Earth Syst. Sci. Data, 6, 123–145, 2014
www.earth-syst-sci-data.net/6/123/2014/
doi:10.5194/essd-6-123-2014

Open Access Earth System Science Data

Data compilation of fluxes of sedimenting material from sediment traps in the Atlantic Ocean

S. Torres Valdés[1], S. C. Painter[1], A. P. Martin[1], R. Sanders[1], and J. Felden[2]

[1]Ocean Biogeochemistry and Ecosystems Research Group. National Oceanography Centre. European Way, Southampton, SO14 3ZH, UK
[2]Center for Marine Environmental Sciences. Universität Bremen. Leobener Strasse, POP 330 440, 28359 Bremen, Germany

Correspondence to: S. Torres Valdés (sinhue@noc.ac.uk)

Received: 14 August 2013 – Published in Earth Syst. Sci. Data Discuss.: 9 September 2013
Revised: 3 February 2014 – Accepted: 24 March 2014 – Published: 17 April 2014

Abstract. We provide a data set assemblage of directly observed and derived fluxes of sedimenting material (total mass, POC, PON, $bSiO_2$, $CaCO_3$, PIC and lithogenic/terrigenous fluxes) obtained using sediment traps. This data assemblage contains over 5900 data points distributed across the Atlantic, from the Arctic Ocean to the Southern Ocean. Data from the Mediterranean Sea are also included. Data were compiled from a variety of sources: data repositories (e.g. BCO-DMO, PANGAEA®), time-series sites (e.g. BATS, CARIACO), published scientific papers and data provided by the originating principal investigators (PIs). All sources are specified within the combined data set. Data from the World Ocean Atlas 2009 were extracted to coincide with flux data to provide additional environmental information where available. Specifically, contemporaneous data were extracted for temperature, salinity, oxygen (concentration, AOU and percentage saturation), nitrate, phosphate and silicate. Data show a broad range of flux estimates, with marked differences between ocean domains. Data also reveal important differences in the contribution that a given variable provides to the total mass flux, which is relevant towards understanding the factors that control the strength of the biological carbon pump. This data set has been submitted to the data repository PANGAEA® (http://www.pangaea.de), who have made it available under doi:10.1594/PANGAEA.807946.

1 Introduction

The export of particulate organic carbon (POC) from the sunlit upper layers to the ocean interior (deep waters and deep ocean sediments), known as the biological carbon pump (BCP), is an important component of the global carbon cycle. However, the BCP is not well constrained, with estimates of carbon transport ranging from 3.4–4.7 (Eppley and Peterson, 1979) to $\sim 20\,\mathrm{Gt\,C\,yr^{-1}}$ depending on the method used (e.g. Laws et al., 2000). In the North Atlantic alone, estimates of the BCP range fourfold from 0.55 to $1.94\,\mathrm{Gt\,C\,yr^{-1}}$, representing 10–20 % of global export fluxes (Sanders et al., 2014). The uncertainty in these estimates reflects the sparseness of observations and to a smaller extent the variety of methods employed.

Currently, several independently compiled data sets of export flux exist but they reside in separate data repositories as individual data sets. Given the importance of the BCP for carbon storage and the need to further constrain its magnitude, we have attempted to bring together into a single compilation, all data currently available on POC fluxes (and related variables) obtained from sediment-trap deployments in the Atlantic Ocean, which includes the adjacent Arctic Ocean, the Atlantic sector of the Southern Ocean, and the Mediterranean Sea (as an adjacent sea). This data set assemblage was put together as part of the EU FP7 (Seventh Framework Programme) EURO-BASIN (Basin-scale Analysis, Synthesis and INtegration) programme (Work Package 2). Data were obtained from a variety of sources including data repositories (e.g. BCO-DMO, PANGAEA®), time-series sites (e.g. BATS, CARIACO), published scientific papers and directly

from the originating PIs. All sources are specified within the data set.

2 Data

Observational studies of export often make use of sediment traps. These are deployed at depths of interest in order to collect particles sinking through the water column. Upon recovery, particles are then analysed primarily to determine their carbon content, but additionally the nitrogen content is also easily obtained. The quantities of ballasting material such as calcium carbonate and opal are also increasingly important variables. The flux rate of material captured by a trap can be calculated from knowledge of the duration a trap is deployed for and the aperture of the trap itself. By obtaining export fluxes at different depths, the efficiency of the carbon pump can be evaluated simply as the fraction of the flux leaving the surface that makes it to a given depth.

2.1 Data sources

The data assemblage presented here includes variables commonly measured in studies concerning export production. These include total mass (Tot_Mass) flux, POC flux, particulate organic nitrogen (PON) flux, biogenic silica ($bSiO_2$) flux, calcium carbonate ($CaCO_3$) flux, particulate inorganic carbon (PIC) flux, and terrigenous or lithogenic (Terr/Litho) material flux. Most data were obtained from data repositories and individual time-series websites. A total of 2679 data points (45 % of total) were derived from 32 smaller data sets obtained from the Data Publisher for Earth and Environmental Science (PANGAEA®) at http://www.pangaea.de; 111 data points (1.9 %) were obtained from the Biological and Chemical Oceanography Data Management Office (BCO-DMO) at http://bcodmo.org (Lee et al., 2009a, b); 1755 data points (29.5 %) were obtained from the Carbon Retention In A Colored Ocean Project Ocean Time Series (CARIACO) at http://www.imars.usf.edu/CAR (Montes et al., 2012); and 784 data points (13.2 %) from the Bermuda Atlantic Time Series (BATS) at http://bats.bios.edu. Data (428 data points, 7.2 %) were also obtained from published journal articles (e.g. Fischer et al., 2000; Bory et al., 2001; Hwang et al., 2009). Finally, a few data sets (190 data points, 3.2 %) were directly obtained from Principal Investigators (Bauerfeind et al., 2009; Lampitt et al., 2010). These combined data sets provide 5947 data points of variables related to export production. In this compilation, a "data point" is an independent measurement or calculation of a given variable. The full data set is organised in columns as indicated in Table 1. The names and acronyms of variables as presented in this table are the most commonly used and least ambiguous terms. Though not all individual data sets contain all the variables listed in Table 1. The total number of data points per variable are presented in Table 2. POC flux contains the largest number of observations (5206 data points) and PIC flux the lowest (1048 data points).

2.2 Methods commonly employed

Across data sets there is considerable inconsistency in the names of variables and reported units. For this compilation we have attempted, to the best of our knowledge, to identify the variable that was actually being dealt with. For instance "biogenic particulate silicon" vs. "biogenic particulate silica", with the first referring to the element silicon (Si) and the second referring to the mineral silica (SiO_2). Upon careful examination of such cases, when enough information was available to identify the correct variable, that variable was standardised so that it is internally consistent within this compilation (e.g. all Si related fluxes are consistently reported as SiO_2). In cases where available information was insufficient to clarify ambiguity, data sets were excluded from the compilation.

2.2.1 Sediment-trap types

The data include observations from a range of named sediment-trap designs: moored automatic Kiel sediment traps (Bauerfeind et al., 2009; Bauerfeind and Nöthig, 2011), cone-shaped SMT 230 Kiel and Mark VI/V traps (Wefer and Fischer, 1993), cone-shaped multi-sampling SMT 230 KMU traps (Romero et al., 2002; Fahl and Nöthig, 2007), conical particle interceptor traps (Antia et al., 1999), conical sediment McLane Mark-7 traps (Hwang et al., 2009), drifting Technicap PPS 5 sediment traps (Goutx et al., 2000), Kiel HDW traps (Jonkers et al., 2010), large-aperture time-series Kiel-type traps (Fischer et al., 2000, 2002; Iversen et al., 2010), Mark-VII automated sediment trap (CARIACO), McLane Mark 78G-21 (Jonkers et al., 2010), multisample moored conical traps (Bory et al., 2001), Parflux Mark 7G-13 time-series sediment trap (Honjo and Manganini, 1993; Jickells, 2003a, b, c, d; Lampitt et al., 2001, 2010), Aquatec Kiel-type sediment trap (Neuer et al., 1997, 2007), indented rotary sphere (IRS) settling velocity and time-series mode sediment traps (Peterson et al., 2005; Goutx et al., 2007; Lee et al., 2009a, b), SMT 234 Aquatec Meerestechnik Kiel trap (Helmke et al., 2005), surface-tethered particle interceptor traps (BATS), and PPS-5 traps (Jonkers et al., 2010). Information is sometimes insufficient to ascertain whether two models are identical. In many studies and within the various data sources, trap specifications are not described. Nevertheless, the specifications of the traps listed above are summarised briefly in Tables 3 and 4.

2.2.2 Sample collection procedure

Before deployment, the collecting cups of sediment traps are filled with ambient seawater. NaCl is typically added to increase the salinity to 40 (Antia et al., 1999;

Table 1. Data set column headers. All fluxes are reported as per day over the period of deployment. We note that only at BATS are samples collected in triplicate. Hence, other than BATS, data under the "replicate 1" and "average" headers contain the same information. Not applicable is denoted NA.

Data column	Label/Variable	Units	Description
1	ID	NA	Data point reference number.
2	Cruise/Project/Area/ STN/ Trap	NA	Cruise reference number or name, name of data, originating project, area where data was collected from, station, trap ID (depending on available information).
3	yyyymmdd1	NA	Date in the format year month day of sediment-trap deployment.
4	yyyymmdd2	NA	Date in the format year month day of sediment-trap recovery.
5	Duration	Days	Duration of sediment-trap deployment.
6	Lat	° N	Decimal latitude of sediment-trap deployment.
7	Long	° E	Decimal longitude of sediment-trap deployment.
8	Depth	m	Depth of sediment-trap deployment.
9	Samp_id1	NA	Sample/cup ID replicate 1.
10	Samp_id2	NA	Sample/cup ID replicate 2 (if available).
11	Samp_id3	NA	Sample/cup ID replicate 3 (if available).
12	Tot_Mass1	$mg\,m^{-2}\,d^{-1}$	Total mass flux replicate 1.
13	Tot_Mass2	$mg\,m^{-2}\,d^{-1}$	Total mass flux replicate 2 (if available).
14	Tot_Mass3	$mg\,m^{-2}\,d^{-1}$	Total mass flux replicate 3 (if available).
15	Tot_Mass_av	$mg\,m^{-2}\,d^{-1}$	Total mass flux average.
16	Tot_Mass_stdev	$mg\,m^{-2}\,d^{-1}$	Total mass standard deviation.
17	POC_1	$mg\,m^{-2}\,d^{-1}$	Particulate organic carbon flux replicate 1.
18	POC_2	$mg\,m^{-2}\,d^{-1}$	Particulate organic carbon flux replicate 2 (if available).
19	POC_3	$mg\,m^{-2}\,d^{-1}$	Particulate organic carbon flux replicate 3 (if available).
20	POC_Av	$mg\,m^{-2}\,d^{-1}$	Particulate organic carbon flux average.
21	POC_stdev	$mg\,m^{-2}\,d^{-1}$	Particulate organic carbon flux standard deviation.
22	PON_1	$mg\,m^{-2}\,d^{-1}$	Particulate organic nitrogen flux replicate 1.
23	PON_2	$mg\,m^{-2}\,d^{-1}$	Particulate organic nitrogen flux replicate 2 (if available).
24	PON_3	$mg\,m^{-2}\,d^{-1}$	Particulate organic nitrogen flux replicate 3 (if available).
25	PON_Av	$mg\,m^{-2}\,d^{-1}$	Particulate organic nitrogen flux average.
26	PON_stdev	$mg\,m^{-2}\,d^{-1}$	Particulate organic nitrogen flux standard deviation.
27	$bSiO_2$	$mg\,m^{-2}\,d^{-1}$	Biogenic silica flux average.
28	$bSiO_2$_stdev	$mg\,m^{-2}\,d^{-1}$	Biogenic silica flux standard deviation.
29	$bSiO_2$_Flag	NA	This flag indicates whether $bSiO_2$ was corrected or not for dissolution of the particular fraction in the sample collecting cups of traps (see Sect. 2.2.6).
30	Mol mass ratio silica to silicon	NA	Molecular mass ratio of silica to silicon used to scale Si to SiO_2 (see Sect. 2.2.6).
31	$CaCO_3$	$mg\,m^{-2}\,d^{-1}$	Calcium carbonate flux average.
32	$CaCO_3$_stdev	$mg\,m^{-2}\,d^{-1}$	Calcium carbonate flux standard deviation.
33	Terr/Litho	$mg\,m^{-2}\,d^{-1}$	Terrigenous or lithogenic (as reported) material flux average.
34	Terr_stdev	$mg\,m^{-2}\,d^{-1}$	Terrigenous or lithogenic material flux standard deviation.
35	PIC	$mg\,m^{-2}\,d^{-1}$	Particulate inorganic carbon flux average.
36	PIC_stdev	$mg\,m^{-2}\,d^{-1}$	Particulate inorganic carbon flux standard deviation.
37	Institution	NA	Affiliation institution of main author and/or data originator (when available).
38	Trap_Type	NA	Sediment-trap type and/or characteristics as described in the source study or data set.
39	Data source	NA	Link to data source and/or data source information.
40	doi	NA	Digital object identifier, as generated by PANGAEA®.
41	Event	NA	Event ID, as recorded by PANGAEA®.
42	Notes	NA	Notes.
43	WOA09_Temp	°C	Temperature from World Ocean Atlas 2009 (WOA09) Climatology.
44	WOA09_Sal	NA	Salinity from WOA09.
45	WOA09_DO	$\mu mol\,L^{-1}$	Dissolved oxygen concentration from WOA09.
46	WOA09_O_{2SAT}	%	Oxygen saturation from WOA09.
47	WOA09_AOU	$\mu mol\,L^{-1}$	Apparent oxygen utilisation from WOA09
48	WOA09_NO_3^-	$\mu mol\,L^{-1}$	Nitrate concentration from WOA09.
49	WOA09_$Si(OH)_4$	$\mu mol\,L^{-1}$	Silicate concentration from WOA09.
50	WOA09_PO_4^{3-}	$\mu mol\,L^{-1}$	Phosphate concentration from WOA09.

Table 2. Sinking material flux range, depth range distribution and number of data points available.

Variable	Number of data points	Range mg m^{-2} d^{-1}		Depth range m	
		Min.	Max.	Min.	Max.
Total mass flux	4735	0.0	5584	15	5031
POC flux	5202	0.0	355.7	15	5031
PON flux	3996	0.0	57.9	20	5031
$bSiO_2$ flux	2895	0.0	590.5	117	5031
PIC flux	1048	0.04	81.4	117	4832
$CaCO_3$ flux	2631	0.0	2505.7	117	5031
Terr/Litho flux	2166	0.0	4528.8	117	5031

Bory and Newton, 2000; Fischer et al., 2002; Fahl and Nöthig, 2007; Neuer et al., 1997). Sufficient formalin to yield 2–3 % formaldehyde (wt/vol) or mercuric chloride (0.14 % final solution) is commonly added to poison the sample to preserve the content (Antia et al., 1999; Fischer et al., 2002; Fahl and Nöthig, 2007; Helmke et al., 2005; Bauerfeind et al., 2009). Following recovery of sediment traps, swimmers (i.e. zooplankton that feed on sedimenting material) are identified and removed from collecting cups (Antia et al., 1999; Bory et al., 2001; Lampitt et al., 2010). Sometimes the samples are sieved (1 mm mesh) to remove large swimmers (e.g. Fischer et al., 2000). Also, samples are sometimes centrifuged following the removal of swimmers and the supernatant is then analysed in order to take into account of any possible dissolution of the material collected (e.g. Waniek et al., 2005). Samples from trap cups are typically split to generate subsamples for the different types of analysis and filtered through preweighed filters which are rinsed with ammonium formate to remove salt and excess formalin (e.g. Bory et al., 2001). The reader is referred to the source references for details of a particular deployment.

2.2.3 Total mass flux

Total mass is obtained by weighing the dried matter collected on a filter. As such, it is sometimes referred to as "dry mass". Total mass flux (Tot_Mass$_{\text{flux}}$, mg m^{-2} d^{-1}) is calculated as Tot_Mass$_{\text{flux}} = \frac{M_w - F_w}{T \cdot A}$, where M_w is the mass dry weight (mg), F_w is the filter weight (mg), T is the deployment time (days), and A is the aperture trap area (m^2) (e.g. Bahr et al., 1997).

2.2.4 POC and PON fluxes

POC and PON are measured using an elemental CHN analyser (e.g. Fischer et al., 2000; Bahr et al., 1997). The fraction of C and N in a given sample is multiplied by Tot_Mass flux to yield POC and PON fluxes (mg m^{-2} d^{-1}). Aliquots destined for the determination of POC and PON are filtered onto combusted (6 h 400 °C GF/F) filters (e.g. Goutx et al., 2000), or polycarbonate filters (25 or 47 mm) (e.g. Hwang et al., 2009). Before drying for CHN analysis, samples are rinsed with 1–6 N HCl to remove carbonate (Fischer et al., 2000; Goutx et al., 2000; Bory et al., 2001; Helmke et al., 2005; Iversen et al., 2010). Filters are then dried. Reported drying temperatures vary, but typically, filters are oven dried at 40 °C (e.g. Goutx et al., 2000), air-dried at 60 °C overnight (e.g. Hwang et al., 2009), or dried on a hot plate set at 80 °C (e.g. Wefer and Fischer, 1993; Helmke et al., 2005). Some authors use freeze drying instead (e.g. Fischer et al., 2002; Waniek et al., 2005).

As a term, POC is frequently used interchangeably with "organic carbon (C_{org})" (e.g. Fischer et al., 1996; Lampitt et al., 2001) or total organic carbon (Wefer and Fischer, 1991; Jonkers et al., 2010). POC, is sometimes estimated as $C_{org} = C_{total} - C_{CaCO_3}$ (e.g. Romero et al., 2002), where C_{total} is the total carbon content of a sample and C_{CaCO_3} is the carbon content in calcium carbonate. Similarly, PON is sometimes referred to as total nitrogen (e.g. Lampitt and Antia, 1997; Jonkers et al., 2010). We suggest POC and PON are the most appropriate terms by reasons of method and most common usage in literature.

2.2.5 Calcium carbonate flux and particulate inorganic Carbon (PIC) flux

$CaCO_3$ and PIC fluxes are typically derived based on molar mass ratios. $CaCO_3$ has been estimated by multiplying PIC by 8.34 (Lampitt et al., 2010) or by 8.33 (Lampitt et al., 2001; Fischer et al., 2002); i.e. $\frac{CaCO_3}{C} \approx 8.33$ (though this is not usually explicitly stated). It has also been calculated as $(C_{total} - C_{org}) \times 8.33$ (e.g. Wefer and Fischer, 1991; Helmke et al., 2005) following CHN analysis; that is, PIC $\times \frac{CaCO_3}{C}$. It has been also determined through mass loss following acidification and then weighing (e.g. Fahl and Nöthig, 2007). Hwang et al. (2009) refer to "biogenic $CaCO_3$", which they estimated by multiplying the "biogenic Ca" by 2.5; i.e. the molar mass ratio $\frac{CaCO_3}{Ca}$. In turn, they obtained "biogenic Ca" as the difference between total Ca and lithogenic Ca. The latter being $0.5 \times$ Al, based on the ratio of Ca to Al of the average continental crust composition (e.g. Wedepohl, 1995; Rudnick and Gao, 2003). Total inorganic carbon is determined by coulometric titration (Hwang et al., 2009). $CaCO_3$ flux is sometimes corrected if organisms containing calcium carbonate, such as pteropods, are present in the sample (e.g. Bauerfeind et al., 2009).

PIC has been calculated as 12 % carbonate by weight (Antia et al., 1999; Bauerfeind et al., 2009), i.e. the C content in $CaCO_3$. PIC content has also been calculated from total Ca concentrations in samples as $CaCO_3$ (Bory et al., 2001). It is also estimated as $C_{total} - C_{org}$; i.e. the difference between the C measured in filtered samples without removal of carbonate, and the C measured in samples treated with HCl. The term "inorganic carbon" as equivalent of PIC is sometimes used

Table 3. Sediment-trap specifications summary.

Trap type	Type of deployment	General specifications	Further information	Used by
Kiel type	Bottom tethered	Fiberglass-reinforced plastic baffle, funnel and frame. Baffle consists of 20 mm × 20 mm × 120 mm cells. 0.5 m^2 aperture, cone with a 34° angle. Bottom of funnel mounted into a PTFE (polytetrafluoroethylene) transfer cylinder. Rotary sampler with 21 collecting bottles.	Zeitzschel et al. (1978) Kremling et al. (1996)	Antia et al. (1999), Bauerfeind and Nöthig (2011) Bauerfeind et al. (2009) Fischer (2005, 2003a, b, c, d) Fischer et al. (2002, 2000) Iversen et al. (2010) Jonkers et al. (2010) Neuer et al. (1997, 2007) Peinert et al. (2001) Raab (2003) von Bodungen et al. (1995) Waniek et al. (2005) Žarić et al. (2005)
Parflux Mark V Parflux Mark VI Parflux Mark 78	Bottom tethered	1.15 m^2 aperture. 520 baffle 52 mm diameter cells with a 2.5 aspect ratio. 36° cone angle. Rotary sampler with 12, 13 or 25 sample cups. 0.5 m^2 aperture. 368 baffle 25 mm 42° cone angle. Rotary sampler with 13 sample cups. 0.5 m^2 aperture. 268 baffle 25 mm diameter cells with a 2.5 aspect ratio. 41° cone angle. Rotary sampler with 21 or 13 wide sample cups.	Honjo and Doherty (1988) Newton et al. (1994) www.mclanelabs.com	Bory et al. (2001) CARIACO time series Fischer (2005, 2003a, b, c, d) Fischer et al. (2002, 2000) Honjo and Manganini (1993) Hwang et al. (2009) Jickells et al. (1996) Jonkers et al. (2010) Lampitt and Antia (1997) Lampitt et al. (2001, 2010) Wefer and Fischer (1991) Žarić et al. (2005)
SMT 230 SMT 234	Bottom tethered	0.5 m^2 aperture. 41 sample cups. 0.5 m^2 aperture. 21 sample cups. Both with a 34° cone angle.	www.kum-kiel.de Helmke et al. (2010)	Fahl and Nöthig (2007) Helmke et al. (2005) Romero et al. (2002) Wefer and Fischer (1991)
Technicap PPS 3 Technicap PPS 5	Bottom Bottom and surface* tethered	0.125 m^2 aperture, cylindro-conical collector with a 2.5 aspect ratio (unbaffled). 1 m^2 aperture, 8 mm baffle cell diameter. Made of Fibreglass.	www.technicap.com Miquel et al. (2011)	Goutx et al. (2000)* Jonkers et al. (2010) DYFAMED time series
Indented Rotary Sphere; IRS	Surface tethered	It consists of a 15 cm diameter cylindrical particle interceptor. An indented rotating sphere valve about halfway down the 1.7 m total length of the trap, which leads to a skewed funnel delivering collected particles to a sample carrousel. The trap can be set to time series (TS) or settling velocities (SV) mode.	Peterson et al. (2005, 2009)	Lee et al. (2009b)

in the literature too (e.g. Lampitt and Antia, 1997; Lampitt et al., 2001).

2.2.6 Biogenic silica flux

Biogenic silica requires more care relative to other variables. This derives from the fact that multiple names and terms are used rather ambiguously. For this compilation we attempted, to the best of our knowledge, to identify the variable that was being dealt with in each instance. We based our evaluation on the methods used and in some cases by contacting originating PIs.

Biogenic silica is typically measured as dissolved silicon with colorimetric methods following extraction from particulate material. Several methods exists (e.g. Eggimann et al., 1980; DeMaster, 1981; Mortlock and Froelich, 1989; Müller and Schneider, 1993), but the methods most commonly used are based on an the alkaline digestion method of Mortlock and Froelich (1989) (e.g. Antia et al., 1999; Bory et al., 2001; Salter et al., 2010) or the sequential leaching method of DeMaster (1981) as modified by Müller and Schneider (1993) (e.g. Wefer and Fischer, 1991, 1993; Romero et al., 2002; Helmke et al., 2005). The former is based on the extraction of opaline silicon into a 2 M solution of Na_2CO_3 at 85 °C for 5 h, after which the digested sample is measured with

Table 4. Sediment-trap specifications summary.

Trap type	Type of deployment	General specifications	Further information	Used by
Particle interceptor traps (PIT)	Surface tethered	Polycarbonate cylinder, 0.0039 m^2 aperture. Plastic baffling consists of circular openings of 1.2 cm diameter. The base holds a 90 mm Poretics polycarbonate membrane filter. The trap frame holds up 15 cylinders.	Bahr et al. (1997)	BATS
Surface tethered traps	Surface tethered	480 mm cylinders with a 125 mm diameter, and 200 mm-long baffle. Inserted in each cylinder are four 480 mm-long, 50 mm-diameter smaller cylinders.	Neuer et al. (2007)	Neuer et al. (2007)
OSU traps	Bottom tethered	2 : 1 height : diameter fiberglass plastic cone, 1 cm × 5 cm baffle, 10 cm aperture. Oregon State University (OSU)-made traps based on Soutar et al. (1977).	Dymond and Lyle (1994)	Dymond and Lyle (2003a, b)
Unnamed trap	Bottom tethered	Small trap, 118 mm diameter cylinder 490 mm working part and baffle. Lower part is conical and connected to a sample collecting flask.	Lisitsyn et al. (1995) Stein (1999)	Shevchenko (2000)
Unnamed drifters	Surface tethered	No information available		Irwin (2002a, b) Martin (2003a, b, c) NGOFS and Tande (2003) OMEX and Wassmann (2004a, b, c, d) OMEX and Wassmann (2004e, f, g, h)
Unnamed traps	Bottom tethered	No information available		Tett (2005) Thomsen and von Bodungen (2001a, b, c)

standard photometric methods using an autoanalyser (Mortlock and Froelich, 1989). The latter is an automated method designed to extract Si from a broader range of compounds. The extraction is carried out with a 1 M solution of NaOH also at 85 °C, but the digestion solution is cycled from and to a digestion vessel; a proportion runs through an autoanalyser and another fraction is circulated back to the digestion vessel until extraction is completed (Müller and Schneider, 1993). There is an issue however, associated with the use of either method. Since the end product of the extraction is Si, this then needs to be "scaled" back to silica (SiO_2). The method by Mortlock and Froelich (1989) uses a factor of 2.4 (the molar mass ratio of $\frac{SiO_2 \cdot 0.4H_2O}{Si}$), which accounts for the average water content of diatomaceous silica. The method by Müller and Schneider (1993) instead uses the molar mass ratio of $\frac{SiO_2}{Si} \approx 2.139$. Another method used is that of Koning et al. (2002) (e.g. Jonkers et al., 2010), which is based on the method by Müller and Schneider (1993). Given the molar mass ratios adopted, and given that some data sets report biogenic Si rather than biogenic SiO_2, which we converted using the molar mass ratio of 2.1, we include a column in the data assemblage where the ratio is indicated. We did this based on whether a study or source used either of the methods above, except when a "conversion factor" was explicitly stated independently of the digestion method used. When information provided was "unclear" about the ratio used, this is pointed out.

In some cases, dissolved silica is first measured in the water used for the collecting cups. Dissolved silica is then measured again following the trap's recovery in order to correct for any opal dissolution (e.g. Jonkers et al., 2010). However, we note that not all the biogenic silica data in this compilation includes such a correction or its application to the data was not clear. We have flagged these data as follows: 0 when corrections were made, 1 when corrections were not made, and 2 when information was not available to ascertain either.

All calculations in the literature are related to the molar mass ratio of silica or its hydrated form (as above), to elemental silicon. However, the terminology used is rather inconsistent. Hwang et al. (2009) report opal as the result of multiplying "biogenic Si" by 2.4, where biogenic Si is the difference between the total Si and the lithogenic-Si (3.5 × Al, an approximation of the ratio of Si to Al in the continental crust). Bauerfeind et al. (2009) define "biogenic particulate silica (bPSi)" in their abstract, which suggests the compound "silicon dioxide" ($SiO_2 \cdot nH_2O$) is being dealt with. However, in the methods section, it is redefined as "biogenic particulate silicon (bPSi)"; hence it is the chemical

element Si that seems to be dealt with. Further, Opal is defined as $2.1 \times$ bPSI; i.e. the mass ratio ($\frac{SiO_2}{Si}$) multiplied by bPSi (Bauerfeind et al., 2009). The following terms are also commonly used in the literature: "$PSiO_2$" (von Bodungen et al., 1995; Peinert et al., 2001; Bauerfeind and Nöthig, 2011), "$PSiO_2$ and $BSiO_2$" (Fischer, 2003a), "PSi" (Fischer, 2005), "BSi" (Ragueneau et al., 2001), "$BSiO_2$" as the sum of $PSiO_2$ and $DSiO_2$ (e.g. Antia et al., 1999; Lampitt et al., 2001; Honjo and Manganini, 2003a, b, c), "$BSiO_2$" (Lampitt and Antia, 1997), "Opal" (Neuer et al., 1997, 2007), "bPSi or biogenic particulate silicon" (opal = $2.1 \times$ bPSi) (Bauerfeind et al., 2009), "opaline silica" (Lampitt et al., 2010) or "biogenic silica (opal)" (Antia et al., 1999; Fischer et al., 2002; Waniek et al., 2005).

Since the ballasting effect of the mineral SiO_2 (opal) is most germane to this database, and since the interest resides in identifying the opal related to particles of biological origin (hence the term "biogenic"), the data we report here is referred to as "biogenic silica" or "biogenic opal". When data was found to be reported as Si, these were converted to SiO_2 using the molar mass ratio $\frac{SiO_2}{Si}$. We suggest the use of lower-case "b" to refer to "biogenic" in combination with the chemical formula SiO_2 (i.e. $bSiO_2$), since upper-case B is the chemical symbol for the element Boron. We also suggest that whether samples of $bSiO_2$ are corrected for dissolution or not in the trap-collecting cups should clearly be stated in future studies.

2.2.7 Lithogenic and/or terrigenous material flux

Lithogenic fluxes are typically estimated as the difference between the total mass flux and what is termed either "biogenic flux", "biogenic matter" or "organic matter flux"; i.e. $CaCO_3 + POC + BSiO_2$ fluxes (e.g. Antia et al., 1999; Bauerfeind et al., 2009). For this purpose, in deriving "organic matter", POC is sometimes multiplied by 2 (Fischer et al., 2002; Bauerfeind et al., 2009) or 2.5 (e.g. Hwang et al., 2009), as this is considered to give a more representative flux of organic matter but, in the literature, this adjustment would benefit from a fuller explanation. Thus, biogenic flux (Bio_{flux}) is $Bio_{flux} = 2 \times POC_{flux} + CaCO_{3flux} + Opal_{flux}$. Lithogenic flux (Litho) is given by $Litho = Tot\_Mass_{flux} - Bio_{Flux}$. Some researchers estimate the lithogenic material from Al concentrations, under the assumption it contains 8.4 % Al (Bory et al., 2001) or by multiplying the Al concentration by 12.15 (e.g. Hwang et al., 2009). The latter is based on the assumption of a crustal Al composition of 8.2 % (1/12.15 = 0.082).

2.3 Data standardisation

This data assemblage contains fluxes from short-duration deployments (hour–days) to longer-duration deployments lasting from months to a year, or over a year. Hence, in order to standardise the data set, all values from long-term deployments, typically reported in grams per square metre per year ($g\,m^{-2}\,yr^{-1}$) (e.g. Wefer and Fischer, 1991, 1993; Fischer et al., 2000; Fischer, 2005; Peinert et al., 2001), were converted to daily values, i.e. milligrams per square metre per day ($mg\,m^{-2}\,d^{-1}$), which is the unit most commonly reported. Long-term deployments, however, can be easily identified; a column is provided which specifies the duration of the deployment. A few daily values were reported in grams per square metre per day ($g\,m^{-2}\,d^{-1}$), and these were also converted to milligrams per square metre per day ($mg\,m^{-2}\,d^{-1}$) for consistency. In a few instances, POC, PIC, and $bSiO_2$ were reported in moles per square metre per year ($mol\,m^{-2}\,yr^{-1}$) (e.g. Antia et al., 1999; Dymond and Lyle, 2003a, b; Honjo and Manganini, 2003d, e, f; Fahl and Nöthig, 2007) or millimole per square metre per day ($mmol\,m^{-2}\,d^{-1}$) (Martin, 2003a, b, c). Again, for consistency, these were converted to milligrams per square metre per day ($mg\,m^{-2}\,d^{-1}$) using the appropriate molecular masses and or molecular mass ratios as required. A column of notes is included, and where unit conversions were done, these are pointed out.

3 Quality control

Given that the data compiled here derives from research already published, we assume that the originating authors have already undertaken steps necessary to assure data quality. We point out however, that attention should be paid to the fact that the use of slightly different "conversion factors" for a given variable inherently adds error to the data, with up to 20 % in the case of lithogenic flux when derived as the difference between total mass flux and "organic matter" flux, and where "organic matter" is calculated using conversion factors of 2 or 2.5 (Sect. 2.2.7). In the case of $bSiO_2$, the error generated is ~12 % , resulting from the use of 2.1, 2.139 or 2.4 when estimated from Si (Sect. 2.2.6). We did not attempt to "harmonise" the data by using a unique factor for a given variable, since this would involve modifying the data from that found in the original sources. However, in the light of the different deployment durations and traps used, different analytical methods employed, different calculation approaches and different units reported, here we have tried, as best as possible, to put the data together in a manner allowing users to trace original data sources for further scrutiny and so that users can decide how to handle the data further for the specific questions they may choose to tackle.

4 Ancillary data

Where possible, data from the World Ocean Atlas 2009 (WOA09) were extracted to coincide with flux data to provide additional environmental information (http://www.nodc.noaa.gov/OC5/WOA09/pr_woa09.html). Specifically, data were extracted for temperature, salinity, oxygen (concentration, AOU and percentage saturation), nitrate, phosphate and silicate. The extraction involves linear

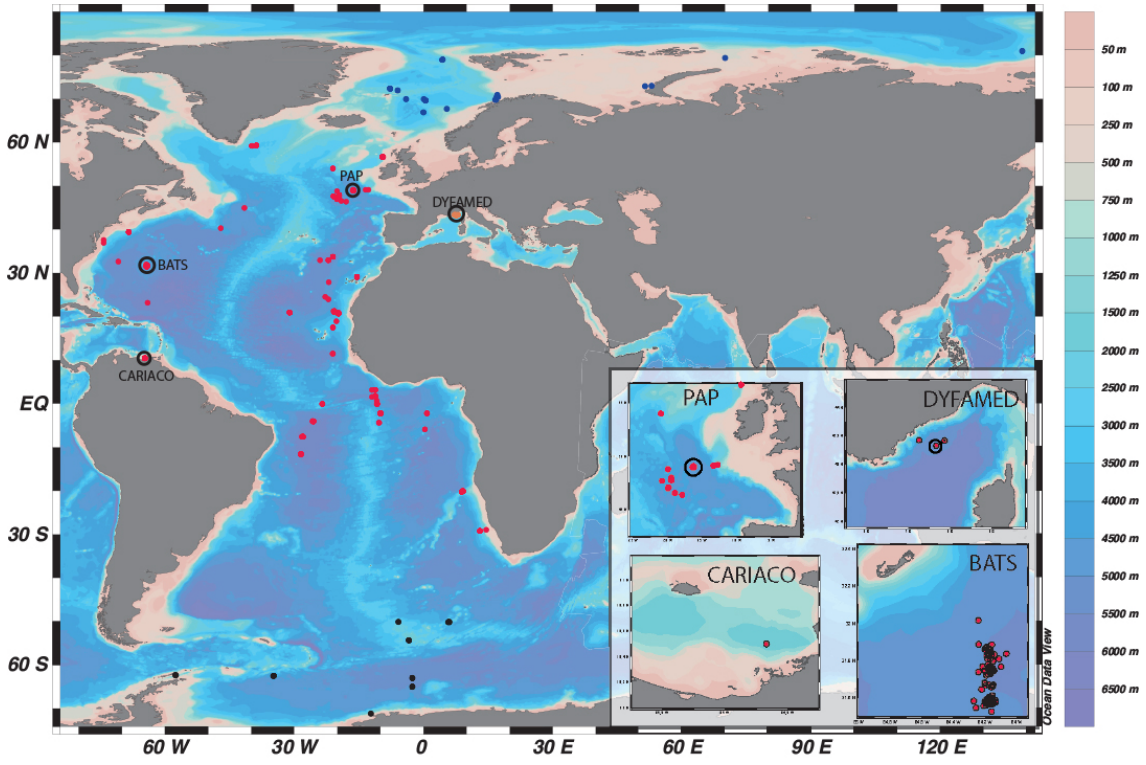

Figure 1. Map showing the location of sediment-trap deployments. Inset figures show expanded maps of regions where the CARIACO, BATS, PAP and DYFAMED time series are located. Locations are colour-coded per ocean domain: Atlantic (red dots), Mediterranean (orange dots), Arctic (blue dots), and Southern Ocean (black dots).

interpolation of WOA09 data to the latitude, longitude and depth of the flux data. Each environmental variable is a weighted average over the period of deployment. Note that as WOA09 is a climatology it cannot provide data for specific years. For example, if a mooring collected flux data from 1 November 1990 until 15 January 1991, the WOA data at the relevant point is averaged over the 76 days comprising the annual climatologies for November (for 30 days), December (for 31 days) and January (15 days). For temperature, salinity and oxygen variables, monthly climatologies are used above 1500 m and annual ones below. For nutrients, monthly climatologies are only available and used above 500 m. The distribution of WOA09 climatologies does not extend close to the coasts. Hence, given the proximity of the CARIACO time-series station to the mainland, ancillary data is not available for this site from WOA09.

5 Data distribution

Figure 1 shows the distribution of the sediment-trap deployments compiled in this data set. Data coverage spans from 1982 to 2011, with the largest amount of observations between 1990 and 2010 (Fig. 2). Figure 3 shows a map with the number of data points available on a $5° \times 5°$ grid. The most abundant contributions to this data set derive from established time-series stations: BATS (31°40′ N, 64°10′ W) 784 data points, 13.2 %; CARIACO (10.5° N, 64.4° W) 1755 data points, 29.5 %; DYnamique des Flux Atmosphériques en MEDiterranée et leur évolution dans la colonne deau (DYFAMED) 43°25′ N, 07°52′ E, 401 data points, 6.7 % of total (Miquel et al., 2011); the Porcupine Abyssal plain (PAP), 49° N, 16°30° W, 366 data points, 6.2 % of total (Lampitt et al., 2001, 2010); the North Atlantic Bloom Experiment (NABE), from 34° N, 21° W to 48° N, 21° W, 170 data points, 2.9 % of total (Honjo and Manganini, 1993; Martin, 2003a, b, c); and the European Station for Time series in the OCean (ESTOC), 29° N, 15.5° W, 124 data points, 2.1 % of total (Neuer et al., 1997). Missing in this compilation are data from the Progamme Océan Multidisciplinaire Méso Echelle (POMME, 30–60° N, 0–30° W), which are not yet publicly available. We are also aware of a few more recent data sets from the ESTOC, but these have copyright restrictions (e.g. Neuer et al., 2007).

Observation depths span from 15 down to 5031 m (Table 2). Tot_Mass, $CaCO_3$ and Terr/Litho exhibit the broadest range of export fluxes (0.0–5585 and 0.0–4529 mg m^2 d^{-1}, respectively), while PON and PIC exhibit the narrowest range (0.0–57.9 and 0.04–81.4 mg m^2 d^{-1}). The largest number of observations, with higher vertical resolution, have been made within the first 1000 m of the water column,

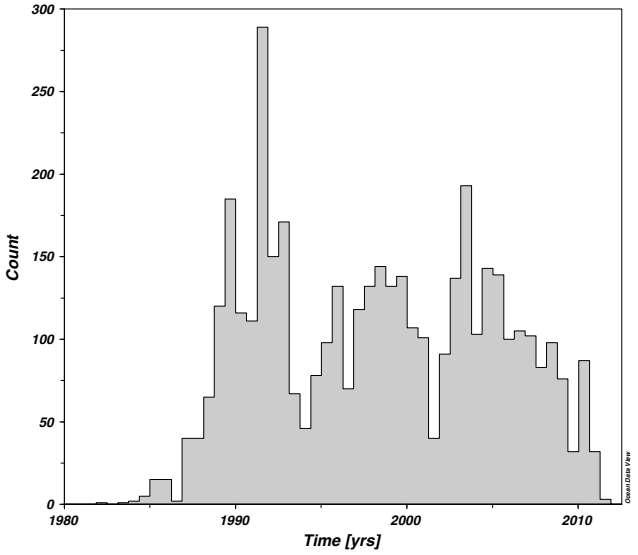

Figure 2. Data–time distribution histogram.

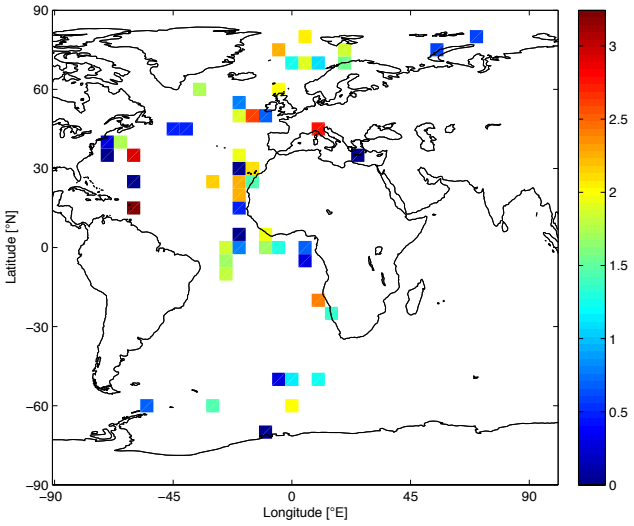

Figure 3. Map showing number of data points on a $5° \times 5°$ grid ($\log_{10}$-scale colour-code).

particularly in the upper 500 m (Fig. 4). At depths greater than 1000 m a preference for sampling at 3000 m is apparent in the data. With the exception of the PIC flux and lithogenic/terrigenous flux, which contain the lowest number of data points (Table 2), all other variables of particle export have been sampled at a similar vertical resolution (Fig. 4).

The overall pattern of particle export fluxes show the expected decrease from upper layers to depth as sinking particles decay and dissolve (Fig. 5). This is particularly clear in the Atlantic Ocean and Mediterranean Sea data (red and orange symbols in Fig. 5). POC, PON, $bSiO_2$ and $CaCO_3$ show a similar vertical structure, with the range of values at a given depth decreasing from surface to depth: from up to 550 mg m^2 d^{-1} POC and 58 mg m^2 d^{-1} PON at 30 m, up to 478 mg^2 d^{-1} $bSiO_2$ at 225 m, and 25 000 mg^2 d^{-1} $CaCO_3$ at 152 m, down to 0–6.5 mg^2 d^{-1} POC at ~ 5000 m, and up to 1.4 mg^2 d^{-1} PON, up to 27 mg^2 d^{-1} $bSiO_2$ and up to 15 mg^2 d^{-1} $CaCO_3$ at ~ 4700 m.

In the upper 1000 m, the largest fluxes of POC and PON occur in the Atlantic and the Arctic domains. Within the Arctic domain, the broad range of POC and PON fluxes in the upper 200 m derive from trap deployments off the northwest coast of Norway (~ 17° E, ~ 70° N). The largest fluxes of $bSiO_2$ in the upper 1000 m are found in the Atlantic and Southern Ocean domains. PIC fluxes are largest in the Atlantic and the Mediterranean Sea. In the Atlantic, PIC data show maximum values at 1400 m, which then decrease at greater depths (Fig. 5). These maximum values at 1400 m, though, derive from trap deployments north of Ireland and may result from the supply of PIC from the shelf or shelf-break front. $CaCO_3$ fluxes are rather comparable among ocean domains, though a larger range is found at about 150 m in the Atlantic. Terr/Litho fluxes show a broad range of values within the upper 1250 m which reduce substantially at greater depths.

The proportion each export variable makes to total mass flux is shown in Fig. 6. The largest contributions of up to 80 % are provided by the Terr/Litho, $CaCO_3$ and $bSiO_2$ fractions but there is a broad range in the contribution each fraction makes to the total mass flux at all sampled depths and within the four ocean domains. In the case of $CaCO_3$ and Terr/Litho the range in the contribution from these fractions to total mass flux appears to narrow with depth which may reflect the attenuation of other variables with depth rather than any systematic change to Terr/Litho and $CaCO_3$ contributions. The largest contribution (up to 90 %) made by $bSiO_2$ to total mass flux derive from trap deployments in the Southern Ocean with apparent peaks at depths of 500 and 4500 m; elsewhere the $bSiO_2$ contribution is smaller but nevertheless a major component of the downward particle flux. The contribution made by POC to total mass flux is broadly similar within all four ocean domains and decreases from ~ 80 % in the upper 500 m to < 20 % at 5000 m revealing a marked attenuation with depth. Both PON and PIC typically contribute < 20 % to total mass flux, but, whilst the contribution from PIC remains fairly constant with depth, there is vertical attenuation of PON with depth such that at depths > 500 m the PON contribution is < 10 %.

6 Conclusions

We have assembled a data set of over 5900 data points of particle flux across the wider Atlantic Ocean and adjacent seas, which will be invaluable in determining seasonal and geographical variability in the biological carbon pump. Our initial examination of this data set already indicates important

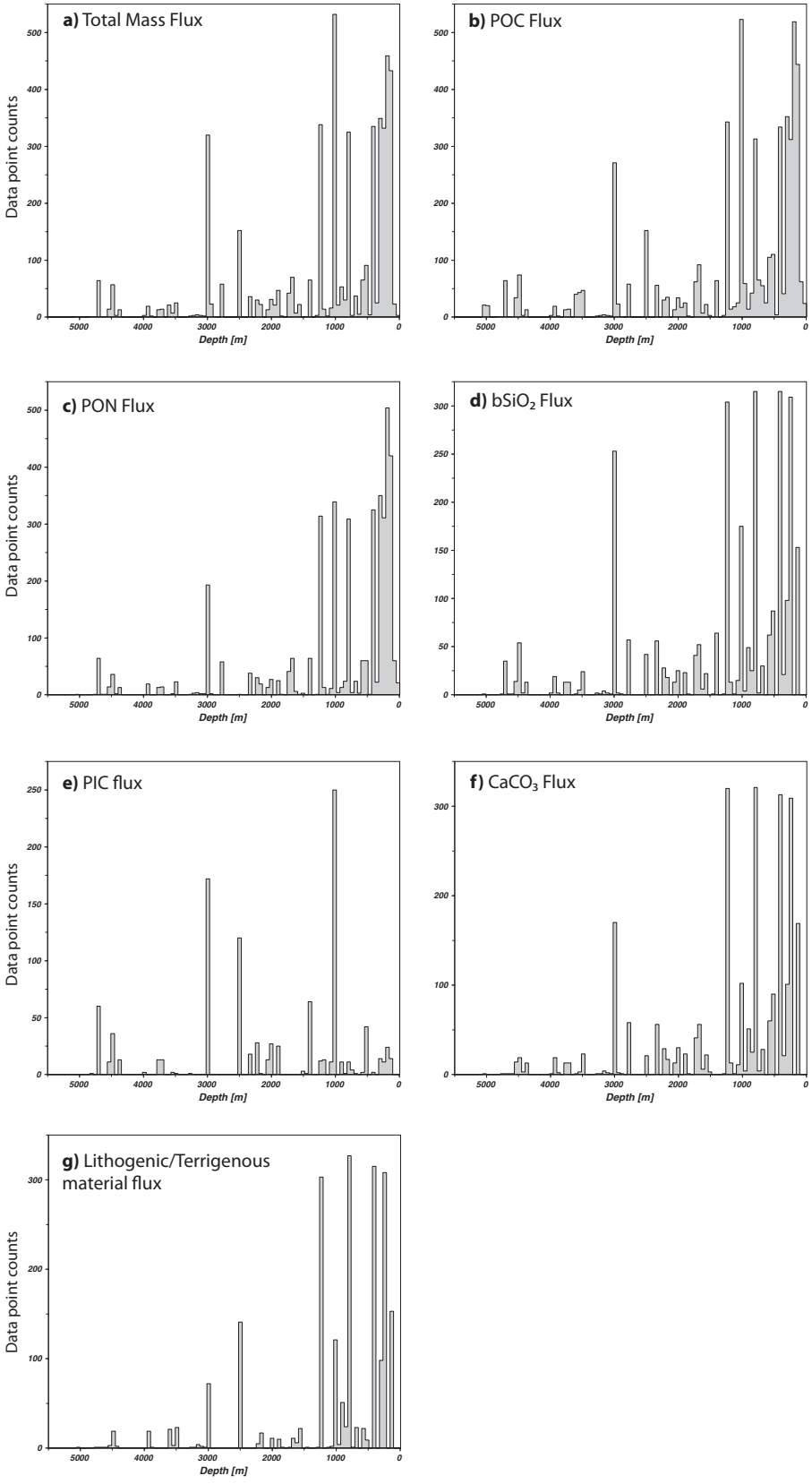

Figure 4. Data points available per depth; **(a)** total mass flux, **(b)** POC flux, **(c)** PON flux, **(d)** $bSiO_2$ flux, **(e)** PIC flux, **(f)** $CaCO_3$ flux, and **(g)** lithogenic/terrigenous material flux.

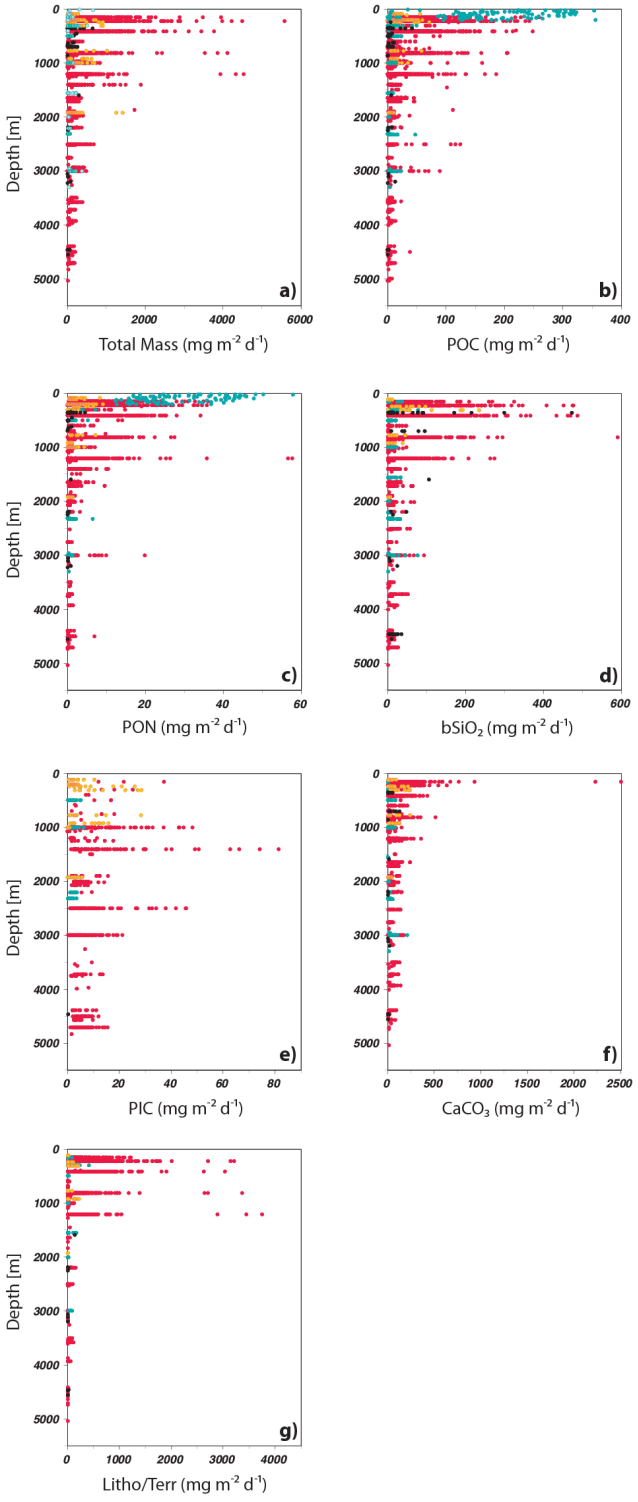

Figure 5. Downward fluxes plotted against depth; **(a)** total mass, **(b)** POC, **(c)** PON, **(d)** $bSiO_2$, **(e)** PIC, **(f)** $CaCO_3$, and **(g)** Litho/Terr. Data points are colour-coded per ocean domain: Atlantic (red dots), Mediterranean (orange dots), Arctic (blue dots), and Southern Ocean (black dots).

differences in the flux estimates between ocean domains and in the contribution particular flux variables make to the total mass flux, which may in turn indicate important differences in the strength of the BCP due to local environmental- and ecosystem-level forcing. Exploring the reasons for such differences remains a major scientific and societal problem particularly given projected changes to the future ocean and this data set will help in this endeavour. This data set has been submitted to the data repository PANGAEA® (http://www.pangaea.de), where it has been made available under doi:10.1594/PANGAEA.807946.

7 List of compiled data sets

Here we list all individual data sets. PANGAEA® digital object identifiers are also given.

– Antia, Avan N (2003): Particle fluxes of L2-B-92_trap. doi:10.1594/PANGAEA.92747

– Antia, Avan N (2003): Particle fluxes of OMEX2_trap. doi:10.1594/PANGAEA.92749

– Antia, Avan N (2003): Particle fluxes of OMEX3_trap. doi:10.1594/PANGAEA.92748

– Antia, Avan N (2003): Particle fluxes of SEEP-7_trap. doi:10.1594/PANGAEA.92746

– Antia, Avan N (2003): Particle Flux of SEEP-10_trap. doi:10.1594/PANGAEA.92745

– Bahr, Fred; Bates, Nicolas R (2013): Total flux, particulate carbon and nitrogen from surface-tethered sediment traps at time series station BATS in 1988 and 1989. doi:10.1594/PANGAEA.805543

– Bahr, Fred; Bates, Nicolas R (2013): Total flux, particulate carbon and nitrogen from surface-tethered sediment traps at time series station BATS in 1990. doi:10.1594/PANGAEA.805545

– Bahr, Fred; Bates, Nicolas R (2013): Total flux, particulate carbon and nitrogen from surface-tethered sediment traps at time series station BATS in 1991. doi:10.1594/PANGAEA.805546

– Bahr, Fred; Bates, Nicolas R (2013): Total flux, particulate carbon and nitrogen from surface-tethered sediment traps at time series station BATS in 1992.

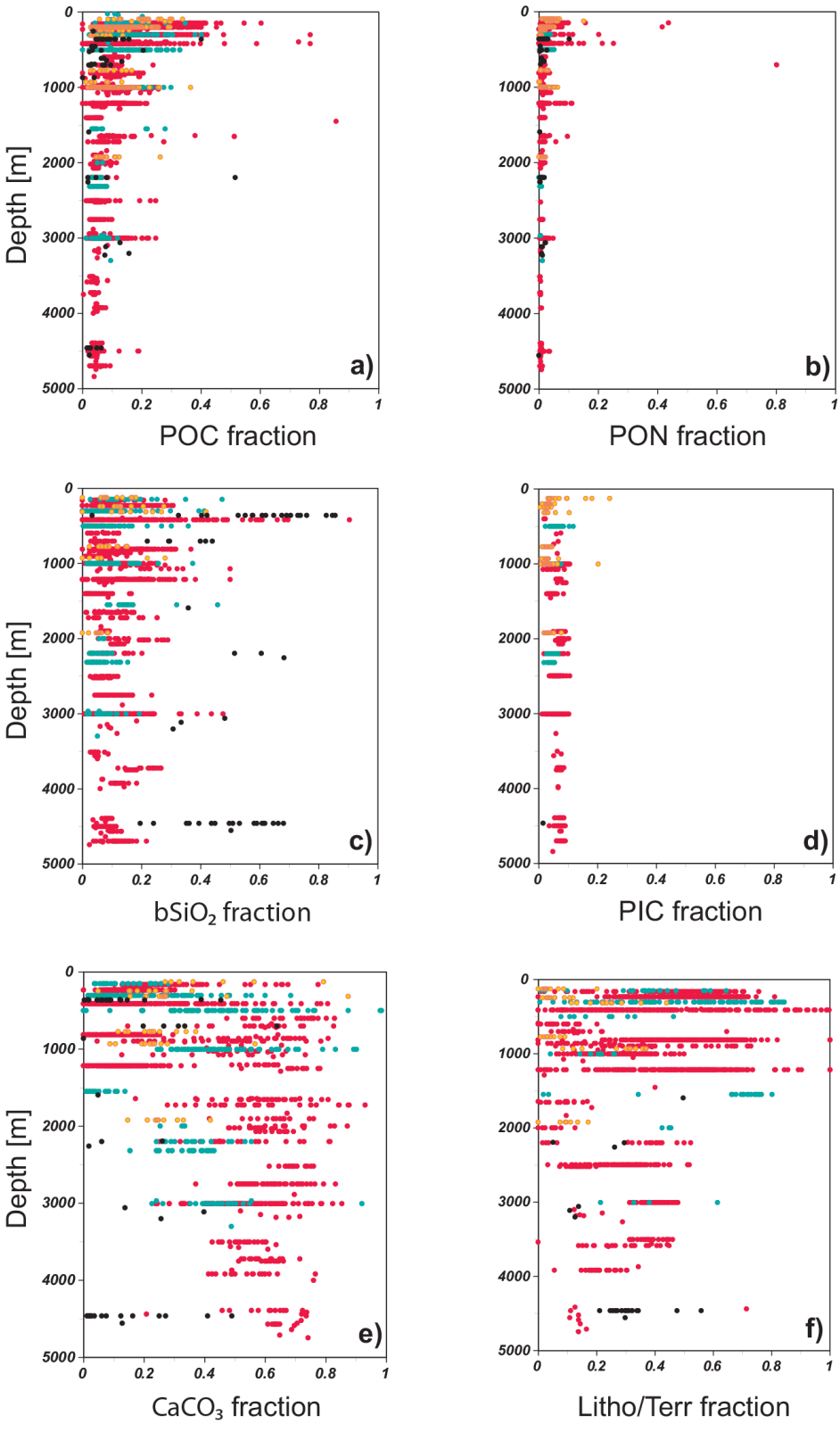

Figure 6. Fraction of POC, PON, and $bSiO_2$, PIC, $CaCO_3$ and Litho/Terr downward fluxes relative to Tot_Mass flux. Data points are colour-coded per ocean domain: Atlantic (red dots), Mediterranean (orange dots), Arctic (blue dots), and Southern Ocean (black dots). Few outliers (fraction > 1) were excluded from the graphs.

doi:10.1594/PANGAEA.805547

– Bahr, Fred; Bates, Nicolas R (2013): Total flux, particulate carbon and nitrogen from surface-tethered sediment traps at time series station BATS in 1993. doi:10.1594/PANGAEA.805548

– Bahr, Fred; Bates, Nicolas R (2013): Total flux, particulate carbon and nitrogen from surface-tethered sediment traps at time series station BATS in 1994. doi:10.1594/PANGAEA.805549

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– Bahr, Fred; Bates, Nicolas R (2013): Total flux, particulate carbon and nitrogen from surface-tethered sediment traps at time series station BATS in 1996. doi:10.1594/PANGAEA.805551

– Bahr, Fred; Bates, Nicolas R (2013): Total flux, particulate carbon and nitrogen from surface-tethered sediment traps at time series station BATS in 1997. doi:10.1594/PANGAEA.805552

– Bahr, Fred; Bates, Nicolas R (2013): Total flux, particulate carbon and nitrogen from surface-tethered sediment traps at time series station BATS in 1998. doi:10.1594/PANGAEA.805553

– Bahr, Fred; Bates, Nicolas R (2013): Total flux, particulate carbon and nitrogen from surface-tethered sediment traps at time series station BATS in 1999. doi:10.1594/PANGAEA.805554

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– Bahr, Fred; Bates, Nicolas R (2013): Total flux, particulate carbon and nitrogen from surface-tethered sediment traps at time series station BATS in 2003. doi:10.1594/PANGAEA.805559

– Bahr, Fred; Bates, Nicolas R (2013): Total flux, particulate carbon and nitrogen from surface-tethered sediment traps at time series station BATS in 2004. doi:10.1594/PANGAEA.805560

– Bahr, Fred; Bates, Nicolas R (2013): Total flux, particulate carbon and nitrogen from surface-tethered sediment traps at time series station BATS in 2005. doi:10.1594/PANGAEA.805561

– Bahr, Fred; Bates, Nicolas R (2013): Total flux, particulate carbon and nitrogen from surface-tethered sediment traps at time series station BATS in 2006. doi:10.1594/PANGAEA.805562

– Bahr, Fred; Bates, Nicolas R (2013): Total flux, particulate carbon and nitrogen from surface-tethered sediment traps at time series station BATS in 2007. doi:10.1594/PANGAEA.805563

– Bahr, Fred; Bates, Nicolas R (2013): Total flux, particulate carbon and nitrogen from surface-tethered sediment traps at time series station BATS in 2008. doi:10.1594/PANGAEA.805564

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– Bahr, Fred; Bates, Nicolas R (2013): Total flux, particulate carbon and nitrogen from surface-tethered sediment traps at time series station BATS in 2010. doi:10.1594/PANGAEA.805566

– Bahr, Fred; Bates, Nicolas R (2013): Total flux, particulate carbon and nitrogen from surface-tethered sediment traps at time series station BATS in 2011. doi:10.1594/PANGAEA.805567

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Acknowledgements. Funding was provided by the European Commission FP7 EURO-BASIN (European Basin-Scale Analysis, Synthesis, and Integration; grant agreement 264 933EU). Additional support was provided by the National Environment Research Council (UK) national capability funds. The authors are grateful to Cindy Lee, Susanne Neuer, Richard Lampitt and Eduard Bauerfeind for the provision of additional data to that already publicly available. We are also grateful to Ian Salter for useful comments on an earlier version of this manuscript, and to two anonymous reviewers for their comments, suggestions and criticism, which helped improve this manuscript. Most figures were produced using the software package ODV (Schlitzer, R., Ocean Data View, www.odv.awi.de, 2014).

Edited by: Y.-W. Luo

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