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A compilation of global bio-optical in situ data for ocean-colour satellite applications

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Abstract. A compiled set of in situ data is important to evaluate the quality of ocean-colour satellite-data records. Here we describe the data compiled for the validation of the ocean-colour products from the ESA Ocean Colour Climate Change Initiative (OC-CCI). The data were acquired from several sources (MOBY, BOUSSOLE, AERONET-OC, SeaBASS, NOMAD, MERMAID, AMT, ICES, HOT, GeP&CO), span between 1997 and 2012, and have a global distribution. Observations of the following variables were compiled: spectral remote-sensing reflectances, concentrations of chlorophyll a, spectral inherent optical properties and spectral diffuse attenuation coefficients. The data were from multi-project archives acquired via the open internet services or from individual projects, acquired directly from data providers. Methodologies were implemented for homogenisation, quality control and merging of all data. No changes were made to the original data, other than averaging of observations that were close in time and space, elimination of some points after quality control and conversion to a standard format. The final result is a merged table designed for validation of satellite-derived ocean-colour products and available in text format. Metadata of each in situ measurement (original source, cruise or experiment, principal investigator) were preserved throughout the work and made available in the final table. Using all the data in a validation exercise increases the number of matchups and enhances the representativeness of different marine regimes. By making available the metadata, it is also possible to analyse each set of data separately. The compiled data are available at doi:10.1594/PANGAEA.854832 (Valente et al., 2015).

1 Introduction

Currently, there are several bio-optical in situ datasets worldwide suitable for validation of ocean-colour satellite data. While some are managed by the data producers, others are in international repositories with contributions from multiple scientists. Many have rigid quality controls and are built specifically for ocean-colour validation. The use of only one of these datasets would limit the number of data in validation exercises. It would therefore be useful to acquire and merge all these datasets into a single unified dataset to maximise the number of matchups available for validation and their distribution in time and space and consequently reduce the uncertainties in the validation exercise. However, merging several datasets together can be a complicated task. First, it is necessary to acquire and harmonise all datasets into a single standard format. Second, during the merging, the duplicates between datasets have to be identified and removed. Third, the metadata should be propagated throughout the process and made available in the final merged product. Ideally, the compiled dataset would be made available as a simple text table, to facilitate ease of access and manipulation. In this work such unification of multiple datasets is presented. This was done for the validation of the ocean-colour products from the ESA Ocean Colour Climate Change Initiative (OC-CCI), but with the intent to serve the broad user community as well.

A merged dataset is not without drawbacks: it is likely to be large and so not always easy to manipulate; because the merging is done on pre-existing, processed databases, one does not have full command of the whole processing chain; and the dataset would be a compilation of observations collected by several investigators using different instruments, sampling methods and protocols, which might even-

tually have been modified by the processing routines used by the repositories or archives. Nevertheless, to minimise these potential drawbacks, we have, for the most part, incorporated only datasets that have emerged from the long-term efforts of the ocean-colour and biological oceanographic communities to provide scientists with high-quality in situ data and implemented additional quality checks on the data to enhance confidence in the quality of the merged product.

In Sect. 2 the methodologies used to harmonise and integrate all data, as well as a description of individual datasets acquired, are provided. In Sect. 3 the geographic distribution and other characteristics of the final merged dataset are shown. Section 4 provides an overview of the data.

2 Data and methods

2.1 Preprocessing and merging

The compiled global set of bio-optical in situ data described in this work has an emphasis, though not exclusively, on open-ocean data from all geographic regions. It is comprised of the following variables: remote-sensing reflectance (rrs), chlorophyll *a* concentration (chla), algal pigment absorption coefficient (aph), detrital and coloured dissolved organic matter absorption coefficient (adg), particle backscattering coefficient (bbp) and diffuse attenuation coefficient for downward irradiance (kd). A similar effort of compiling bio-optical in situ data from different sources has been recently published by Nechad et al. (2015). Given their focus on selected coastal regions, most of the data presented here are not part of their compilation. The variables rrs, aph, adg, bbp and kd are spectrally dependent, and this dependence is hereafter implied. The data were compiled from 10 sources of in situ data (MOBY, BOUSSOLE, AERONET-OC, SeaBASS, NOMAD, MERMAID, AMT, ICES, HOT, GeP&CO), each described in Sect. 2.2. The compiled in situ observations have a global distribution and cover the recent period of satellite ocean-colour data between 1997 and 2012. The listed variables were chosen as they are the operational satellite ocean-colour products of the ESA OC-CCI project, which currently focuses on the use of three ocean-colour satellite platforms to create a time series of satellite data: the Medium Resolution Imaging Spectrometer (MERIS) of ESA, the Moderate Resolution Imaging Spectroradiometer (MODIS) of NASA, and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) of NASA, .

Rrs is a primary ocean-colour product routinely produced by several space agencies. It is defined as $\mathrm{rrs} = \mathrm{Lw} / \mathrm{Es}$, where Lw is the upward water-leaving radiance and Es is the total downward irradiance at sea level. Remote-sensing reflectance is related to irradiance reflectance (Rw) approximately through $\mathrm{rrs} = \mathrm{Rw} / Q$, where Q ranges from 3 to 5 in natural waters and is equal to π for an isotropic (Lambertian) light field. Another quantity that is often required is the "normalised" water-leaving radiance (nLw) (Gordon and Clark, 1981), which is related to remote-sensing reflectance via $\mathrm{rrs} = \mathrm{nLw} / \mathrm{Fo}$, where Fo is the top-of-the-atmosphere solar irradiance. If not directly available, remote-sensing reflectance was calculated through the equations described above, depending on the format of the original data. The original data were acquired in an advanced form (e.g. time-averaged, extrapolated to surface) from six data sources particularly designed for ocean-colour validation (MOBY, BOUSSOLE, AERONET-OC, SeaBASS, NOMAD, MERMAID), therefore only requiring the conversion to a common format. In the processing made by the space agencies, the quantity rrs is normalised to a single Sun-viewing geometry (Sun at zenith and nadir viewing) taking in account the bidirectional effects as described in Morel and Gentili (1996) and Morel et al. (2002). Thus, for consistency with the satellite rrs product, only in situ rrs that included the latter normalisation was included in the compilation.

Chlorophyll *a* concentration is the traditional measure for phytoplankton biomass and one of the most widely used satellite ocean-colour products (IOCCG, 2008). To validate satellite-derived chlorophyll *a* concentration, two different variables were compiled: one of these represents chlorophyll *a* measurements made through fluorometric or spectrophotometric methods, referred to hereafter as chla_fluor and the other is the chlorophyll concentration derived from HPLC (high-performance liquid chromatography) measurements, referred to hereafter as chla_hplc. The chlorophyll data were compiled from eight data sources: BOUSSOLE, SeaBASS, NOMAD, MERMAID, AMT, ICES, HOT and GeP&CO. One requirement for chla_fluor measurements was that they were made using in vitro methods (i.e. based on extractions of chlorophyll *a*). Although this severely decreased the number of observations, since in situ fluorometry (e.g. fluorometers mounted on CTDs) is widely available in oceanographic databases, it was decided to exclude such data because of potential problems with the calibration of in situ fluorometers. The variable chla_hplc was calculated by summing all reported chlorophyll *a* derivatives, including divinyl chlorophyll *a*, epimers, allomers and chlorophyllide *a*. The two chlorophyll variables are retained separately in the database to facilitate their use. HPLC measurements are considered of higher quality, but fluorometric measurements are more abundant. Thus one option for users is to use chla_fluor only when there are no chla_hplc measurements available. To be consistent with satellite-derived chlorophyll values, which are derived from the light emerging from the upper layer of the ocean, all chlorophyll observations found in the top 10 m (replicates at the same depth or measurements at multiple depths) were averaged if the coefficient of variation among observations was less than 50 %; otherwise they were discarded. The averages were then assigned to the surface. The depth of 10 m was chosen as a compromise between clear oligotrophic and turbid eutrophic waters. Other methods, such as chlorophyll depth averages using local attenuation conditions (Morel and Maritorena, 2001), require

observations at multiple depths, which, given our decision to use only in vitro measurements, would have reduced considerably the final number of observations.

With regard to the inherent optical properties (aph, adg, bbp), if not already calculated and provided in the contributed datasets, they were computed from related variables that were available: particle absorption (ap), detrital absorption (ad), coloured dissolved organic matter (CDOM) absorption (ag) and total backscattering (bb). The following equations were used $adg = ad + ag$, $ap = aph + ad$ and $bb = bbp + bbw$. For the latter equation, the variable bbw was computed using $bbw = bw / 2$, where bw is the scattering coefficient of seawater derived from Zhang et al. (2009). The diffuse attenuation coefficient for downward irradiance (kd) did not require any conversion and was compiled as originally acquired. Observations of inherent optical properties (surface values) and diffuse attenuation coefficient for downward irradiance, were acquired from three data sources particularly designed for ocean-colour validation (SeaBASS, NOMAD, MERMAID) and were thus already subject to the processing routines of these datasets.

The merged dataset was compiled from 10 sets of in situ data, which were obtained individually either from archives that incorporate data from multiple contributors (SeaBASS, NOMAD, MERMAID and ICES) or from particular measurement programs or projects (MOBY, BOUSSOLE, AERONET-OC, HOT, GeP&CO, AMT) and were subsequently homogenised and merged. Data contributors are listed in Table 2. There were methodological differences between datasets. Therefore, after acquisition, and prior to any merging, each set of data was preprocessed for quality control and conversion to a common format. During this process, data were discarded if they had (1) unrealistic or missing date, time and geographic coordinate fields; (2) poor quality (e.g. original flags) or a method of observation that did not meet the criteria for the dataset (e.g. in situ fluorescence for chlorophyll concentration); and (3) spuriously high or low data. For the latter, the following limits were imposed: for chla_fluor and chla_hplc $[0.001–100]\ mg\ m^{-3}$; for rrs $[0–0.15]\ sr^{-1}$; for aph, adg and bbp $[0.0001–10]\ m^{-1}$; for kd $[aw(\lambda)–10]\ m^{-1}$, where aw is the pure water absorption coefficients derived from Pope and Fry (1997). Also during this stage, three metadata strings were attributed to each observation: dataset, subdataset and pi. The dataset contains the name of the original set of data, and can only be one of the following: “aoc”, “boussole”, “mermaid”, “moby”, “nomad”, “seabass”, “hot”, “ices”, “amt” or “gepco”. The subdataset starts with the dataset identifier and is followed by additional information about the data, in the format <dataset>_<cruise/station/site>) (e.g. seabass_car71). The pi contains the name of the principal investigator(s). An effort was made to homogenise the names of principal investigators from the different sets of data. These three metadata are the link to trace each observation to its origin and were propagated throughout the processing. Finally, this processing stage ended with each set of data being scanned for replicate variable data and replicate station data, which when found, were averaged if the coefficient of variation was less than 50 %; otherwise they were discarded. Replicates were defined as multiple observations of the same variable, with the same date, time, latitude, longitude and depth. Replicate station data were defined as multiple measurements of the same variable, with the same date, time, latitude and longitude. For the latter case, a search window of 5 min in time and 200 m in distance was given, to account for station drift. A small number of observations that were identified as replicates had different subdataset identifiers (i.e. a different cruise name). These observations were considered suspicious if the values were different and were discarded. If the values were the same, one of the observations was retained. This possibly originated from the same group of data being contributed to an archive by two different principal investigators.

Once each set of data was homogenised, all data were integrated into a unique table. This final merging focused on the removal of duplicates between the sets of data. Although some duplicates are known (e.g. MOBY, BOUSSOLE, AERONET-OC and NOMAD data are found in SeaBASS and MERMAID sets of data), others are unknown (e.g. how much of GeP&CO, ICES, AMT, HOT is within NOMAD, SeaBASS and MERMAID). Therefore, duplicates were identified using the metadata (dataset and subdataset) when possible and temporal–spatial matches as an additional precaution. For temporal–spatial matches, several thresholds were used, but typically 5 min and 200 m were taken to be enough to identify most duplicated data, which reflected small differences in time, latitude and longitude, between the different sets of data. Larger thresholds were used in some cases as a cautionary procedure. This was the case when searching for NOMAD data in other datasets because NOMAD includes a few cases where merging of radiometric and pigment data was done with large spatial-temporal thresholds (Werdell and Bailey, 2005). With regard to all data, if duplicates were found, data from the NOMAD dataset were selected first, followed by data from individual projects (MOBY, BOUSSOLE, AERONET-OC, AMT, HOT and GeP&CO) and finally for the remaining datasets (SeaBASS, MERMAID and ICES). This procedure was chosen to preserve the NOMAD dataset as a whole, since it is widely used in ocean-colour validation. After all data were free of duplicates, they were merged consecutively by variable in the final table. During this process, we also searched for rows (stations) that were separated from each other by time differences less than 5 min and horizontal spatial differences of less than 200 m. When such rows were found, the observations in those rows were merged into a single row. The compiled merged data were compared with the original sets to certify that no errors occurred during the merging. As a final step, a water-column (station) depth was recorded for each observation, which was the closest water-column depth from the ETOPO1 global relief model (National Geophys-

ical Data Center ETOPO1; Amante and Eakins, 2009). For observations where the closest water depth was above sea level (e.g. data collected very near the coast), it was given the value of zero.

Data processing thus included two major steps: preprocessing and merging. The first step was related to each set of contributing datasets in particular and aimed to identify problems and convert the data of interest to a standard format. The second step dealt with the integration of all data into one unique file and included the elimination of duplicated data between the individual sets of data acquired. In the next subsections a brief overview of each original set of data is provided.

2.2 Preprocessing of each set of data

2.2.1 Marine Optical Buoy (MOBY)

The Marine Optical Buoy (MOBY) is a fixed mooring system operated by the National Oceanic and Atmospheric Administration (NOAA) that provides a continuous time series of water-leaving radiance and surface irradiance in the visible region of the spectra from 1997 onwards. The site is located a few kilometres west of the Hawaiian island of Lāna'i where the water depth is about 1200 m. Since its deployment, MOBY measurements have been the primary basis for the on-orbit vicarious calibrations of the SeaWiFS and MODIS ocean-colour sensors. A full description of the MOBY system and processing is provided in Clark et al. (2003). Data are freely available for scientific use at the MOBY Gold directory. The products of interest are the Scientific Time Series files, which refer to MOBY data averaged over sensor-specific wavelengths and particular hours of the day (around 20:00–23:00 UTC). For this work, the satellite band-average products for SeaWiFS, MODIS AQUA and MERIS were compiled from the January 2005 reprocessing for the early data and from the latest reprocessing for data after 2011. The "inband" average subproduct was used, and to maintain the highest quality, only data determined from the upper two arms (Lw1) and flagged "good" quality were acquired. Data from the MOBY203 deployment were discarded due to the absence of surface irradiance data. The compiled variable was the remote-sensing reflectance, rrs, which was computed from the original water-leaving radiance (Lw) and surface irradiance (Es). The water-leaving radiances were corrected for the bidirectional nature of the light field (Morel and Gentili, 1996; Morel et al., 2002) using the same look-up table and method as that used in the SeaWiFS Data Analysis System (SeaDAS) processing code. As mentioned before, the MOBY data compiled in this work are sensor-specific. Therefore, attention is necessary to use the correct MOBY data when validating a particular sensor. The way MOBY data are stored in the final merged table is consistent with the original wavelengths; however, these wavelengths can differ from what is sometimes expected to be the central wavelength of a given band and sensor. Irrespective of the wavelength where MOBY data are stored in the final table, for validation of bands 1–6 of SeaWiFS, MOBY data stored in the final merged table at 412, 443, 490, 510, 555 and 670 nm, respectively, should be used. For validation of bands 1–6 of MODIS AQUA, MOBY data stored in the final merged table at 416, 442, 489, 530, 547 and 665 nm, respectively, should be used. Finally, for validation of bands 1–7 of MERIS, MOBY data stored in the final merged table at 410.5, 440.4, 487.8, 507.7, 557.6, 617.5 and 662.4 nm, respectively, are the appropriate data.

2.2.2 BOUée pour l'acquiSition de Séries Optiques à Long termE (BOUSSOLE)

The BOUée pour l'acquiSition de Séries Optiques à Long termE (BOUSSOLE) project started in 2001 with the objective of establishing a time series of bio-optical properties in oceanic waters to support the calibration and validation of ocean-colour satellite sensors (Antoine et al., 2006). The project is composed of a monthly cruise program and a permanent optics mooring (Antoine et al., 2008). The mooring collects radiometry and inherent optical properties (IOPs) in continuous mode every 15 min at two depths (4 and 9 m nominally). The monthly cruises are devoted to the mooring servicing, to the collection of vertical profiles of radiometry and IOPs, and to water sampling at 11 depths from the surface down to 200 m, for subsequent analyses including phytoplankton pigments, particulate absorption, CDOM absorption and suspended particulate matter load. The BOUSSOLE mooring is in the western Mediterranean Sea at a water depth of 2400 m. All pigment (2001–2012) and radiometric (2003–2012) data were provided by the principal investigator. The compiled variables were rrs and chla_hplc. Observations of the diffuse attenuation coefficient (kd) were not included in the present compilation, as they were under internal quality revision at the time of data acquisition. Remote-sensing reflectance was computed from the original "fully normalised" water-leaving radiance (nLw_ex), which is the "normalised" water-leaving radiance (nLw previously described), with a correction for the bidirectional nature of the light field (Morel and Gentili, 1996; Morel et al., 2002). The solar irradiance (Fo) was computed from two available variables in the original set of data – nLw and rrs – using the equation $Fo = nLw / rrs$. Only radiometric observations that meet the following criteria were used: (1) tilt of the buoy was less than 10°; (2) the buoy was not lowered by more than 2 m as compared to its nominal water line (to ensure the Es reference sensor is above water and exempt from sea spray); and (3) the solar irradiance was within 10 % of its theoretical clear-sky value (determined from Gregg and Carder, 1990). The latter criterion was used to select clear skies only. An additional quality control was to remove observations that were 50 % higher or lower than the daily average. This removed a small number of spikes in the time series. The final

quality control step was to remove days where the standard deviation was more than half of the daily average. This was meant to identify days with high variability. Very few days ($N = 2$) were removed with this test. These quality control criteria were applied per wavelength, which resulted in some observations with an incomplete spectrum.

2.2.3 AErosol RObotic NETwork-Ocean Color (AERONET-OC)

The AErosol RObotic NETwork-Ocean Color (AERONET-OC) is a component of AERONET, including sites where sun photometers operate with a modified measurement protocol leading to the determination of the fully normalised water-leaving radiance (Zibordi et al., 2006, 2009). The result of collaboration between the Joint Research Centre (JRC) and NASA, this component has been specifically developed for the validation of ocean-colour radiometric products. The strength of AERONET-OC is "the production of standardised measurements that are performed at different sites with identical measuring systems and protocols, calibrated using a single reference source and method, and processed with the same codes" (Zibordi et al., 2006, 2009). All high-quality data (level 2) were acquired from the project website for 11 sites: Abu_Al_Bukhoosh (∼ 25° N, ∼ 53° E), COVE_SEAPRISM (∼ 36° N, ∼ 75° W), Gloria (∼ 44° N, ∼ 29° E), Gustav_Dalen_Tower (∼ 58° N, ∼ 17° E), Helsinki Lighthouse (∼ 59° N, ∼ 24° E), LISCO (∼ 40° N, ∼ 73° W), Lucinda (∼ 18° S, ∼ 146° E), MVCO (∼ 41° N, ∼ 70° W), Palgrunden (∼ 58° N, ∼ 13° E), Venice (∼ 45° N, ∼ 12° E) and WaveCIS_Site_CSI_6 (∼ 28° N, ∼ 90° W). The compiled variable was rrs. Remote-sensing reflectance was computed from the original fully normalised water-leaving radiance (see Sect. 2.2.2 for definition). The solar irradiance (Fo), which is not part of the AERONET-OC data, was computed from the Thuillier (2003) solar spectrum irradiance by averaging Fo over a wavelength-centred 10 nm window. Data were compiled for the exact wavelengths of each record, which can change over time for a given site depending on the specific instrument deployed.

2.2.4 SeaWiFS Bio-optical Archive and Storage System (SeaBASS)

The SeaWiFS Bio-optical Archive and Storage System (SeaBASS) is one of the largest archives of in situ marine bio-optical data (Werdell et al., 2003). It is maintained by NASA's Ocean Biology Processing Group (OBPG) and includes measurements of optical properties, phytoplankton pigment concentrations, and other related oceanographic and atmospheric data. The SeaBASS database consists of in situ data from multiple contributors, collected using a variety of measurement instruments with consistent, community-vetted protocols, from several marine platforms such as fixed buoys, hand-held radiometers and profiling instruments. Quality control of the received data includes a rigorous series of protocols that range from file format verification to the inspection of the geophysical data values (Werdell et al., 2003). Radiometric data were acquired through the Validation search tool, which provided in situ data with matchups for particular ocean-colour sensors (Bailey and Werdell, 2006). The criteria in the search query were defined to have the minimal flag conditions in the satellite data in order to retrieve a greater number of matchups and therefore in situ data. Regarding phytoplankton pigment data, they were acquired through the Pigment search tool, which provides pigment data directly from the archives. As stated in the SeaBASS website (see Pigment tab at http://seabass.gsfc.nasa.gov/seabasscgi/search.cgi), the Pigment search tool was originally designed to return only in vitro fluorometric measurements, which is consistent with our approach, but over time chlorophyll *a* measurements made using other methods (e.g. in situ fluorometry) were included in the retrieved pigment data. In the pigment data used in this work, a large number of in situ fluorometric measurements from continuous underway instruments were identified and discarded. These data were firstly identified from cruises with more than 50 observations per day and then re-checked on the SeaBASS website to confirm whether indeed they were continuous underway measurements. A total of 148 015 such measurements were identified and discarded. Given the large volume of this group of data, it is possible that some chlorophyll *a* observations from in situ methods may have escaped the scrutiny and made it into the final merged dataset. In the future, the SeaBASS plans to add ancillary information to the extractions, which will enable users to distinguish the different types of chlorophyll measurements. The compiled variables from SeaBASS data were: rrs, chla_hplc, chla_fluor, aph, adg, bbp and kd. No conversion was necessary since all variables were acquired in the desired format.

2.2.5 NASA bio-Optical Marine Algorithm Data set (NOMAD)

The NASA bio-Optical Marine Algorithm Data set (NOMAD) is a publicly available dataset compiled by the NASA OBPG at the Goddard Space Flight Center. It is a high-quality global dataset of coincident radiometric and phytoplankton pigment observations for use in ocean-colour algorithm development and satellite-data product-validation activities (Werdell and Bailey, 2005). The source bio-optical data are the SeaBASS archive; therefore, many dependencies exist between these two datasets, which were addressed during the merging. The current version (Version 2.0 ALPHA, 2008) includes data from 1991 to 2007 and an additional set of observations of inherent optical properties. The current version was used in this work, but with an additional set of columns of remote-sensing reflectance corrected for the bidirectional effects (Morel and Gentili, 1996; Morel et al., 2002). This additional set of columns was provided directly

by the NOMAD creators. The compiled variables were rrs, chla_hplc, chla_fluor, aph, adg, bbp and kd. Conversion was only necessary for aph, adg and bbp and followed the procedures described in Sect. 2.1. For the calculation of bbp the variable bb was used with a smooth fitting to remove noise. A portion of the NOMAD data were optically weighted (for methods, see Werdell and Bailey, 2005). These data are not consistent with the protocols chosen in this work, but these observations were retained since NOMAD is a widely used dataset in ocean-colour validation.

2.2.6 MERIS Match-up In situ Database (MERMAID)

The MERIS Match-up In situ Database (MERMAID) provides in situ bio-optical data matched with concurrent and comparable MERIS Level 2 satellite ocean-colour products (Barker, 2013a, b). The MERMAID in situ database consists of data from multiple contributors, measured using a variety of instruments and protocols, from several marine platforms such as fixed buoys, hand-held radiometers and profiling instruments. Comprehensive quality control and protocols are used by MERMAID to integrate all the data into a common and comparable format (Barker, 2013a, b). Access to MERMAID data is limited to the MERIS Validation Team, the MERIS Quality Working Group and to the in situ data contributors. For this work, access has been granted to the MERMAID database through a signed service-level agreement. The MERMAID data include subsets of several datasets used in this compilation (MOBY, AERONET-OC, BOUSSOLE, NOMAD). These observations were removed from the MERMAID dataset to avoid duplication (as discussed in Sect. 2.1). The compiled variables were rrs, chla_hplc, chla_fluor, aph, adg, bbp and kd. Remote-sensing reflectance was calculated by dividing by π the original irradiance reflectance provided. Conversion was also necessary for aph, adg and bbp and followed the procedures described in Sect. 2.1.

2.2.7 Hawaii Ocean Time-series (HOT)

The Hawaii Ocean Time-series (HOT) programme provides repeated comprehensive observations of the hydrography, chemistry and biology of the water column at a station located 100 km north of O'ahu, Hawai'i, from October 1988 onwards (Karl and Michaels, 1996). This site is representative of the North Pacific subtropical gyre. Cruises are made approximately once a month to the deep-water station ALOHA (A Long-Term Oligotrophic Habitat Assessment; 22°45′ N, 158°00′ W). Pigment data (chla_hplc and chla_fluor) were extracted directly from the project website. Radiometric measurements from the HOT project are also available, but observations of rrs and kd from the HOT project were acquired in this work as part of the SeaBASS dataset.

2.2.8 Geochemistry, Phytoplankton, and Color of the Ocean (GeP&CO)

The Geochemistry, Phytoplankton, and Color of the Ocean (GeP&CO) is part of the French PROcessus Océaniques et Flux (PROOF) programme and aims to describe and understand the variability of phytoplankton populations and to assess its consequences for the geochemistry of the oceans (Dandonneau and Niang, 2007). It is based on the quarterly travels of the merchant ship *Contship London* from France to New Caledonia. A scientific observer embarked on each travel and operated the sampling for surface water, filtration and various measurements at several hours of each day. The experiment started in October 1999 and finished in July 2002. Pigment data were extracted from the project website. The compiled variable was chla_hplc.

2.2.9 Atlantic Meridional Transect (AMT)

The Atlantic Meridional Transect (AMT) is a multidisciplinary programme, which undertakes biological, chemical and physical oceanographic research during an annual voyage between the UK and destinations in the South Atlantic (Robinson et al., 2006). The programme was established in 1995 and since then has completed 23 research cruises. Pigment data between 1997 (AMT5) and 2005 (AMT17) were provided by the British Oceanographic Data Centre (BODC) following a specific request. For any interest in the original data, the BODC is the point of contact, which ensures that if there are any updates, the most recent data are supplied. The compiled variables are chla_hplc and chla_fluor.

2.2.10 International Council for the Exploration of the Sea (ICES)

The International Council for the Exploration of the Sea (ICES) is a network of more than 4000 scientists from almost 300 institutes, with 1600 scientists participating in activities annually. The ICES Data Centre manages a number of large dataset collections related to the marine environment covering the North East Atlantic, Baltic Sea, Greenland Sea and Norwegian Sea. The majority of data originate from national institutes that are part of the ICES network of member countries. Data were provided (on 28 April 2014) from the ICES database on the marine environment (Copenhagen, Denmark) following a specific request. The ICES data were made available under the ICES data policy and if there is any conflict between this and the policy adopted by the users, then the ICES policy applies. The compiled variables were chla_hplc and chla_fluor.

3 Results

In this work several sets of bio-optical in situ data were acquired, homogenised and merged into a single table. The

table is comprised of in situ observations between 1997 and 2012, with a global distribution, and include the following variables: remote-sensing reflectance (rrs), chlorophyll *a* concentration (chla), algal pigment absorption coefficient (aph), detrital and coloured dissolved organic matter absorption (adg), particle backscattering coefficient (bbp), and diffuse attenuation coefficient for downward irradiance (kd). All observations in the table were processed in such a way that they can be compared directly with satellite-derived ocean-colour data. The table consists of 80 524 rows and 267 columns. Each row represents a unique station in space and time, separated from each other by at least 5 min and 200 m. For each observation in a given station, there are three metadata strings: dataset, subdataset and pi. The columns of the table take the form described in Table 1. The contributors of data in the table are shown in Table 2. Regarding spectral variables, all original wavelengths were preserved, which requires a large number of unique wavelengths to be maintained in the database. No band shifting was performed (though some archived data in SeaBASS and MERMAID may have been merged with nearby wavelengths) and no minimum number of wavelengths per observation was imposed. This allows further manipulation of the table for different purposes. In the following paragraphs, the table is analysed and the final group of observations is described for each contributing dataset; however, the numbers reported here do not reflect the original numbers in each dataset, since duplicates across contributing datasets were removed (e.g. removed NOMAD and others from MERMAID).

Observations of remote-sensing reflectance are available at 134 unique wavelengths (i.e. columns), between 405 and 1022.1 nm (Fig. 1). In total there are 44 191 observations (i.e. rows) with remote-sensing reflectance in the table. The total number of observations are partitioned per contributing datasets as follows: AERONET-OC (17 405), BOUSSOLE (17 364), MOBY (4513), NOMAD (3326), MERMAID (885) and SEABASS (698). The data from AERONET-OC, BOUSSOLE and MOBY correspond to continuous time series and hence the higher number of observations. The data distribution at 44*X* nm and 55*X* nm is provided in Fig. 2a and b, respectively. Data were first searched at 445 and 555 nm and then with a search window of up to 8 nm to also include data at 547 nm. Median values at 44*X* nm range from 0.003 m^{-1} (AERONET-OC) and 0.009 m^{-1} (MOBY), whereas at 55*X* nm the median values lie between 0.001 m^{-1} (MOBY) and 0.004 m^{-1} (AERONET-OC). The observations are evenly distributed on a monthly basis in the Northern Hemisphere (Fig. 3). In the Southern Hemisphere, where the number of stations is smaller, there is a decrease in the number of observations during the austral winter months (Fig. 3). For additional analysis, rrs band ratios were plotted against each other (490 : 555 vs. 412 : 443, Fig. 4). Most points are within the boundaries of the NOMAD dataset, but some scattered points were found. These points were retained in the table to allow further manipulation with different quality control criteria. Complementary analysis of remote-sensing reflectance data is made when other variables are concurrently available and discussed further on in the text (see Figs. 11 and 16). The geographic distribution of remote-sensing reflectance observations (Fig. 5) shows a higher number of observations in some coastal regions, such as those of North America and Northern Europe. The central regions of the ocean show a lower number of observations, with the Atlantic Ocean having the highest density in relation to the other oceans. Best geographic coverage is provided by the NOMAD database. Data from SeaBASS are smaller in number but are still important. Data from MERMAID are mainly located along the coasts of Europe, North America and the central region of the North Atlantic Ocean.

For chlorophyll *a* concentration, two types of observations were compiled, one measured by fluorometric or spectrophotometric methods (chla_fluor), and the other measured

Table 1. The standard variables, nomenclatures and units in the final table.

Variable/column	Description and units
time	GMT, <YYYY-MM-DD>T<HH:MM:SS>Z
lat	Decimal degree, −90 : 90, south negative
lon	Decimal degree, −180 : 180, west negative
depth_water	Sampling depth (m) – all assigned to zero
chla_hplc	Total chlorophyll *a* concentration determined from HPLC method (mg m^{-3})
chla_fluor	Chlorophyll *a* concentration determined from fluorometric or spectrophotometric methods (mg m^{-3})
rrs_<band>	Remote-sensing reflectance (sr^{-1})
aph_<band>	Algal pigment absorption coefficient (m^{-1})
adg_<band>	Detrital plus CDOM absorption coefficient (m^{-1})
bbp_<band>	Particle backscattering coefficient (m^{-1})
kd_<band>	Diffuse attenuation coefficient for downward irradiance (m^{-1})
etopo1	Water depth from ETOPO1 (m)
chla_hplc_dataset	Metadata string for chla_hplc
chla_hplc_subdataset	Metadata string for chla_hplc
chla_hplc_pi	Metadata string for chla_hplc
chla_fluor_dataset	Metadata string for chla_fluor
chla_fluor_subdataset	Metadata string for chla_fluor
chla_fluor_pi	Metadata string for chla_fluor
rrs_dataset	Metadata string for rrs
rrs_subdataset	Metadata string for rrs
rrs_pi	Metadata string for rrs
aph_dataset	Metadata string for aph
aph_subdataset	Metadata string for aph
aph_pi	Metadata string for aph
adg_dataset	Metadata string for adg
adg_subdataset	Metadata string for adg
adg_pi	Metadata string for adg
bbp_dataset	Metadata string for bbp
bbp_subdataset	Metadata string for bbp
bbp_pi	Metadata string for bbp
kd_dataset	Metadata string for kd
kd_subdataset	Metadata string for kd
kd_pi	Metadata string for kd

Table 2. Original sets of data and data contributors in the final table.

Data source	Description	Data contributors
Marine Optical Buoy (MOBY)	Daily observations of remote-sensing reflectance, measured by a fixed mooring system, located west of the Hawaiian island of Lāna'i. Data compiled between 1997–2012. Data were obtained from the MOBY website. Compiled standard variable: rrs.	Paul DiGiacomo, Kenneth Voss
BOUée pour l'acquiSition de Séries Optiques à Long termE (BOUSSOLE)	High frequency (15 min) observations of remote-sensing reflectance, from a fixed mooring system, located in the western Mediterranean Sea. Measurements of chlorophyll *a* concentration are also available at the mooring locations. Remote-sensing reflectance and chlorophyll *a* data were compiled between 2003–2012 and 2001–2012, respectively. Data were provided by David Antoine. Compiled standard variables: rrs, chla_hplc.	David Antoine
AErosol RObotic NETwork-Ocean Color (AERONET-OC)	Daily observations of remote-sensing reflectance, measured by modified sun photometers. Data compiled between 2002–2012. Sites included: Abu_Al_Bukhoosh (∼ 25° N, ∼ 53° E), COVE_SEAPRISM (∼ 36° N, ∼ 75° W), Gloria (∼ 44° N, ∼ 29° E), Gustav_Dalen_Tower (∼ 58° N, ∼ 17° E), Helsinki Lighthouse (∼ 59° N, ∼ 24° E), LISCO (∼ 40° N, ∼ 73° W), Lucinda (∼ 18° S, ∼ 146° E), MVCO (∼ 41° N, ∼ 70° W), Palgrunden (∼ 58° N, ∼ 13° E), Venice (∼ 45° N, ∼ 12° E) and WaveCIS_Site_CSI_6 (∼ 28° N, ∼ 90° W). Data were obtained from the AERONET-OC website. Compiled standard variable: rrs.	Robert Arnone (WaveCIS), Sam Ahmed (LISCO), Vittorio Brando (Lucinda), Dick Crout (WaveCIS), Hui Feng (MVCO), Alex Gilerson (LISCO), Rick Gould (WaveCIS), Brent Holben (COVE-SEAPRISM), Susanne Kratzer (Palgruden), Heidi M. Sosik (MVCO), Giuseppe Zibordi (Abu Al Bukhoosh & Gloria & Gustav Dalen Tower & Helsinki Lighthouse & Venice)
SeaWiFS Bio-optical Archive and Storage System (SeaBASS)	Global archive of in situ marine data from multiple contributors. Bio-optical global data between 1997–2012 were extracted from the SeaBASS website. Pigment data were extracted using the Data Search tool, which provides data directly from the archives. Radiometric data were extracted using the Validation tool, which only provides in situ data with matchups for ocean-colour sensors. Compiled standard variables: rrs, chla_hplc, chl_fluor, aph, adg, bbp and kd.	Robert Arnone, Kevin Arrigo, William Balch, Ray Barlow, Mike Behrenfeld, Şükrü Beşiktepe, Emmanuel Boss, Chris Brown, Douglas Capone, Ken Carder, Francisco Chavez, Alex Chekalyuk, Jay-Chung Chen, Dennis Clark, Hervé Claustre, Jorge Corredor, Glenn Cota, Yves Dandonneau, Heidi Dierssen, David Eslinger, Piotr Flatau, Robert Frouin, Carlos García, Joaquim Goes, Gwo-Ching Gong, Rick Gould, Larry Harding, Jon Hare, Stan Hooker, Chuanmin Hu, Sung-Ho Kang, Gary Kirkpatrick, Oleg Kopelevich, Sam Laney, Zhongping Lee, Ricardo Letelier, Marlon Lewis, Antonio Mannino, John Marra, Chuck McClain, Christophe Menkes, Mark Miller, Greg Mitchell, Ru Morrison, James Mueller, Frank Muller-Karger, James Nelson, Norman Nelson, Mary Jane Perry, David Phinney, John Porter, Collin Roesler, David Siegel, Mike Sieracki, Jeffrey Smart, Raymond Smith, Heidi M. Sosik, James Spinhirne, Dariusz Stramski, Rick Stumpf, Ajit Subramaniam, Chuck Trees, Michael Twardowski, Kenneth Voss, Marcel Wernand, Ronald Zaneveld, Eric Zettler, Giuseppe Zibordi, Richard Zimmerman
NASA bio-Optical Marine Algorithm Data set (NOMAD)	High-quality global dataset of coincident bio-optical in situ data. The dataset was built upon SeaBASS archive. The current version (version 2.0 ALPHA, 2008) was used with an additional set of columns of remote-sensing reflectance corrected for the bidirectional nature of the light field, provided by NOMAD creators. Data compiled between 1997–2007. Compiled standard variables: rrs, chla_hplc, chl_fluor, aph, adg, bbp and kd.	Robert Arnone, Kevin Arrigo, William Balch, Ray Barlow, Mike Behrenfeld, Chris Brown, Douglas Capone, Ken Carder, Francisco Chavez, Dennis Clark, Hervé Claustre, Jorge Corredor, Glenn Cota, David Eslinger, Piotr Flatau, Robert Frouin, Rick Gould, Larry Harding, Stan Hooker, Oleg Kopelevich, Marlon Lewis, Antonio Mannino, John Marra, Mark Miller, Greg Mitchell, Tiffany Moisan, Ru Morrison, Frank Muller-Karger, James Nelson, Norman Nelson, David Siegel, Raymond Smith, Timothy Smyth, James Spinhirne, Dariusz Stramski, Rick Stumpf, Ajit Subramaniam, Kenneth Voss
MERIS Match-up In situ Database (MERMAID)	Global database of in situ bio-optical data matched with concurrent MERIS Level 2 satellite ocean-colour products. The Extract matchup tool was used to acquire data. Data were compiled between 2002 and 2012. Access was granted through a signed Service Level Agreement. Compiled standard variables: rrs, chla_hplc, chl_fluor, aph, adg, bbp and kd.	Simon Bélanger, Jean-François Berthon, Vanda Brotas, Elisabetta Canuti, Pierre Yves Deschamps, Annelies Hommersom, Mati Kahru, Holger Klein, Hubert Loisel, David McKee, Greg Mitchell, Michael Ondrusek, Michel Repecaud, David Siegel, Giuseppe Zibordi
Atlantic Meridional Transect (AMT)	Multidisciplinary programme that makes biological, chemical and physical oceanographic measurements during an annual voyage between the United Kingdom and destinations in the South Atlantic. It has compiled observations of chlorophyll *a* concentration between 1997 (AMT5) and 2005 (AMT17). Data were provided by the British Oceanographic Data Centre (BODC). Compiled standard variables: chla_hplc, chl_fluor.	Ray Barlow, Stuart Gibb, Victoria Hill, Patrick Holligan, Gerald Moore, Leonie O'Dowd, Alex Poulton, Emilio Suarez

Table 2. Continued.

International Council for the Exploration of the Sea (ICES)	Database of several collections of data related to the marine environment. It has compiled observations of chlorophyll *a* concentration in the northern European seas, between 1997 and 2012. Data were provided by the ICES database on the marine environment (2014, Copenhagen, Denmark). Compiled standard variables: chla_hplc, chl_fluor.	Not available
Hawaii Ocean Time-series (HOT)	Multidisciplinary programme that makes repeated biological, chemical and physical oceanographic observations near O'ahu, Hawai'i. Measurements of chlorophyll *a* concentration between 1997–2012 were extracted from the project website. Compiled standard variables: chla_hplc, chl_fluor.	Bob Bidigare, Matthew Church, Ricardo Letelier, Jasmine Nahorniak
Geochemistry, Phytoplankton, and Color of the Ocean (GeP&CO)	Program of in situ data collection aboard merchant ship from France to New Caledonia, between 1999 and 2002. Measurements of chlorophyll *a* concentration were obtained from the project website. Compiled standard variables: chla_hplc.	Yves Dandonneau

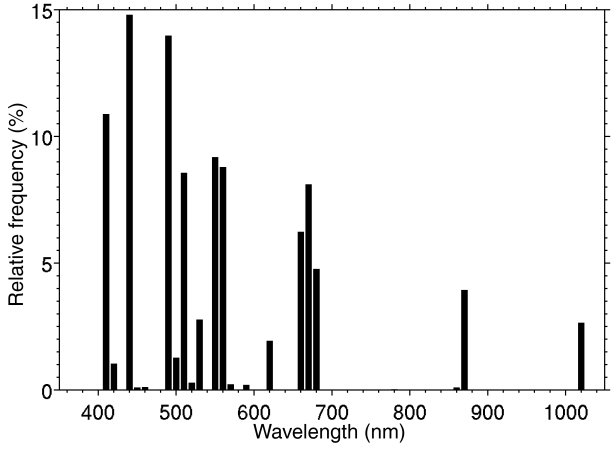

Figure 1. Relative spectral frequency of remote-sensing reflectance in the final table, using 10 nm wide class intervals, defined as the ratio of the number of observations at a particular waveband to the total number of observations at all wavebands, multiplied by 100 to report results in percentage. Data at a total of 134 unique wavelengths, between 405 and 1022.1 nm, were compiled.

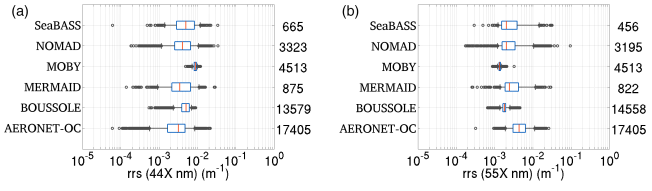

Figure 2. The distribution of **(a)** rrs at 44*X* nm and **(b)** rrs at 55*X* nm. Data were first searched at 445 and 555 nm and then with a search window of up to 8 nm to include data at 547 nm. The black boxes delimit the percentiles 0.25 and 0.75 of the data and the black horizontal lines show the extension of up to the 5th and 95th percentiles. The red line represents the median value and the black circles the values below (and above) the percentile 0.05 (0.95). The number of measurements of each dataset is reported on the right axis of the graph.

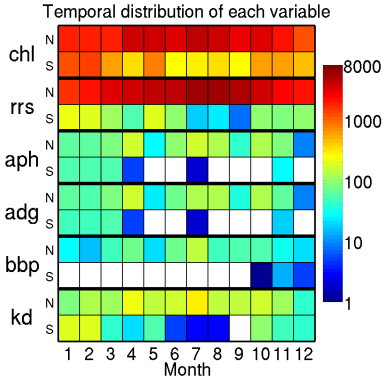

Figure 3. Temporal distribution of chlorophyll *a* concentration (chl), remote-sensing reflectance (rrs), algal pigment absorption coefficient (aph), detrital plus CDOM absorption coefficient (adg), particle backscattering coefficient (bbp) and the diffuse attenuation coefficient for downward irradiance (kd) in the final table. All chlorophyll data were considered, but for a given station HPLC data were selected if available. Colours indicate the number of stations available for each variable, as a function of months and the hemispheres of data acquisition (N – Northern Hemisphere; S – Southern Hemisphere).

by HPLC methods (chla_hplc). A comparison of both measurements (Fig. 6), when available at the same station shows good agreement (Trees et al., 1985). As stated before, the analysis was done on the final merged table; thus, no data were filtered and the good relation can in part be explained by the quality control implemented by the data providers and curators of repositories such as NOMAD and SeaBASS (Werdell and Bailey, 2005). The total number of rows with concurrent chla_fluor and chla_hplc is 2002, with contributions from NOMAD (32 %), SeaBASS (47 %), MERMAID (11 %), HOT (7 %), AMT (2 %) and GeP&CO (1 %). The chla_fluor observations are available at 27 933 stations (rows), with values ranging from 0.0011 to 100 mg m^{-3} (Fig. 7). They are from NOMAD (2350), SeaBASS (15 728),

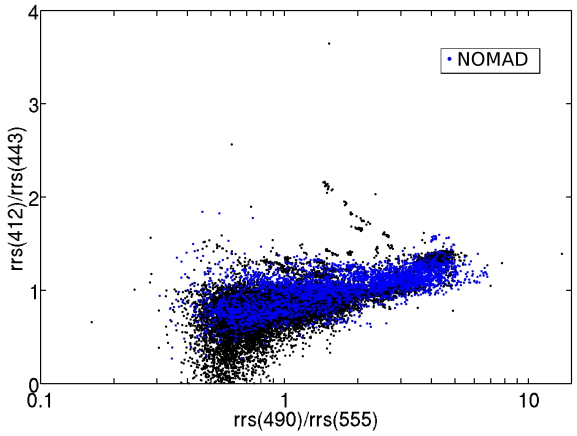

Figure 4. Ranges of remote-sensing reflectance band ratios (412 : 443 and 490 : 555) for all data. The points from the NOMAD dataset are shown in blue for reference. The total number of points is divided between MOBY (4513), AERONET-OC (17 293), BOUSSOLE (3533), NOMAD (3120), SeaBASS (432) and MERMAID (677). To maximise the number of ratios per dataset, a search window of up to 12 nm was used when the four wavelengths (412, 443, 490, 555) were not simultaneously available. The effect of different search windows was negligible in the ratio distribution.

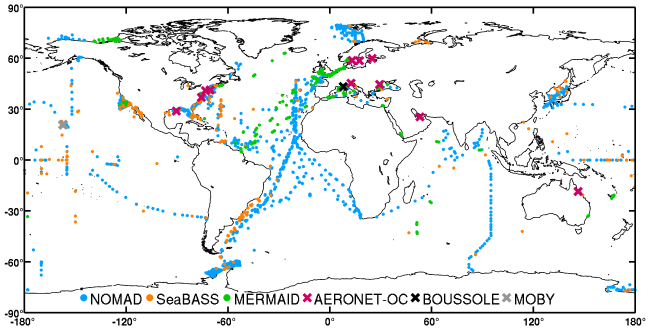

Figure 5. Global distribution of remote-sensing reflectance per dataset in the final table. The data sources are identified with different colours. Points show locations where at least one observation is available. Crosses show sites from where time series data of remote-sensing reflectance are available.

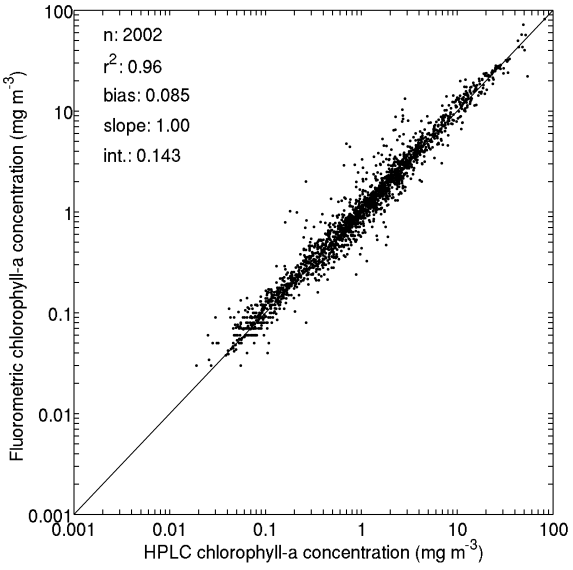

Figure 6. Comparison of coincident observations of chlorophyll *a* concentration derived with different methods (chla_fluor and chla_hplc). The data were transformed prior to regression analysis to account for their log-normal distribution.

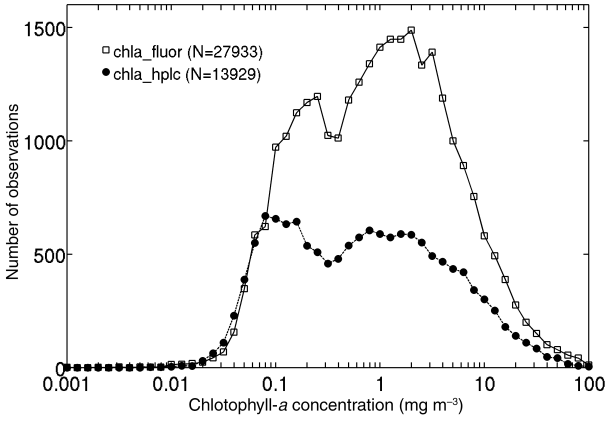

Figure 7. Number of observations per chlorophyll *a* concentration acquired with different methods (chla_fluor and chla_hplc).

MERMAID (3711), ICES (5421), HOT (559) and AMT (164). The total number of chla_hplc observations is 13 918, ranging from 0.006 to 99.8 mg m^{-3} (Fig. 7), with contributions from NOMAD (1309), SeaBASS (5920), MERMAID (707), ICES (2994), HOT (153), GeP&CO (1536), BOUSSOLE (397) and AMT (902). The combined chlorophyll dataset (all chlorophyll data considered, but for a given station HPLC data were selected if available) has a total of 39 849 observations, with 11, 41 and 48 % from oligotrophic (< 0.1 mg m^{-3}), mesotrophic (0.1–1 mg m^{-3}) and eutrophic (> 1 mg m^{-3}) waters, respectively. When compared with the proportions of the world ocean in these trophic classes, i.e. 56 % oligotrophic, 42 % mesotrophic and 2 % eutrophic (Antoine et al., 1996), oligotrophic waters are under-represented and eutrophic waters are over-represented in the compilation. The combined chlorophyll dataset is evenly distributed between each month of the year in the Northern Hemisphere, but in the Southern Hemisphere there are relatively few data points during the winter months compared with the rest of the year (Fig. 3). The spatial distribution of the chlorophyll values for the combined dataset (Fig. 8) shows a good agreement with known biogeographical features, such as low chlorophyll values in the subtropical gyres and high values in temperate, coastal and upwelling regions. Many regions show a good spatial coverage (e.g. Atlantic and Pacific oceans), while others are poorly sampled (e.g. Southern and

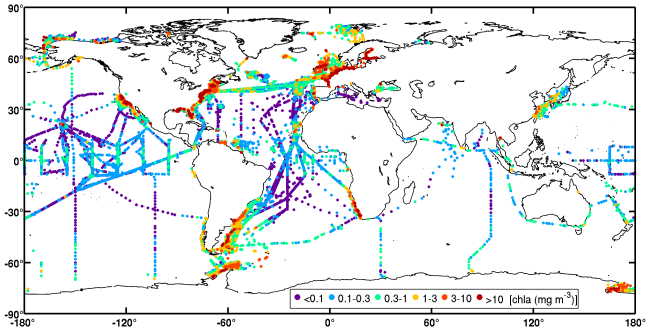

Figure 8. Global distribution of chlorophyll *a* concentration per intervals of the observed value. All chlorophyll data were considered, but for a given station HPLC data were selected if available.

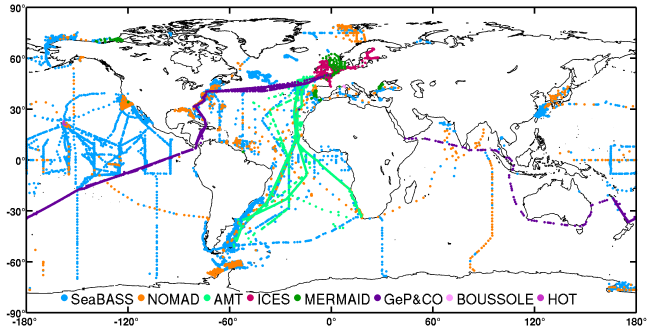

Figure 9. Global distribution of chlorophyll *a* concentration per dataset in the final table. All chlorophyll data were considered, but for a given station HPLC data were selected if available.

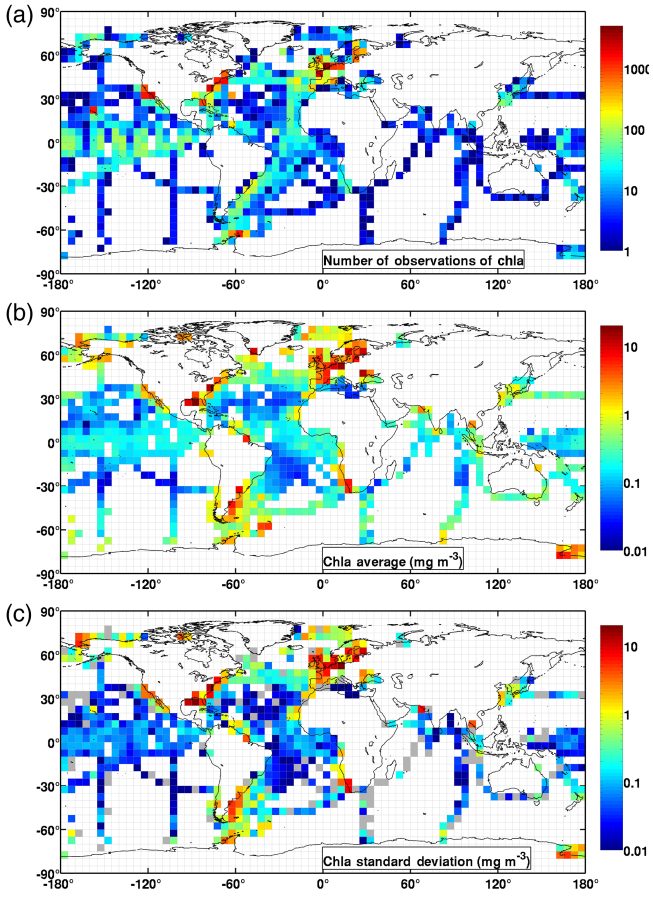

Figure 10. The chlorophyll *a* (mg m^{-3}) data partitioned into 5° × 5° boxes showing the **(a)** number of observations, **(b)** average value and **(c)** standard deviation in each box. All chlorophyll data were considered, but for a given station HPLC data were selected if available. In the standard deviation plot, grey represents boxes with zero standard deviation (i.e. one observation).

Indian oceans). Of the contributing datasets, NOMAD and SeaBASS provide a good spatial coverage in many regions (Fig. 9). The ICES and MERMAID data are mainly located along the coastal regions of Europe. The AMT data cover the central part of the Atlantic Ocean. For additional analysis and as an example of the applications of the compiled dataset, the combined chlorophyll data (chla_fluor and chla_hplc) were partitioned into 5° × 5° boxes and for each box the number of observations, average value and standard deviation were computed (Fig. 10 a, b and c, respectively). The number of observations can be very high (> 1000) in some boxes along the European and North American coastlines and relatively low (< 20) in oceanic regions. Again there is an appearance in the average value map (Fig. 10b) of well-known biogeographical features, such has the lower chlorophyll in the subtropical gyres and high values in coastal and upwelling areas. There is a close correspondence between the spatial patterns of the averaged and standard deviation maps (Fig. 10 b and c), which may be an indicator of the data quality.

Coincident observations of chlorophyll *a* concentration and remote-sensing reflectance are available at 3562 stations. These observations are mostly from NOMAD (85 %), MERMAID (10 %) and SeaBASS (5 %). The maximum of three band ratios of remote-sensing reflectance is plotted against chlorophyll *a* concentration (Fig. 11). The chla values used are the combined HPLC and fluorometric chlorophyll *a*, and for rrs the closest spectral observation within 2 nm was used. The maximum band ratios were calculated using the maximum value from [rrs(443) / rrs(555), rrs(490) / rrs(555), rrs(510) / rrs(555)] or [rrs(443) / rrs(560), rrs(490) / rrs(560), rrs(510) / rrs(560)] if rrs(555) was not available. The relationship between maximum band ratio and chlorophyll is close to the NASA OC4 and OC4E v6 standard algorithm (http://oceancolor.gsfc.nasa.gov/cms/atbd/chlor_a), equally based on maximum band ratios, providing confidence in the quality of the compiled data.

The inherent optical properties (aph, adg and bbp) are available at 27 unique wavelengths between 405 and 683 nm. There are a total of 1276, 1123 and 638 observations for aph, adg and bbp, respectively. For aph the total number of observations is distributed among NOMAD (1190),

Table 3. Summary of median values for aph, adg and bbp at 44*X* and 55*X* nm for each dataset (as shown in Fig. 12a–f). Data were first searched at 445 and 555 nm and then with a search window of up to 8 nm to include data at 547 nm.

	Median aph		Median adg		Median bbp	
	44*X* nm	55*X* nm	44*X* nm	55*X* nm	44*X* nm	55*X* nm
SeaBASS	0.0549	0.0074	0.0711	0.0222	0.0035	0.0025
MERMAID	0.0353	0.0046	0.0515	0.0112	0.0030	0.0022
NOMAD	0.0282	0.0052	0.1149	0.0286	0.0080	0.0052

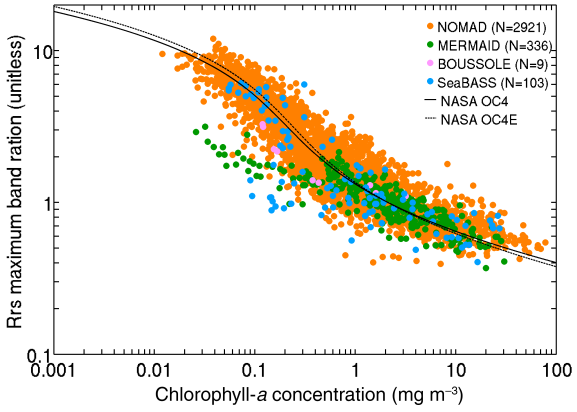

Figure 11. A remote-sensing reflectance maximum band ratio (as defined in text) ([443,490,510] / 555 or [443,490,510] / 560 if 555 not available) as a function of chlorophyll *a* concentration. All chlorophyll data were considered, but for a given station HPLC data were selected if available. Data within 2 nm of the wavelengths were used. For reference the solid and dotted line show the NASA OC4 and OC4E v6 standard algorithms, respectively (http://oceancolor.gsfc.nasa.gov/cms/atbd/chlor_a). The total number of points was 3369, of which 86% were from NOMAD.

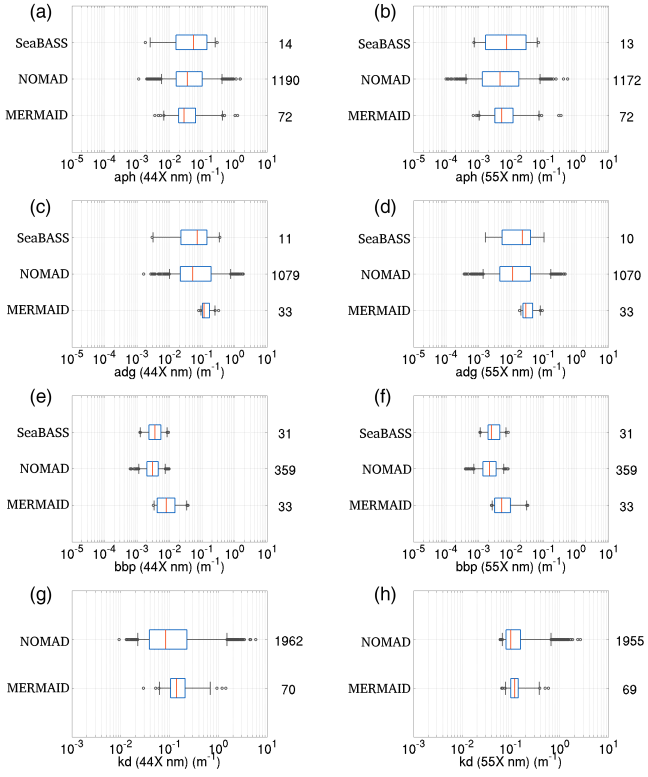

Figure 12. The distribution of **(a)** aph at 44*X* nm, **(b)** aph at 55*X* nm, **(c)** adg at 44*X* nm, **(d)** adg at 55*X* nm, **(e)** bbp at 44*X* nm, **(f)** bbp at 55*X* nm, **(g)** kd at 44*X* nm and **(h)** kd at 55*X* nm. Data were first searched at 445 and 555 nm and then with a search window of up to 8 nm to include data at 547 nm. The graphical convention is identical to Fig. 2.

SeaBASS (14) and MERMAID (72). For adg the contributions are as follows: NOMAD (1079), SeaBASS (11) and MERMAID (33). The bbp observations come from NOMAD (371), SeaBASS (32) and MERMAID (235). Data distribution of aph, adg and bbp at 44*X* and 55*X* nm for each dataset is provided in Fig. 12a–f. Median values of aph, adg and bbp at 44*X* and 55*X* nm for each dataset are summarised in Table 3. For additional analysis, the following band ratios for the absorption coefficients were calculated: aph(490) / aph(443), aph(412) / aph(443), adg(443) / adg(490) and adg(412) / adg(443). Data within 2 nm of the wavelengths were used to maximise the number of points. The distribution of the ratios is shown in Fig. 13. Several observations were found to be above the thresholds used in the IOCCG report 5 (IOCCG, 2006) for quality control (see dotted vertical black lines in Fig. 13). These points are highlighted here for information but retained in the database, as these were mostly from NOMAD and there was an interest to preserve this dataset as a whole. Also, not discarding this data allows further manipulation with different quality control criteria. On the annual scale, the observations of the inherent optical properties are strongly underrepresented in the Southern Hemisphere where there is a complete absence of data in several months of the year (Fig. 3). Overall, the geographic coverage for observations of aph, adg and bbp (Fig. 14) is poor, with most open-ocean regions not being sampled, with the exception of the Atlantic Ocean. Small clusters of data are located in particular coastal regions.

Finally, for the diffuse attenuation coefficient for downward irradiance (kd), there are 25 unique wavelengths between 405 and 709 nm. There are a total of 2454 obser-

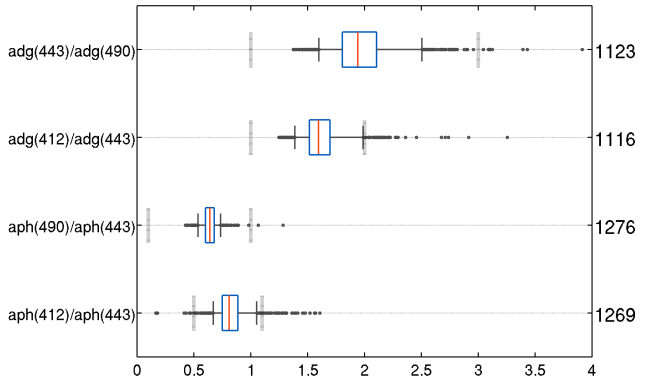

Figure 13. The distribution of absorption coefficient band ratios: adg(443) / adg(490), adg(412) / adg(443), aph(490) / aph(443) and aph(412) / aph(443). Data within 2 nm of the wavelengths were used. The graphical convention is identical to Fig. 2. The vertical dashed lines show the lower and upper thresholds used for quality control in the IOCCG report 5 (IOCCG, 2006). The total number of points are divided between NOMAD (93–96 %), MERMAID (3–6 %) and SeaBASS (1 %).

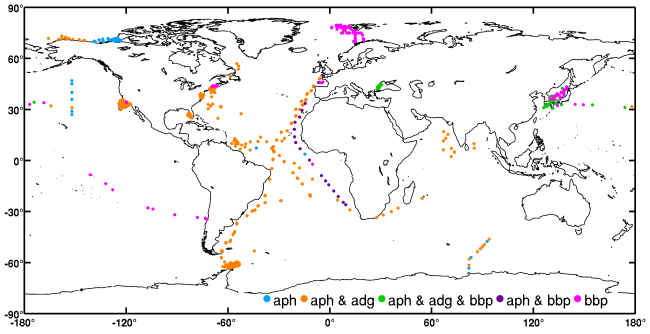

Figure 14. Global distribution of observations of inherent optical properties (algal pigment absorption coefficient aph, detrital plus CDOM absorption coefficient adg and particle backscattering coefficient bbp) in the final table.

vations, from NOMAD (2266), SeaBASS (118) and MERMAID (70). Data distribution of kd at 44X and 55X nm for each dataset is shown in Fig. 12g and h. No kd data at these wavelengths were available for the SeaBASS dataset (only at 490 nm). Median values of kd at 44X nm span between 0.08 m^{-1} (NOMAD) to 0.1 m^{-1} (MERMAID), whereas at 55X nm the kd values are approximately 0.1 m^{-1} (NOMAD and MERMAID). NOMAD provides the best geographic coverage (Fig. 15), with a higher coverage in the Atlantic, compared with other oceans. With the exception of the coastal regions of North America and the Japan Sea, most coastal regions are not sampled. In the Northern Hemisphere, kd is distributed roughly evenly across all months of the year, but in the Southern Hemisphere there are few data points during the austral winter and none at all in September (Fig. 3).

Although most of the stations with concurrent variables are mainly from the NOMAD dataset, for completeness, an examination of bio-optical relationships is provided (Fig. 16). The relation between aph at 443 nm and chlorophyll a (Fig. 16a) agrees with the relation proposed by Bricaud et al. (2004). A total of 1070 points exist with these two variables available (93 % from NOMAD). The relation between the sum of aph and adg at 443 nm and rrs at 443 nm (Fig. 16b) shows a similar dispersion, with the exception of some scattered points, to an equivalent analysis on the IOCCG report 5 (see their Fig. 2.3). Again, the scattered data were retained in the final table to preserve the NOMAD dataset. A total of 1112 points exist for which these three variables are available (97 % from NOMAD). The relation between the ratio rrs(490) / rrs(555) and kd(490) (Fig. 16c) shows a good agreement with the NASA KD2S standard algorithm (http://oceancolor.gsfc.nasa.gov/cms/atbd/kd_490). A total of 2280 points exist for which these three variables are available (93 % from NOMAD). The relation between the ratio rrs(490) / rrs(555) and bbp at 555 nm (Fig. 16c) shows a good agreement with the relation suggested by Tiwari and Shanmugam (2013). A total of 357 points exist for which these three variables are available (91 % from NOMAD).

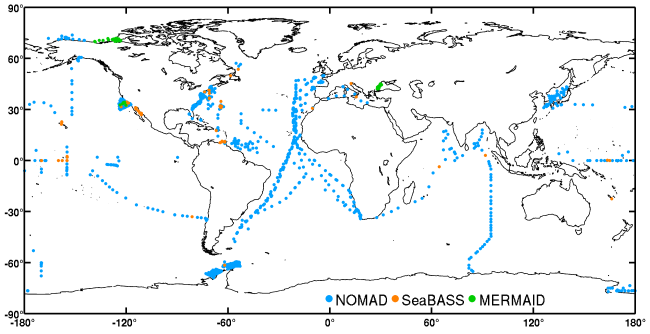

Figure 15. Global distribution of diffuse attenuation coefficient for downward irradiance (kd) per dataset in the final table.

4 Conclusions

A compilation of bio-optical in situ data is presented in this work. The compiled data have global coverage and span from 1997 to 2012, covering the recent period of ocean-colour satellite observations. They resulted from the acquisition, homogenisation and integration of several sets of data obtained from different sources. Minimal changes were made to the original data, except for those necessary for conversion to standard format and quality control. In situ measurements of the following variables were compiled: remote-sensing reflectance, chlorophyll a concentration, algal pigment absorption coefficient, detrital and coloured dissolved organic matter absorption coefficient, particle backscattering coefficient and diffuse attenuation coefficient for downward irradiance.

The final set of data consists of a substantial number of in situ observations, available in a simple text table, and processed in a way that could be used directly for the evaluation

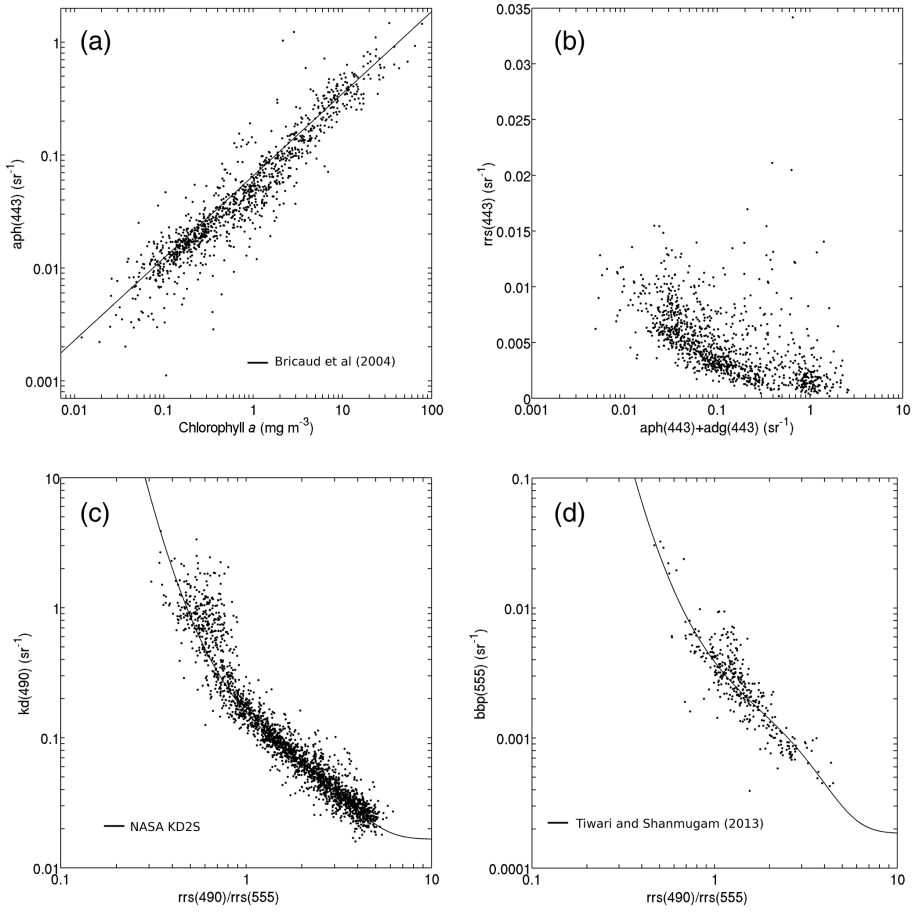

Figure 16. Examples of bio-optical relationships in the final merged table. Panel **(a)**: aph(443) vs. chlorophyll *a*. Total number of points (1070) is divided between MERMAID (70), NOMAD (991) and SeaBASS (9). For reference the solid line show the regression from Bricaud et al. (2004). Panel **(b)**: [aph(443) + adg(443)] vs. rrs(443). Total number of points (1112) is divided between MERMAID (33) and NOMAD (1079). Panel **(c)**: [rrs(490) / rrs(555)] vs. kd(490). The total number of points (2280) is divided between MERMAID (62), NOMAD (2117) and SeaBASS (101). For reference the solid line show the NASA KD2S standard algorithm (http://oceancolor.gsfc.nasa.gov/cms/atbd/kd_490). Panel **(d)**: [rrs(490) / rrs(555)] vs. bbp(555). The total number of points (357) is divided between MERMAID (33) and NOMAD (324). For reference the solid line show the relation proposed by Tiwari and Shanmugam (2013). A search window of 2 nm was used for panels **(a)** and **(b)**, and a search window of 5 nm was used for panels **(c)** and **(d)** to include data at 560 nm when not available at 555 nm.

of satellite-derived ocean-colour data. The major advantages of this compilation are that it merges six commonly used data sources in ocean-colour validation (MOBY, BOUSSOLE, AERONET-OC, SeaBASS, NOMAD, MERMAID) and four additional sets of chlorophyll *a* concentration data (AMT, ICES, HOT and GeP&CO) into a simple text table free of duplicated observations. This compilation was initially created with the intention of evaluating the quality of the satellite ocean-colour products from the ESA OC-CCI project. The objective of publishing the compilation is to make it easy for the broader community to use it.

5 Data availability

Interested researchers may download the data at https://doi.pangaea.de/10.1594/PANGAEA.854832. For more information on data format see Appendix B.

Appendix A: Notation

ad	Detrital absorption coefficient (m^{-1})
adg	Detrital plus CDOM absorption coefficient (m^{-1})
AERONET-OC	AErosol RObotic NETwork-Ocean Color
ag	CDOM absorption coefficient (m^{-1})
AMT	Atlantic Meridional Transect
ap	Particle absorption coefficient (m^{-1})
aph	Algal pigment absorption coefficient (m^{-1})
aw	Pure water absorption coefficient (m^{-1})
bb	Total backscattering coefficient (m^{-1})
bbp	Particle backscattering coefficient (m^{-1})
bbw	Backscattering coefficient of seawater (m^{-1})
BOUSSOLE	BOUée pour l'acquiSition de Séries Optiques à Long termE
CDOM	Coloured dissolved organic matter
chla	Chlorophyll *a* concentration ($mg\,m^{-3}$)
chla_fluor	Chlorophyll *a* concentration determined from fluorometric or spectrophotometric methods ($mg\,m^{-3}$)
chla_hplc	Total chlorophyll *a* concentration determined from HPLC method ($mg\,m^{-3}$)
Es	Surface irradiance (or above-water downwelling irradiance) ($mW\,cm^{-2}\,\mu m^{-1}$)
ESA	European Space Agency
Fo	Top-of-the-atmosphere solar irradiance ($mW\,cm^{-2}\,\mu m^{-1}$)
GeP&CO	Geochemistry, Phytoplankton, and Color of the Ocean
HOT	Hawaii Ocean Time-series
HPLC	High-performance liquid chromatography
ICES	International Council for the Exploration of the Sea
kd	Diffuse attenuation coefficient for downward irradiance (m^{-1})
Lw	Water-leaving radiance (or above-water upwelling radiance) ($mW\,cm^{-2}\,\mu m^{-1}\,sr^{-1}$)
MERIS	Medium Resolution Imaging Spectrometer
MERMAID	MERIS Match-up In situ Database
MOBY	Marine Optical Buoy
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
nLw	Normalised water-leaving radiance ($mW\,cm^{-2}\,\mu m^{-1}\,sr^{-1}$)
nLw_ex	nLw with a correction for bidirectional effects ($mW\,cm^{-2}\,\mu m^{-1}\,sr^{-1}$)
NOMAD	NASA bio-Optical Marine Algorithm Data set
OC-CCI	Ocean Colour Climate Change Initiative
rrs	Remote-sensing reflectance (sr^{-1})
SeaBASS	SeaWiFS Bio-optical Archive and Storage System
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
Rw	Irradiance reflectance (dimensionless)

Appendix B: Data table

The compiled data are available at doi:10.1594/PANGAEA.854832. The merged text table described in this work, considered here as the main table, is accompanied by four extra files. One extra file is a csv table with detailed information about the number of observations per variable, dataset, subdataset and pi. Two other extra files are text tables generated from the main table, and are provided to help with the analysis of spectral data. These two files contain the spectral data aggregated within ±2 and ±6 nm, respectively, of SeaWiFS, MODIS AQUA and MERIS sensor bands. The files are generated by assigning, in each row of the main table, the closest spectral observation within 2 nm (or 6 nm) of a sensor band. The centre wavelength of each band and sensor used in the generation of the files is the following: SeaWiFS bands 1–8 were centred at [412, 443, 490, 510, 555, 670, 765, 865] nm, respectively; MODIS-AQUA bands 1–9 were centred at [412, 443, 488, 531, 547, 667, 678, 748, 869] nm, respectively; and MERIS bands 1–13 were centred at [412, 442, 490, 510, 560, 620, 665, 681, 709, 753, 779, 865, 885] nm, respectively. An exception to this procedure was made to confirm that the correct MOBY data are stored in the files (see Sect. 2.2.1. for discussion on how MOBY wavelengths are stored in the main file). Finally, a readme file is provided to help the user.

Author contributions. The first six authors belong to the ESA OC-CCI team and contributed to the design of the compilation. The remaining authors are listed alphabetically and are data contributors (see their respective dataset on Table 2) or individuals responsible for the development of a particular dataset (Jeremy Werdell for NOMAD and Katherine Barker for MERMAID). All data contributors (listed on Table 2) were contacted for authorisation of data publishing and offered co-authorship. In the case of the ICES dataset the permission for publishing was given by the ICES team. All the authors have critically reviewed the manuscript.

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