Development of Operational Systems

The Marine Remote Sensing Unit currently processes and disseminates MODIS Case 1 and MERIS Case 1 and Case 2 products for the east coast of South Africa (www.afro-sea.org.za). It is clear from the findings presented here that the standard MERIS Case 2 products do not work very effectively in the Natal Bight, and different or additional products should be provided. Ideally the default products offered (for MERIS) should be from the Case 2 Regional Processor, as these products appeared most effective for the region. However, provision of C2R products would entail operational processing from Level 1, which the MRSU does not currently undertake due to resource limitations. It is suggested that in the short term, the Fluorescence Line Height products should be provided for diagnostic purposes, as these can be relatively easily added to the existing Level 2 processing chain. In the long term, the MRSU should seek to implement a Level 1 based processing chain incorporating both the SMILE correction and the C2R processor. Recommendations for dissemination of further MODIS products can only be made after additional validation efforts.

The MRSU should also undertake to retrospectively process the entire MERIS and MODIS archives for the region using the same processing schemes, and make these data publicly available. New global reprocesses will be made available for both MODIS and MERIS in 2010, and the resources should be sourced to make such data available to the user community.

6.4 Uptake and Impact

Effective use of these operational remote sensing products requires the development and empowerment of a user community – scientists, coastal and resource management agencies, fishing and marine industries, and other interested parties. Two activities are critical in developing this user community: an extensive and widely published user scoping workshop, and training/educational workshops and auto-didactic material. It is suggested further development of a national operational marine and freshwater earth observation capability should prioritise these workshops, whether funded by the WRC or other initiatives.

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