Generalized satellite image processing: eight years of ocean colour data for any region on earth

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ABSTRACT

During the past decade, the world's oceans have been systematically observed by orbiting spectroradiometers such as MODIS and MERIS. These sensors have generated a huge amount of data with unprecedented temporal and spatial coverage. The data is freely available, but not always accessible for marine researchers with no image processing experience. In order to provide historical and current oceanographic parameters for the jellyfish forecasting in the JELLYFOR project, a tool for the generalized processing and archiving of satellite data was created (GRIMAS). Using this generalized software, the large amount of remote sensing data can be accessed, and parameters such as chlorophyll *a* concentration (CHL), sea surface temperature (SST) and total suspended matter concentration (TSM) can be extracted and gridded for any region on earth. Time-series and climatologies can be easily extracted from this data archive. The products generated can be based on the standard products, as supplied by space agencies, or can be new or regionally calibrated products. All available MODIS and MERIS L2 images from an eight year period (2003-2010) were processed in order to create a gridded dataset of CHL, SST (MODIS only) and of TSM for the three JELLYFOR regions. For two of the regions, data for an extended region was also processed. Multi-year composites (climatologies) of satellite data and time-series can provide a wealth of information for different projects in any region. Climatologies from the two sensors are in good agreement, while significant differences can occur on a scene per scene basis. Total suspended matter concentrations match favourably with *in situ* data derived from sensors on autonomous buoys. MODIS sea surface temperature corresponds closely to temperature continuously measured underway on research vessels.

Keywords: *ocean colour, chlorophyll, total suspended matter, sea surface temperature, data archive, Southern North Sea, English Channel, Catalan Sea, Irish Sea, Atlantic Ocean*

1 INTRODUCTION

The Moderate Resolution Imaging Spectroradiometer (MODIS) and the Medium Resolution Imaging Spectroradiometer (MERIS) are multi-spectral sensors on board EOS-PM (‘Aqua’) and ENVISAT, two polar orbiting satellites launched in 2002. Since then, they have been systematically recording our planet’s land and oceans. Oceanographic parameters related to ocean colour, such as chlorophyll *a* (CHL) and total suspended matter (TSM) concentrations, can be derived from the spectral bands of these sensors. Because of the inclusion of thermal infrared bands, MODIS is also capable of retrieving sea surface temperature (SST).

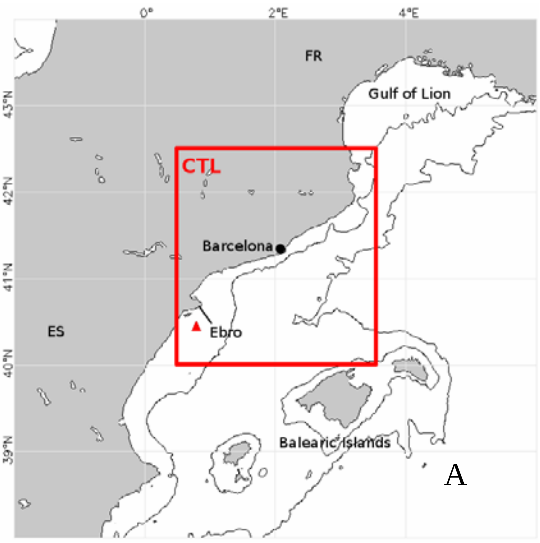
These data products are freely available, but can overwhelm the users by sheer numbers of files and the processing can seem threatening, particularly if the user requires multi-temporal or time-series data rather than single images. We have developed software that processes the available data to a common grid, and stores these data in a transparent manner (GRIMAS[1]). GRIMAS also includes a toolbox with multiple capabilities, for example: linking remote sensing data with in situ data and the extraction of time-series or multi-temporal climatologies. In this paper we present the vast amount of data that is available from ocean colour satellites, and how valuable these data can be for different applications. The GRIMAS software allows, for any region on earth, to quickly process (depending on network speed, processing power and the size of the region) the data from the MODIS, MERIS and SeaWiFS sensors. Modularity ensures that new datasets or sensors can be added in the future.

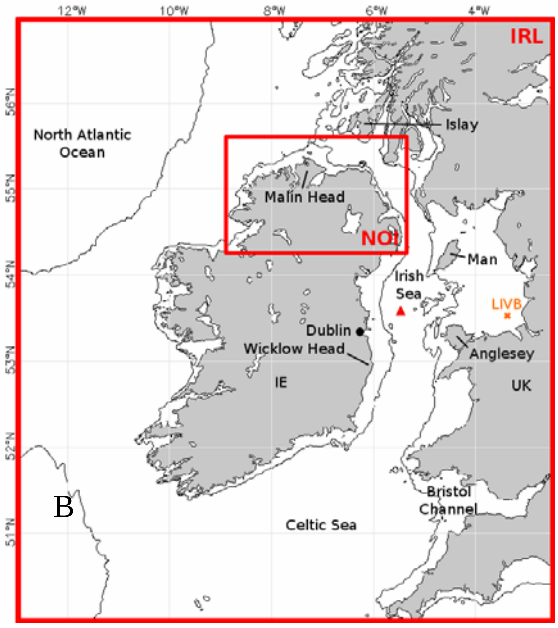
2 METHODS

2.1 Regions in the JELLYFOR project

Data were collected and processed for the three regions in the JELLYFOR project: the Catalan Sea (CTL; 40.00°N – 42.50°N, 0.50°E – 3.50°E), the North Ireland Coast (NOI; 54.25°N – 55.61°N, 5.35°W – 8.89°W) and the Belgian Coastal Zone (BCZ; 50.85°N – 51.80°N, 1.80°E – 4.00°E). For BCZ and NOI, data for an enlarged area (respectively

SNC and NOI, see figure 1) were also collected.





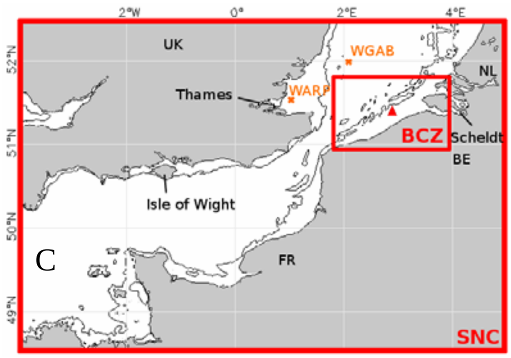


Figure 1. Location of the three JELLYFOR regions in a larger context. Bathymetry extracted from the GEBCO 0.5' database[2]. A) Western Mediterranean with the Catalan region (CTL), isobaths 200 and 2000 metres, B) Irish waters (IRL) with the North Irish region (NOI), isobaths 50 and 1000 metres and C) the Southern North Sea and English Channel (SNC) and the Belgian Coastal Zone (BCZ), with 20 metre isobath. Complete MODIS and MERIS reduced resolution (RR) archives were processed for CTL, IRL (including NOI) and SNC (including BCZ). Red triangles show the locations for the time-series given in figure 5. SmartBuoy locations are plotted in orange (IRL and SNC).

2.2 Processing of satellite data

All available data from MODIS and MERIS were collected for the regions in section 2.1, for the eight full years the sensors were both in orbit (2003-2010). MODIS data originates from NASA's Ocean Color website (http://oceancolor.gsfc.nasa.gov/) and the MERIS data was downloaded from ESA's MERCI application (http://merci-srv.eo.esa.int/merci/). Between 2003 and 2008, MODIS data from the 2009.1 reprocessing (http://oceancolor.gsfc.nasa.gov/REPROCESSING/R2009/) is used, and for 2009—2010 data from the 2010.0 reprocessing (http://oceancolor.gsfc.nasa.gov/WIKI/OCReproc20100MA.html) is used. All MERIS data is from the second MERIS reprocessing[3].

All scenes from both sensors were processed using the GRIMAS toolbox, which provides extraction of data, projection to a common grid, and analysis tools. Chlorophyll products were extracted from both MODIS and MERIS (chlor_a and algal_2, respectively), and an additional quality check was performed to exclude the MODIS chlorophyll product in turbid waters[4]. For MODIS, the total suspended matter concentrations were computed from remote rensing reflectance at 667 nm[5] and for MERIS the standard product (total_susp) was extracted from the image files. The algorithm used to calculate MODIS total suspended matter is calibrated for turbid waters, so an uncertainty is associated with the product in clearer waters (TSM < 1 g/m^3). However, the algorithm can be recalibrated with *in situ* data. Sea surface temperature was extracted from the MODIS data (sst). For the MERIS datasets, the appropriate product confidence flags are used to exclude unreliable or unusable data, while for MODIS a combination of flags was used (see further details in [1]).

To create multi-temporal composites, the data is first combined (binned) on a daily basis; i.e. the available data for each day is combined in a single file per sensor. Adjacent overpasses are stitched together, and in case of overlap (MODIS) the data from the most favourable viewing angle is chosen. Then the arithmetic mean of the available files for a certain period is calculated. GRIMAS can rapidly locate pixels for a given date and time (or time-frame) and location (either latitude and longitude, or a frequently used 'station' set in one of the configuration files). Extraction of time-series from or finding match-ups in a gridded dataset is fast – the pixel(s) of interest are at the same location in each file, and can thus be rapidly accessed once the required position is located in the grid. Unless specified otherwise, the median value from a 5x5 pixel box over the station with at least 13 valid pixels is used in time-series plots and in the match-up analysis.

2.3 Intersensor comparison

GRIMAS processes all available data to a common grid, which makes comparisons between datasets trivial. Comparisons between MODIS and MERIS CHL and TSM were made. Two approaches were used to compare the data, the first based on individual scenes, and the second on multi-temporal bins. For the first method; each gridded image from one sensor is matched to the images of another sensor, within a certain timeframe (eg. overpass time ±1 hours). Valid pixels present on both images are included in a (logarithmic) correlation analysis. The second method matches a multi-temporal bin (eg. one year, or in this paper, a multi-year climatology) from one sensor to that of another. Valid pixels in both datasets are included in the correlation analysis. An additional filter can be used to exclude pixels computed with less than a certain number of images.

2.4 Other input data

Underway seawater temperature measurements from the RV Belgica (from a Seabird SBE21, CTD probe with intake at ~3m http://www.mumm.ac.be/NL/Monitoring/Belgica/index.php), are used to validate MODIS SST in the BCZ/SNC regions. Underway seawater temperature measurements from two vessels from the Irish Marine Institute (Celtic Explorer and Celtic Voyager, http://www.marine.ie/home/services/researchvessels/) are used to validate MODIS SST in the NOI/IRL regions.

Half-hourly TSM data from three of CEFAS' SmartBuoys (location plotted in figure 1) are used to validate satellite-derived products. These data are estimated from continuous measurements of turbidity, calibrated with TSM measurements from samples taken with Aqua Monitor samplers and from a rosette sampler. Two buoys are in the SNC region; Warp Anchorage (WARP, approx. 51.53°N, 1.03° E, data from 2003-2009) and West Gabbard (WGAB, approx. 51.98°N, 2.08°E, data from 2003-2009). One buoy is in the IRL region; Liverpool Bay (LIVB, approx. 53.53°N, 3.38°W, data from 2003-2006).

3 RESULTS

3.1 Remotely sensed oceanography

For each of the regions, long-term annual averages were computed from eight yearly means of the five datasets (MODIS: CHL/TSM/SST, MERIS: CHL/TSM). These climatologies give a broad overview of the oceanography of the region. Other composites can be generated to examine inter-annual or seasonal differences. By combining remote sensing data from multiple years, the effects of these differences and of the ever changing cloud cover are reduced. Time-series were extracted for a single point in every region (figure 2), but are available for every sea pixel in the regions.

3.1.1 Catalan region (CTL)

For the CTL region, the climatologies reveal low CHL concentrations, with little variation in space (figure 3, first column). A similar pattern is also found in the TSM dataset (second column), except for higher concentrations in the Ebro river plume in the south-west of the region and near shore close to Barcelona (41.38°N, 2.18°E). In the SST dataset, a relatively cold water mass can be traced from the north-east to the middle of the region, following the shelf edge (see bathymetry). These colder waters originate from the Gulf of Lion where they are formed by upwelling caused by cold and dry continental winds such as the Mistral and the Tramontane, especially in winter and spring[6]. These waters are important for the thermohaline circulation in the Mediterranean Sea, as they are associated with the formation of Western Mediterranean Deep Water (WMDW). The higher SST in the south of the region can be associated with the warm and strongly stratified coastal waters of the Balearic Islands (just outside of CTL, see figure 1a).

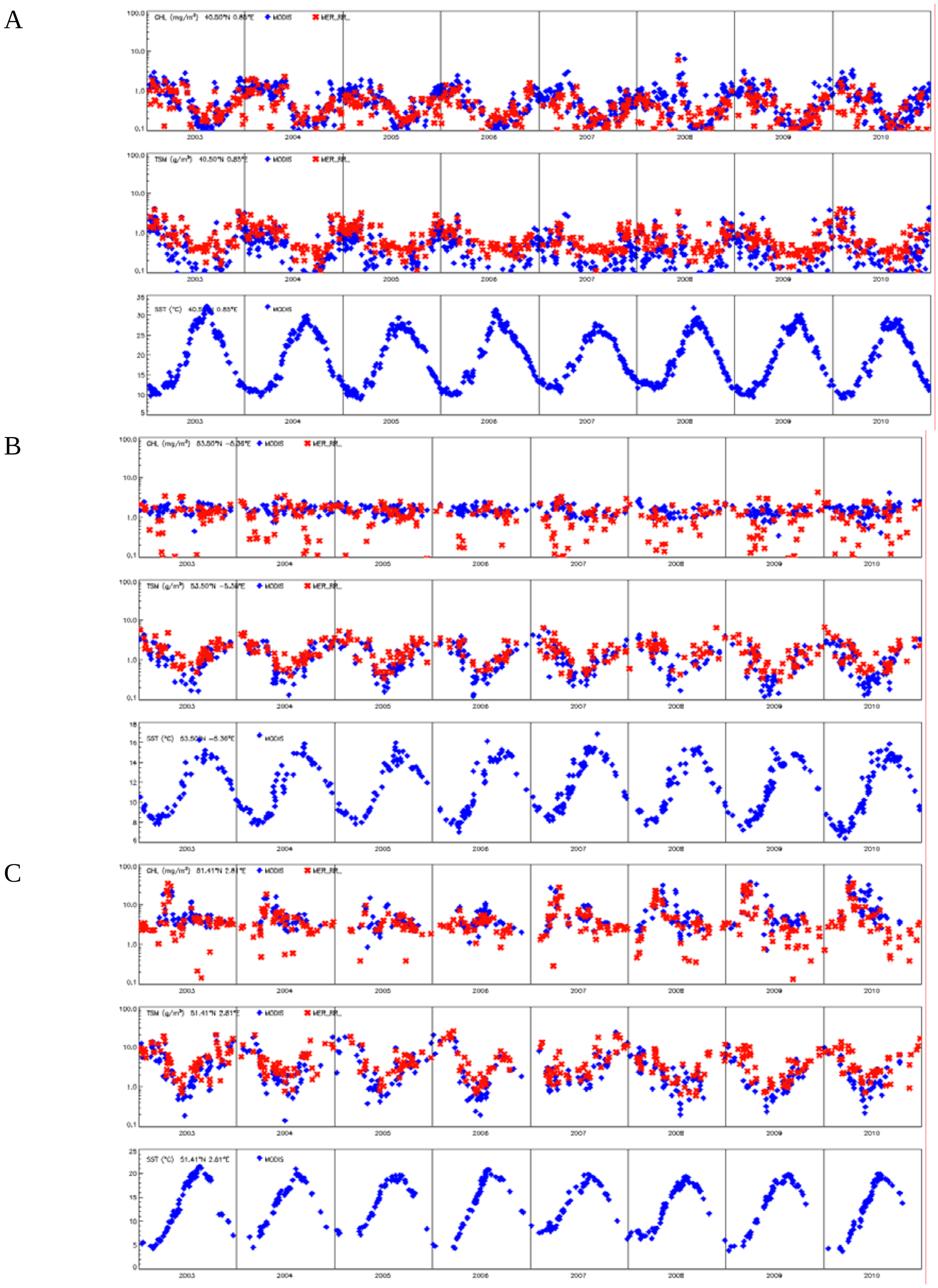


Figure 2: Time-series for A) 40.50°N and 0.85°E (CTL, near the Ebro plume), B) 53.50°N and 5.35°W (IRL, Irish Sea between Dublin and Anglesey) and C) 51.41°N and 2.81°E (SNC, monitoring station W05). Top, middle and bottom rows are chlorophyll *a* concentration (CHL, mg/m³), total suspended matter concentration (TSM, g/m³) and sea surface temperature (SST, °C – MODIS only) respectively. Blue diamonds: MODIS, orange crosses: MERIS.

Time-series (figure 2a) were extracted from a coastal station near the mouth of the Ebro, and show seasonal fluctuations of CHL, TSM, and SST. Coastal waters in the CTL region are influenced by the freshwater input of two rivers, the Ebro and the Rhône (just north of the region; in the Gulf of Lion). During winter and spring higher concentrations of TSM are found, when the discharge of both rivers is highest (max. and min. in March and August[7]), and when storms caused by dry continental winds occur. High chlorophyll concentrations are also found in spring and winter, while lowest values occur during summer and autumn. The water in the western Mediterranean Sea is well-mixed in winter, and stratified in summer[8]. Thermal stratification in summer and autumn is associated with nutrient depletion and low phytoplankton concentrations[9]. Inter-annual differences are easily visible in the temperature dataset, e.g. the respectively warm and cold summers of 2003 and 2007.

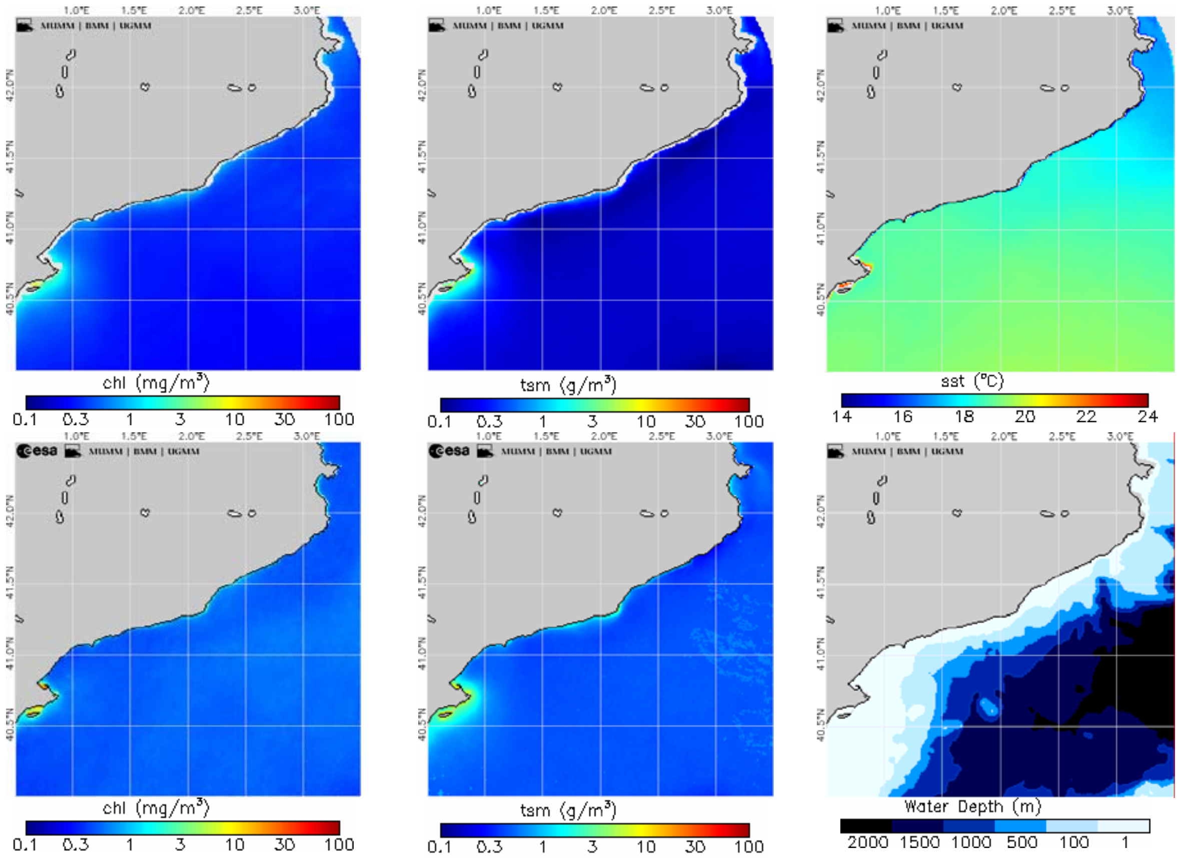


Figure 3: Multi-year climatologies for the CTL region, constructed based on eight yearly means (2003-2010) of ocean colour data. First row: MODIS CHL, TSM and SST. Bottom row: MERIS CHL and TSM and GEBCO bathymetry. Data in the top right corner of the MODIS composites is missing due to a cropping error in the ordering of some images.

3.1.2 Waters around Ireland (IRL)

Three main water bodies can be found in the IRL region: the North Atlantic Ocean in the west, the Celtic Sea in the south and the Irish Sea between Ireland and the United Kingdom. The nature of these waters reveals itself in the different datasets (figure 4). To the north of Ireland, at around Malin Head, a temperature difference is found between the cold waters from the Irish Sea and the warm waters of the North Atlantic. The water in the Irish Sea is cold and well mixed all year round because of strong tidal currents, except in regions with small tidal amplitudes[10]. Warm waters, associated with the shelf edge, are found in the south, south-west and north-west of the region; the warm North Atlantic Current, a branch of the Gulf Stream, and the North Atlantic Slope Current.

Low CHL and TSM concentrations are found offshore in the Celtic Sea and Atlantic Ocean, and higher concentrations are found in the Irish Sea (figure 4, columns 1 and 2). The main bathymetric feature of the Irish Sea is a long deep channel that runs north to south between the land masses of Ireland and the United Kingdom. Compared to the rest of the Irish Sea, lower TSM concentrations are found in this channel, and especially west of the Isle of Man. Here, thermally stratified waters occur during summer (see also the relatively high SST), caused by the small tidal amplitude and the increased water depth[11,12,13]. The highest TSM concentrations are found in the Bristol Channel, where significant amounts of sediment enter the Celtic Sea from the Severn[14]. High concentrations are also found in the shallow eastern Irish Sea, with maxima close to the English coast, west of Islay, in the shallow waters near-shore south of Dublin (at Wicklow Head) and north and west of Anglesey. Because of large tidal ranges and soft sediments, extensive inter-tidal mudflats occur in the English estuaries in the eastern Irish Sea (e.g. [15]). At Wicklow Head and north of Anglesey, tidal currents are known to be strongest in the region[16]. The time-series for a station between Dublin and Anglesey (IRL, figure 2b) shows little variation in CHL, and strong differences in TSM between summer and winter. The low summer TSM can be explained by the thermal stratification of this part of the Irish Sea, while in winter the waters are well mixed[11].

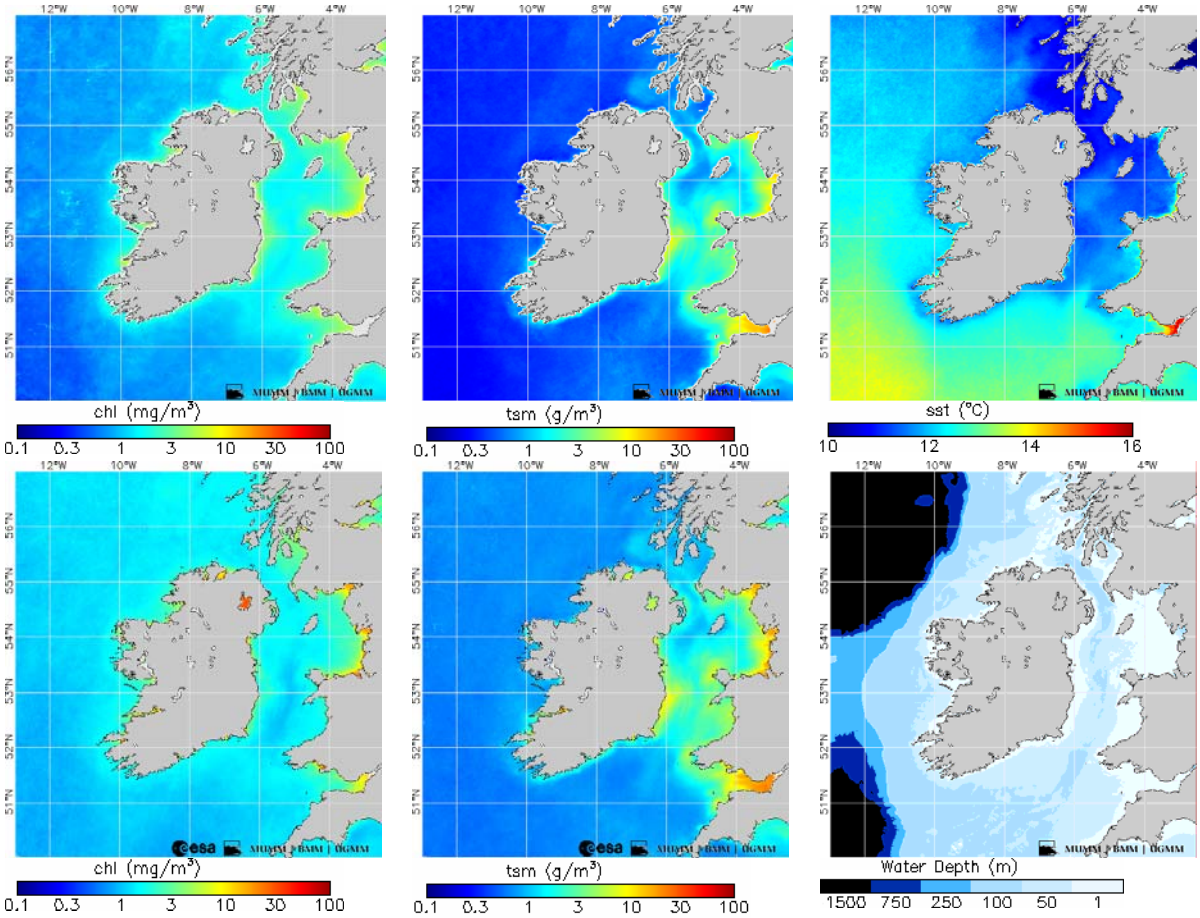


Figure 4: Multi-year climatologies for the IRL region, constructed based on eight yearly means (2003-2010) of ocean colour data. First row: MODIS CHL, TSM and SST. Bottom row: MERIS CHL and TSM and GEBCO bathymetry.

3.1.3 Southern North Sea and English Channel (SNC)

High concentrations of TSM are found in the shallow waters of the BCZ and near the Thames estuary, while the lowest concentrations are found offshore, in the deeper parts of the English Channel (figure 5). CHL is generally higher in the Southern North Sea than in the English Channel, and especially in the coastal areas, where there is a high nutrient input from rivers[17]. A gradient from high SST to low SST is observed from the western edge to the northern edge of the region. Higher temperatures are also found along the coast and in coastal areas near the Thames estuary, the Bristol Channel and the Belgian coast, where the shallow water column heats faster in summer[18]. In station W05 (SNC, figure 2c) a fluctuation of TSM is observed: the lowest concentrations occur during summer, and the highest concentrations during winter, when resuspension of sediments is higher because of increased winds[18,19,20,21]. In the chlorophyll dataset, an annual spring bloom event can be observed[17].

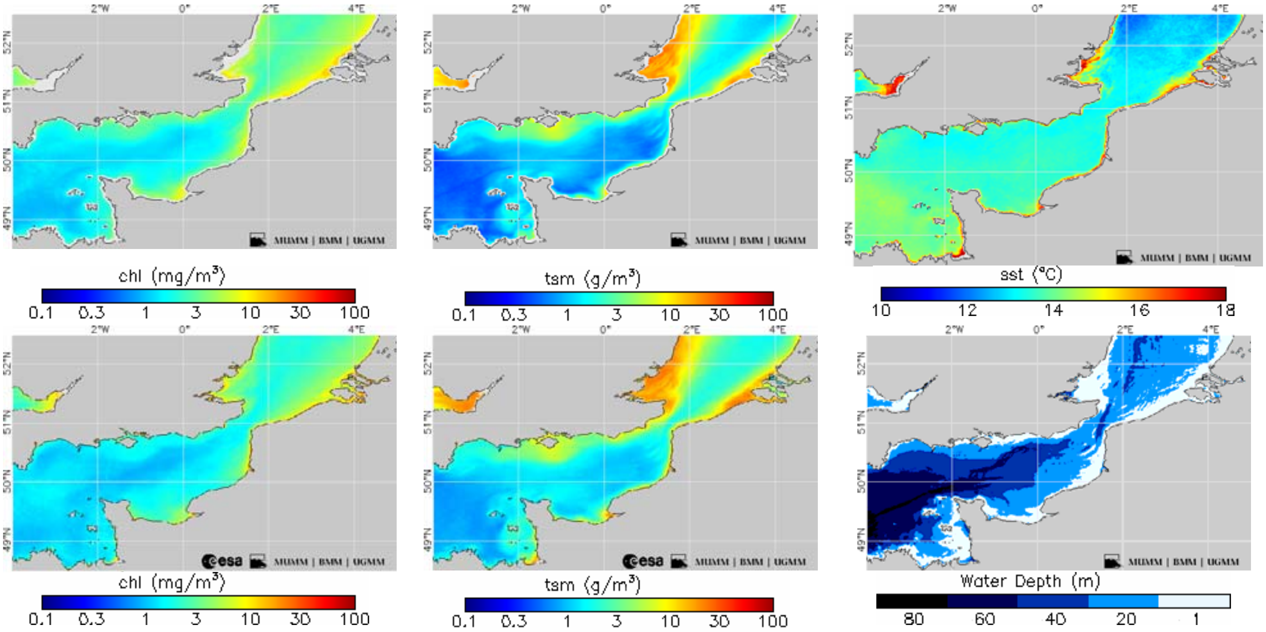


Figure 5: Multi-year climatologies for the SNC region, constructed based on eight yearly means (2003-2010) of ocean colour data. First row: MODIS CHL, TSM and SST. Bottom row: MERIS CHL and TSM and GEBCO bathymetry.

3.2 Intercomparison of MODIS and MERIS data

3.2.1 Scene per scene

Considerable scatter is found when the pixels (several millions: CTL ~3M, IRL ~60M, SNC ~15M) on all scenes within a time-frame are compared (figure 6, odd rows). For SNC and IRL, scenes taken within one hour from each other are compared. For CTL, scenes up to two hours apart were compared as there is a larger difference in overpass time for this region.

Very poor, poor and moderate correlations are found for the CTL, IRL and SNC TSM datasets (R^2 of 0.05, 0.34 and 0.57). The largest deviations are found in the lower concentration range, partly because the algorithm used for the calculation of MODIS TSM (Nechad *et al.*, 2010) is designed for turbid waters (TSM > 1g/m³), and not for waters where the suspended matter mainly consists of phytoplankton – such as the CTL region, and some offshore parts of IRL and SNC.

For the scene per scene comparisons of CHL, the correlations are also poor. Large differences are found for MODIS values between 1 and 5 mg/m³, where MERIS returns values between 0.05 and 10 mg/m³. The MERIS algal_2 product has been found to be quite noisy, especially for low concentrations (see section 3.2.3 and [22]). The highest density of points (yellow to red) in the plots is grouped quite close to the 1:1 line. The lowest densities, the dark blue pixels, correspond to only a handful or less observations. The significant amount of noise found in the datasets (see also section 3.2.3 and figure 7) can contribute to this low-density scatter. This is also supported by the very tight scatter in the comparisons of the climatologies.

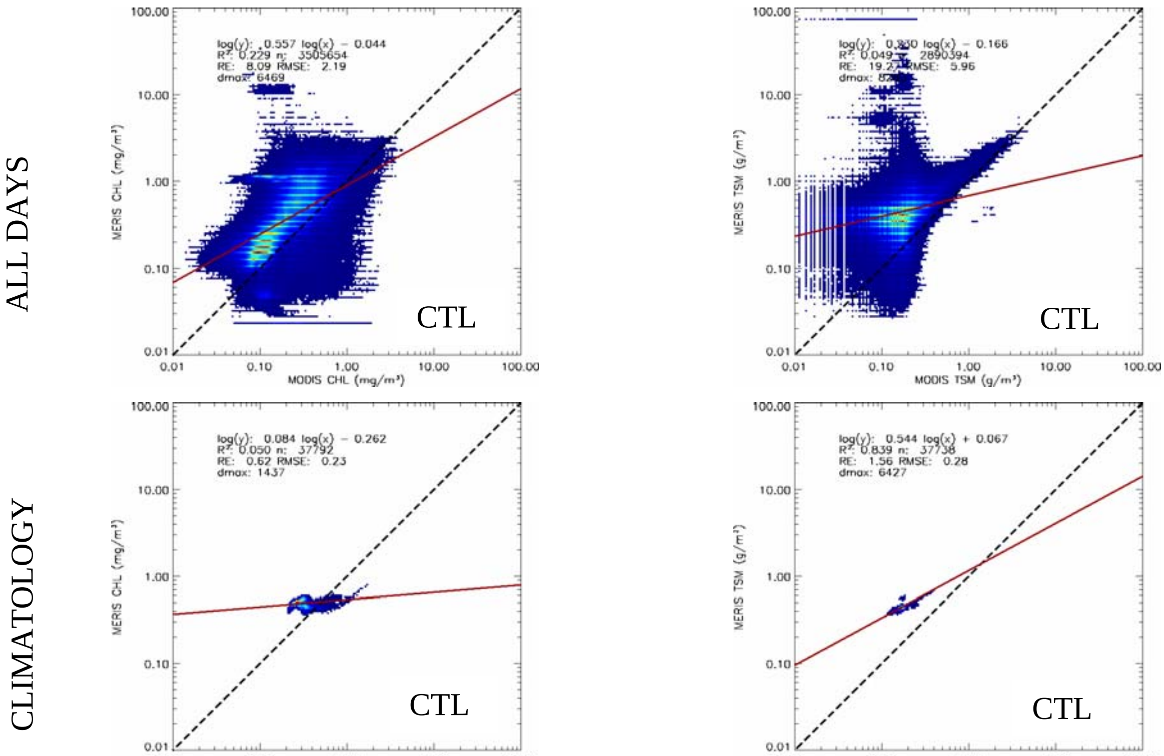


Figure 6: Intercomparison of MODIS and MERIS datasets. First column: chlorophyll *a* concentrations (CHL), second column, total suspended matter concentrations (TSM). Odd rows: comparison on a scene per scene basis, even rows: comparison of the multi-year climatologies from section 3.1. The black dotted line is the 1:1 line, and the red solid line is the regression line. Blue to red colours denote low to high densities of pixels, the highest density (red) in each plot is given by dmax, while the lowest densities (dark blue) are usually less than 5. The total number of compared pixels is given by n.

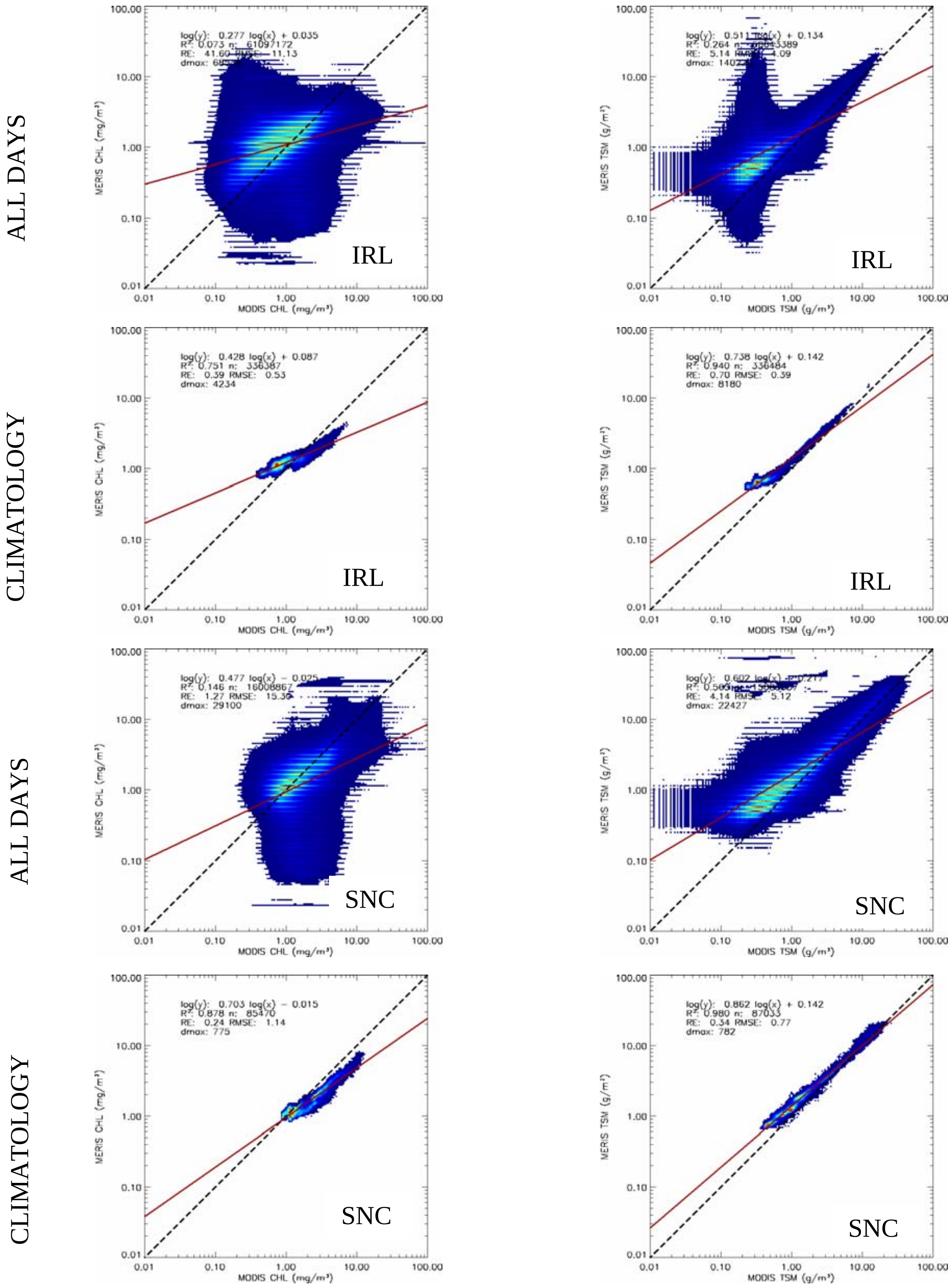


Figure 6 (continued)

3.2.2 Climatologies

A large amount of the scatter disappears when comparing the climatologies from section 3.1 (figure 6, even rows). As can be expected creating average composites, the patterns found correspond well to the highest densities of pixels found in the scene per scene comparisons. Good correlations are found for the TSM datasets, with R^2 0.98, slope 0.86 and R^2 0.94, slope 0.74 and R^2 0.84 and slope 0.54 for SNC, IRL and CTL respectively. The slope for the CTL dataset shows there is a difference between MODIS and MERIS TSM at low concentrations – this is in fact also observed at low concentrations in the SNC and IRL TSM datasets (where it has less impact on the correlation statistics). The CHL datasets in the SNC and IRL regions compare favourably: R^2 0.88, slope 0.70 and R^2 0.75, slope 0.43. A very poor correlation is found for the CTL CHL datasets (R^2 0.05 and slope 0.08), due to the very small data range found in the MERIS composite. The slope in IRL shows there is a systematic difference in CHL products in these waters.

3.2.3 Single Day Comparison

An example of two scenes that are compared is given in figure 7. Some noise is present in all four images, but considerably more in the MERIS CHL image. Along track striping is also visible in the MERIS image. There is a moderate correlation between the TSM images (R^2 0.59) but none between the CHL images (R^2 0.11). The largest differences between the CHL images are found in the southern Irish Sea and Celtic Sea, where MERIS gives much lower concentrations than MODIS (see also the high density of pixels at MODIS ~2.0 and MERIS ~0.1 mg/m³ in scatterplot). At very low MODIS CHL, in the waters of the Atlantic Ocean, a larger spread of MERIS CHL is observed. A similar pattern is found in the TSM dataset of the Atlantic, where MODIS gives quite homogenous, low concentrations, and where in the MERIS image patches of higher values are found. This is also clear in the left hand side of the scatterplot, for MODIS values between 0.07 and 0.3 g/m³.

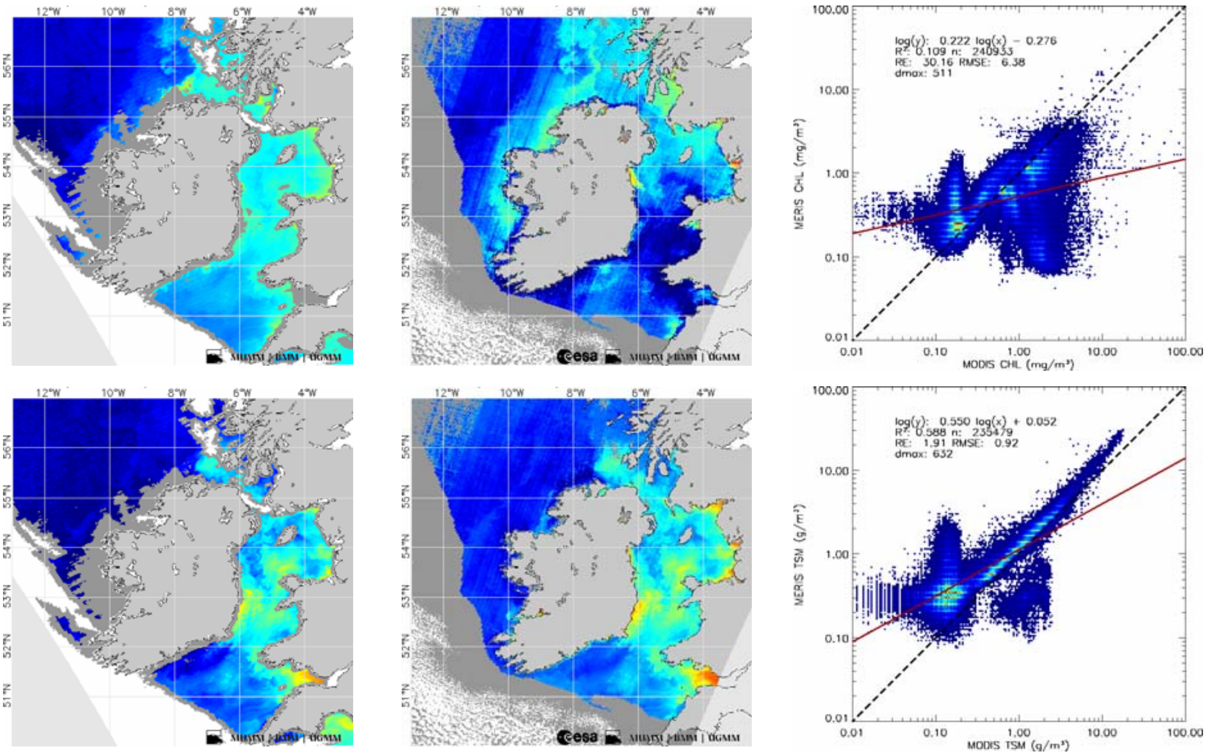


Figure 7: MODIS and MERIS CHL (top row) and TSM (bottom row) images for 8 March 2010 (at 12:25 and 11:29 UTC). Clouds, missing data (out of scene), land and products of low quality are masked in white, light gray, gray and dark gray. Same colour scales as figures 2-4.

3.3 Validation with *in situ* data

Half hourly TSM measurements from CEFAS' SmartBuoy network were used to validate satellite data (figure 8). Because of the high measuring frequency, this method can give up to ten times the number of match-ups, compared to *in situ* measurements from water samples. Correlations are found to be moderate for the more turbid WARP station (R^2 = 0.74 for MODIS and 0.65 for MERIS), and better for the clearer WGAB station (R^2 = 0.78 for MODIS and 0.81 for MERIS). Relative errors are 29% and 32% for WARP and 44% and 37% for WGAB (MODIS/MERIS). Good correlations are also found for LIVB (R^2 = 0.87 for MODIS and 0.81 for MERIS), relative errors are 39% and 33%. The deviation between satellite and in situ is higher for lower concentrations (<10 g/m³), with an underestimation by the satellites.

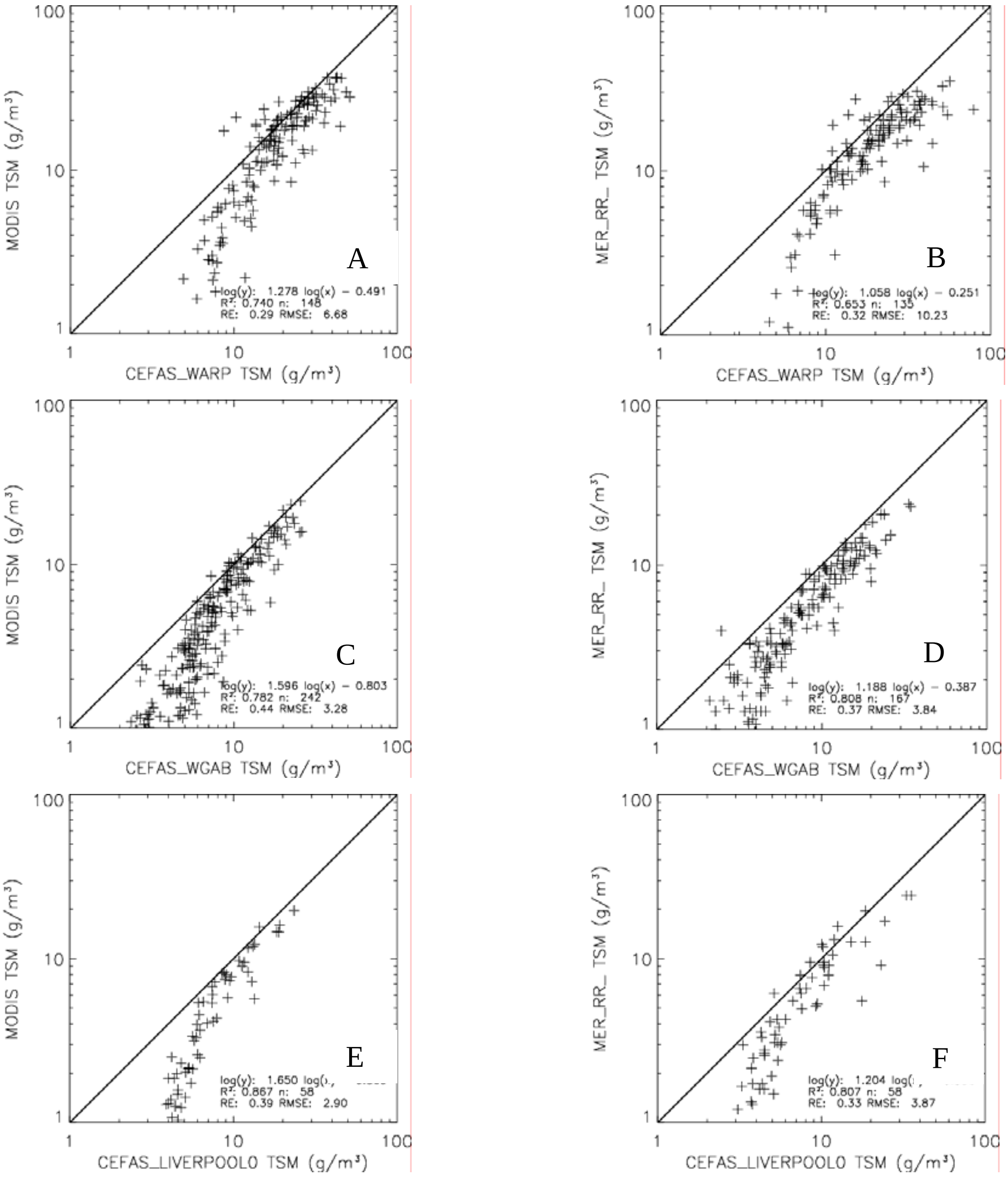


Figure 8: MODIS and MERIS TSM matched with SmartBuoy TSM for A and B, the WARP location, C and D the WGAB location and E and F for the LIVB location.

The MODIS sea surface temperature dataset was matched to temperature data collected using underway systems on three vessels, one for the SNC and two for the IRL region. There are clear differences and limitations in both measuring systems, for example the fact that the underway system measures temperature of water from a few metres deep that was pumped through a few metres of tubing in the ships' hull and that the MODIS sensor actually measures the skin sea surface temperature. However, excellent correlations are found (figure 9).

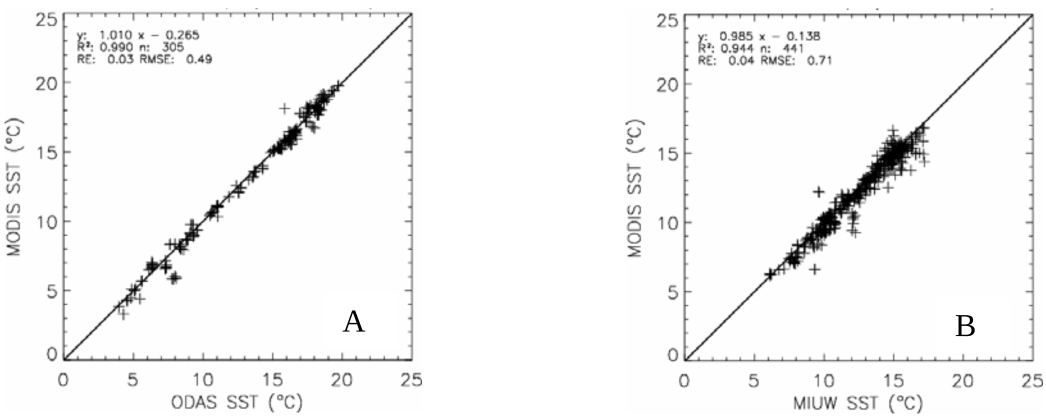


Figure 9: Correlation between seawater temperature from underway data and MODIS SST for A) SNC (RV Belgica), correlation coefficient 0.99 and slope 1.01 and IRL (Celtic Explorer and Celtic Voyager), correlation coefficient 0.94 and slope 0.96. Data from a one hour window (± 30 minutes) around the satellite overpass was used for the comparison.

4 CONCLUSIONS

Eight years (and counting) of ocean colour data can provide a large amount of data on unprecedented temporal and spatial scales. Time-series for any location and multi-temporal means are a great asset for many projects dealing with the marine environment. By using standard products and the GRIMAS software, a powerful data archive that gives a broad overview can be quickly generated. The reliability of the data archive can be increased when additional in situ measurements are available. Customized products made with SeaDAS, BEAM or ODESA can also serve as input data for GRIMAS. In fact, any geolocated dataset could be imported if a data reader is available or written.

A good agreement is found between in situ measurements from SmartBuoys and remote sensing TSM products. Even with the quality issues of the underway data in mind, the MODIS SST product corresponds very well with the seawater temperatures measured continuously on three different research vessels.

On a scene per scene basis, some discrepancies are found between MODIS and MERIS data, probably caused by sensor and algorithm differences. Differences in overpass time could also contribute to the difference, although scenes within a certain (short) time-range were compared. When comparing multi-temporal bins, these differences reduce considerably. Especially at low concentrations, MODIS and MERIS values differ – even when comparing multi-temporal bins. It should be noted that the algal_2 dataset from MERIS used here is quite noisy – see also Ruddick *et al.*, 2008. This is improved in the current, third, reprocessing of the data, dissemination of which will follow later in 2011.

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REFERENCES

[1] Vanhellemont, Q., Nechad, B., Ruddick, K., "GRIMAS: Gridding and archiving of satellite-derived ocean colour data for any region on earth", submitted to the proceedings of the CoastGIS 2011 conference. (2011)

[2] Wessel, P., Smith, W. H. F., "A Global Self-consistent, Hierarchical, High-resolution Shoreline Database", *J.*

Geophys. Res., 101, #B4, pp. 8741-8743 (1996)
[3] MERIS Quality Working Group, "MERIS 2nd reprocessing: Changes Description", 27/09/2005 (2005)
[4] Park, Y-P., Ruddick, K., Lacroix, G., "Detection of algal blooms in European waters based on satellite chlorophyll data from MERIS and MODIS", *International Journal of Remote Sensing*, Volume 31 Issue 24 (2010)
[5] Nechad, B., Ruddick, K.G., Park., Y., "Calibration and validation of a generic multisensor algorithm for mapping of total suspended matter in turbid waters", *Remote Sensing of Environment* 114: 854-866 (2010)
[6] Smith, R. O., Bryden, H. L., Stansfield K., "Observations of new western Mediterranean deep water formation using Argo floats 2004–2006" *Ocean Sci.*, 4, 133–149 (2008)
[7] Struglia, M. A., Matiotti, A.,, Filograsso, A., "River Discharge into the Mediterranean Sea: Climatology and Aspects of the Observed Variability", *Journal of Climate*, 17, 4740—4751 (2004)
[8] Salat, J., Font, J., "Water mass structure near and offshore the Catalan coast during winter in 1982 and 1983". *Annal. Geophys., B*, 5(1): 49-54 (1987)
[9] Stemmanna, L., Gorsky, G., Marty J-C., Picheral, M., Miquel J-C., "Four-year study of large-particle vertical distribution (0–1000 m) in the NW Mediterranean in relation to hydrology, phytoplankton, and vertical flux" *Deep-Sea Research II* 49 2143–2162 (2002)
[10] Pugh, D. T., "Tides, surges and mean sea-level" John Wiley and Sons, 486p. (1996)
[11] Hill, A. E., Durazo, R., Smeed D.A., "Observations of a cyclonic gyre in the western Irish Sea", *Cont. Shelf Res.* 14, 479—490 (1994)
[12] Hill, A. E., Brown, J., Fernand, L., "The western Irish Sea gyre: A retention system for Norway lobster (*Nephrops norvegicus*)?", *Oceanologica Acta.* 19, 357—368 (1996)
[13] Xing, J., Davies, A. M., "Application of three dimensional turbulence energy models to the determination of tidal mixing and currents in a shallow sea" *Prog. Oceanog.* 35, 153—205 (1995)
[14] McLaren, P., Collins, M. B., Gao, S. Powys, R. I. L., "Sediment dynamics of the Severn Estuary and inner Bristol Channel" *Journal of the Geological Society* v. 150, 589—603 (1993)
[15] Clifton, J., McDonald, P., Plater, A., Oldfield, F., "Derivation of a grain-size proxy to aid the modelling and prediction of radionuclide activity in salt marshes and mud flats of the eastern Irish Sea" *Estuarine, coastal and Shelf Research* 49, 511—518 (1999)
[16] Bowers, D.G., Gaffney, S., White, M., Bowyer, P., "Turbidity in the southern Irish Sea", *Contintental Shelf Research* 22, 2115—2126 (2002)
[17] Rousseau, V., Park, Y., Ruddick, K., Vyverman, W., Parent, J.-Y., Lancelot, C., "Phytoplankton blooms in response to nutrient enrichment" *Current status of eutrophication in the Belgian Coastal Zone* 45—59 (2006)
[18] Ruddick, K., Lacroix, G., "Hydrodynamics and meteorology of the Belgian Coastal Zone" *Current status of eutrophication in the Belgian Coastal Zone* 1—15 (2006)
[19] Eisma, D., Kalf, J., "Distribution and particle size of suspended matter in the Southern Bight of the North Sea and the Eastern Channel" *Netherlands Journal of Sea Research* 13, 298—324 (1997)
[20] Eleveld, M. A., Pasterkamp, R., van der Woerd, H. J.; Pietrzak, J. D., "Remotely sensed seasonality in the spatial distribution of sea-surface suspended particulate matter In the southern North Sea" *Estuarine, Coastal and Shelf Science* 80, 103—113 (2008)
[21] Fettweis, M., Nechad, B. Van den Eynde, D., "An estimate of the suspended particulate matter (SPM) transport in the southern North Sea using SeaWiFS images, in situ measurements and numerical model results" *Continental Shelf Research* 27, 1568—1583 (2007)
[22] Ruddick, K., Park, Y., Astoreca, R., Neukermans, G., Van Mol, B., "Validation of MERIS water products in the Southern North Sea: 2002-2008", ESA Special Publication SP-666 (2008)