

# SCIENTIFIC DATA

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## Concentrations and ratios of particulate organic carbon, nitrogen, and phosphorus in the global ocean

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Knowledge of concentrations and elemental ratios of suspended particles are important for understanding many biogeochemical processes in the ocean. These include patterns of phytoplankton nutrient limitation as well as linkages between the cycles of carbon and nitrogen or phosphorus. To further enable studies of ocean biogeochemistry, we here present a global dataset consisting of 100,605 total measurements of particulate organic carbon, nitrogen, or phosphorus analyzed as part of 70 cruises or time-series. The data are globally distributed and represent all major ocean regions as well as different depths in the water column. The global median C:P, N:P, and C:N ratios are 163, 22, and 6.6, respectively, but the data also includes extensive variation between samples from different regions. Thus, this compilation will hopefully assist in a wide range of future studies of ocean elemental ratios.

<b>Design Type(s)</b>	observation design • time series design • data integration • biogeochemistry
<b>Measurement Type(s)</b>	atomic element profiling
<b>Technology Type(s)</b>	data collection method
<b>Factor Type(s)</b>	period
<b>Sample Characteristic(s)</b>	marine biome • Atlantic Ocean • Indian Ocean • Mediterranean Sea • Pacific Ocean • Southern Ocean

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## Background & Summary

One of the fundamental tenets of ocean biogeochemistry is the Redfield ratio. Redfield identified a similarity between the N:P ratio of plankton living in the surface ocean and that of dissolved nitrate and phosphate in the deep ocean<sup>1,2</sup>. He hypothesized that the deep ocean nutrient concentrations were controlled by the elemental requirements of the surface plankton. This concept has been extended to include other elements like carbon and remains a cornerstone for our understanding of ocean biogeochemistry. Despite the importance of this ratio, there is no obvious mechanism for a globally consistent C:N:P ratio of 106:16:1 (i.e., Redfield ratio), and there is substantial elemental variation among ocean taxa<sup>3–6</sup>. Furthermore, many small plankton are not homeostatic but instead, the cellular elemental content varies depending on growth conditions<sup>7</sup>. Thus, it has become apparent that changes in biodiversity or cell physiology can lead to variations in marine plankton elemental stoichiometry.

Variations in elemental content and ratios of marine microbial communities have multiple important implications. Broecker and Henderson have proposed that increased plankton C:N:P ratios and thus increased CO<sub>2</sub> uptake in the ocean could explain the glacial to inter-glacial variation in atmospheric CO<sub>2</sub> concentration<sup>8</sup>. Rates of N<sub>2</sub> fixation as well as competition between phytoplankton and N<sub>2</sub>-fixers are also dependent upon an assumed N:P ratio (specifically the Redfield ratio). Recently, multiple researchers have argued that our understanding (or lack thereof) of cellular elemental stoichiometry has a large influence on our ability to estimate the global ocean N budget<sup>9,10</sup>.

It has been observed that specific phytoplankton groups as well as particulate organic matter display regional differences in elemental stoichiometry<sup>11–14</sup>. For example, the C:P, N:P, and C:N ratios all appear to be above Redfield proportions in the oligotrophic gyres, near Redfield proportions in upwelling regions like the Eastern Equatorial Pacific Ocean, and below Redfield proportions in colder, nutrient rich high latitude environments<sup>11,12</sup>. The ratios may also vary between the gyres depending on the nutrient supply ratio and the resulting degree of nitrogen versus phosphorus limitation. Thus, rather than globally static C:N:P ratios, differences in environmental conditions and plankton community composition can lead to variations in the elemental composition of plankton and particulate organic material<sup>14,11–13,15</sup>. In addition, we also observe extensive variations in the ratios of particulate nutrients which cannot be explained with common physio-chemical parameters<sup>11,12</sup>. Thus, future studies are needed to identify factors causing this variation.

The elemental stoichiometry of ocean plankton communities has also been the focus in many model studies<sup>10,15–17</sup>. This includes models describing cellular elemental composition in response to changes in light intensity, nutrients, or other environment conditions<sup>16,17</sup>. Other models focus on identifying regional differences in the elemental stoichiometry<sup>15</sup>. Thus, models have indicated that the elemental stoichiometry of cells, communities, and ocean regions are not constant but vary depending on biodiversity and environmental conditions. However, we currently do not have global datasets to evaluate the output of such models.

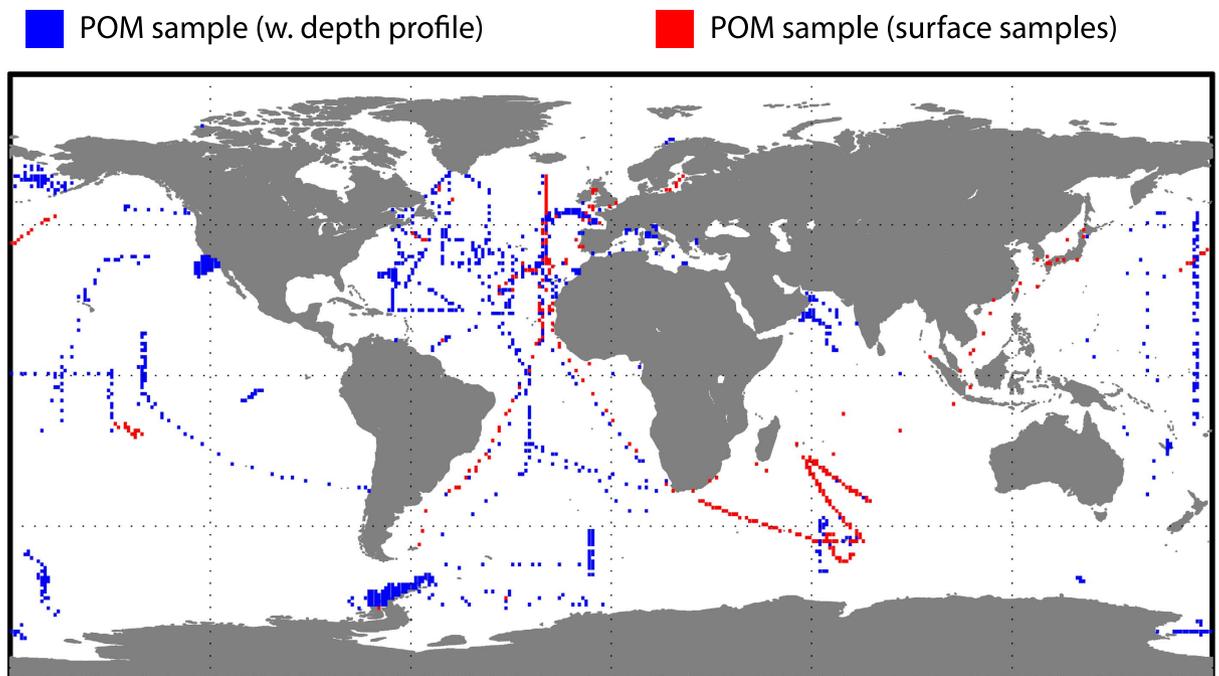
To address this issue, we here present a compilation of measurements of marine particulate organic carbon (POC), nitrogen (PON), and phosphorus (POP) from 70 cruises or time-series during the last 40 years (Table 1 (available online only))<sup>12,18–67</sup>. The dataset includes a total of 100,605 discrete measurements of particulate organic nutrients including 6940 POP, 46728 PON, and 46937 POC measurements. This leads to 5948 N:P, 5573 C:P, and 45476 C:N observations. Due to the common concurrent and largely automated measurements of PON and POC, these two particulate nutrients are over-represented in comparison to the sparse measurements of POP.

It is worth noting that this represents an aggregated dataset collected by many independent researchers (Table 1 (available online only)). Even though most studies utilize the same techniques and sample volumes, there are likely many small deviations in the technical approach. As a result, some care should be taken when comparing values.

The data covers 5336 unique stations from all major ocean regions (Figure 1). 89% of the samples originate from the top 200 m of the water and thus the dataset is skewed towards processes occurring in or near the euphotic zone (Figure 2a). The data is also biased towards regions of oceanographic research. This includes samples near the Palmer Station in the Southern Ocean, North Atlantic Ocean and Eastern North Pacific Ocean (including the HOT site and California Current) (Figure 2b and Figure 2c). Thus, this compilation of data identifies regions where we currently have very sparse data (e.g., the South Pacific, South Atlantic, and Eastern Indian Ocean). Overall, the median C:P, N:P, and C:N ratios are 163, 22, and 6.6, respectively, in this dataset but the data span a wide range for all three ratios (Figure 2d–f). Combined with the wide geographic extent of the data, this compilation will enable a range of analyses of elemental concentrations or ratios in particulate organic matter.

## Methods

Nearly all POC and PON measurements were done by collecting seawater particles onto glass-fibers filters (i.e., GF/F) and quantified using an combustion GC-IR based elemental analyzer<sup>68</sup>. The only exceptions were ‘EUMELI’ and ‘OLIPAC’, where PON was measured using a chemical oxidation technique<sup>38</sup>. Particulate phosphorus was quantified using the ash-hydrolysis method<sup>26,69</sup>. We operationally defined station IDs as samples taken within a 1° × 1° area on the same day<sup>11</sup>.



**Figure 1.** Global distribution of POM measurements in the dataset. A depth profile was defined as at least two unique depths from the same station.

The data was gathered by searching available databases (i.e., PANGAEA, BCO-DMO, JGOFS, and IFREMER) as well as published literature. We aggregated all available datasets in order to create the most exhaustive global description of particulate organic nutrients and thus did not exclude any specific cruises or time-series. The only data excluded were samples subjected to a prior manipulation or incubation.

### Data Records

The dataset includes the following fields for each record:

- Cruise
- Year
- Month
- Day
- Latitude (−90 to 90)
- Longitude (−180 to 180)
- Sampling depth (m)
- Particulate organic Carbon ( $\mu\text{M}$ )
- Particulate organic Nitrogen ( $\mu\text{M}$ )
- Particulate organic Phosphorus ( $\mu\text{M}$ )

#### Data Record 1

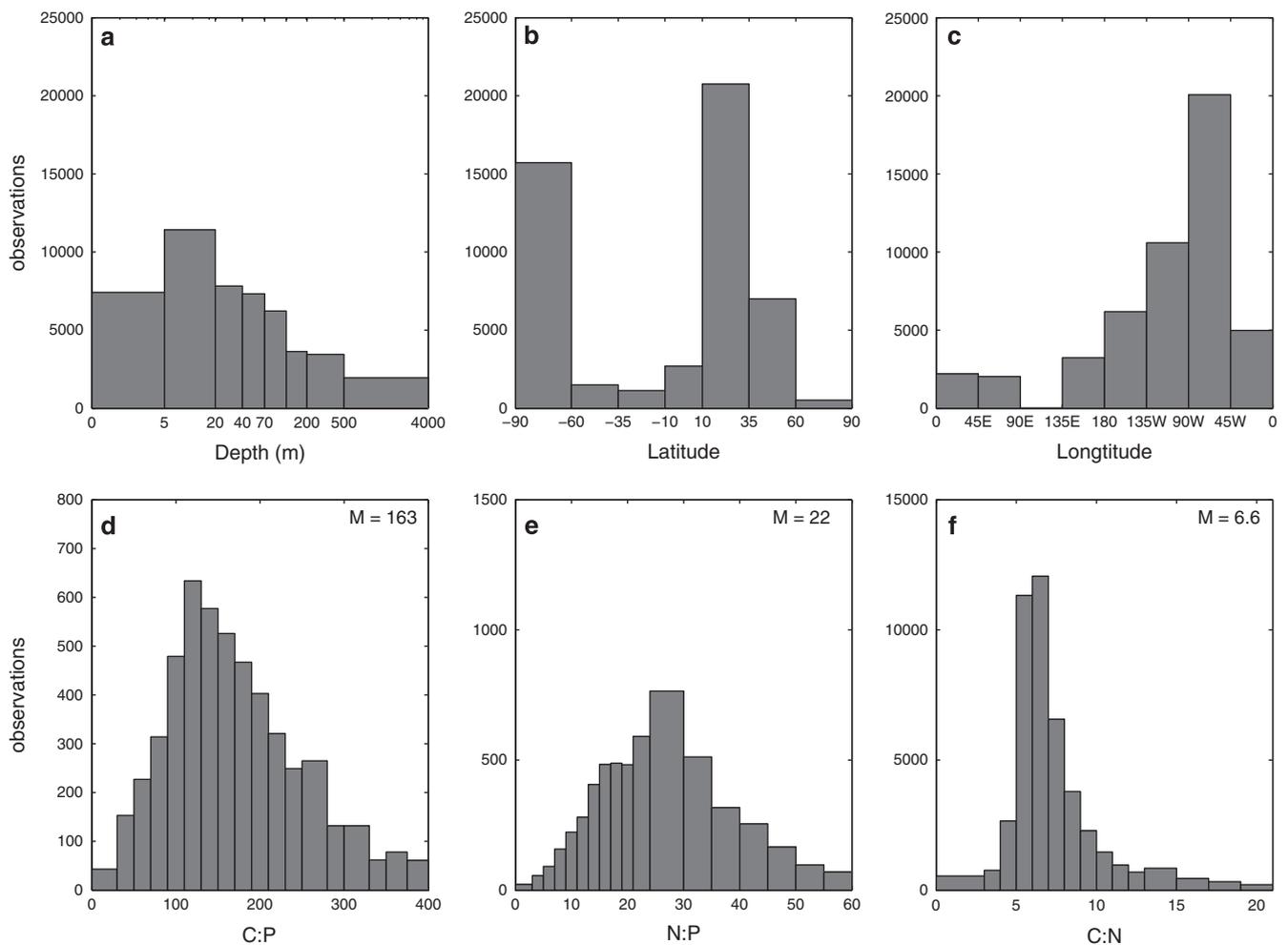
The database files (June 20, 2014 version) in csv format were uploaded to Dryad (Data Citation 1). A file containing all the fields listed above is available. ‘−9999’ denotes missing data.

#### Data Record 2

The particulate nutrient data were also uploaded to the Biological and Chemical Oceanography Data Management Office system (BCO-DMO) (Data Citation 2) with all the fields listed above. The database is organized at level 0 by cruise dataset (Table 1 (available online only)), level 1 by stations, and level 2 with the POM data. ‘−9999’ describes missing data. This dataset will be updated if new data becomes available.

### Technical Validation

In our experience, when all precautions are taken, variance between replicate samples for elemental analysis can be  $< 5\%$ , assuming the actual sample is above the analytical blank. However, not all precautions are always taken, for example it is rare that when sampling for POC that the entire Niskin bottle is drained, well mixed and then subsampled. It is known that as the sample sits in the bottle, large particles sink to the bottom and often below the spigot resulting in an underestimation of particulate matter concentrations in the seawater sample<sup>70</sup>. There is also the question of limit of detection. For particulate analyses, this depends in part upon the volume you are filtering, the concentration of your



**Figure 2.** Summary of POM measurements and ratios in the aggregated dataset. Histogram of the number of observations across depths (a), latitude (b), and longitude (c) as well as the range of C:P (d), N:P (e), and C:N (f) elemental ratios. *M* represents the median value. Please note a difference in the total number of observations for each elemental ratio.

analyte of interest and overall cleanliness of your procedures<sup>71</sup>. For example, in the Sargasso Sea, where particulate nutrients are very low, we filter 4 liters of seawater for particulate organic phosphorus<sup>26</sup> to ensure that the sample well exceeds the blank. In our experience making these measurements using the methods reported here, reasonable blank measurements for POC, PON and POP are  $\sim 0.5 \mu\text{M}$ ,  $\sim 0.04 \mu\text{M}$  and  $\sim 3 \text{ nM}$ , respectively. It is common practice to subtract blanks from analyzed samples, and we assume that has been done for all reported data however, we cannot be fully confident in how that blank correction was conducted. Whether blank-corrected samples are significantly different than zero is a different question and depends upon the actual value and variability of the blank which is not commonly reported in published works or available datasets. However, we are confident that blank-corrected particulate organic matter concentrations greater than  $\sim 0.5 \mu\text{M}$  POC,  $\sim 0.05 \mu\text{M}$  PON and  $5 \text{ nM}$  POP are valid numbers to report. This benchmark may change between ocean regimes and with specific protocols. We should also note that some samples give either very high or low elemental ratios. These could arise from analytical artifacts, for example, one or both values in the ratio being close to the analytical detection limit, as well as other sampling artifacts. However, we currently do not have a good handle on the spatio-temporal variation in particulate nutrient concentrations and ratios and thus, it is difficult to give precise guidelines for flagging possible artifacts and thus really high/low values should be examined more closely and used with caution.

#### Usage Notes

The dataset can be used to identify novel regional or environmentally driven patterns in both the concentration of particulate organic matter as well as the ratios of different elements. Within this dataset are observations from time-series stations and thus temporal analysis of particulate organic matter

concentrations and ratios can also be evaluated. Further, the data can be utilized to evaluate outputs from ocean biogeochemical models.

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## Data Citations

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### Author Contributions

A.C.M. conducted the data analysis and wrote the first draft of the manuscript with input from all authors. All authors contributed to the data compilations.

### Additional information

Table 1 is only available in online version of this paper.

**Competing financial interests:** The authors declare no competing financial interests.

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