We thank the reviewer for his continued efforts to improve our manuscript and hope that the changes in this current version are acceptable. The following is a point-to-point reply to questions and suggestions by the reviewer.

The re-submission of the paper "The Ballast Effect of Lithogenic Matter and its Influences on the Carbon Fluxes in the Indian Ocean" by Rixen et al. has addressed some points brought up by both reviewers, most notably the omission of the box model calculations and of the "POCexcess" term used. These have reduced the bulk of the document.

For re-evaluation towards final publication I concentrated on specific revisions based on review comments already made, the arguments made in the discussion and the general readability of the document.

Readability: Unfortunately it is not my opinion that this has improved, and this is the primary setback to recommending publication. The abstract alone makes difficult reading. The second sentence refers to the "open Indian Ocean" i.e. all except the JAM site.

We used the term 'open' to characterize areas which are non or hardly influenced by river discharges and not to describe the distance of the sampling site to the coast. This is in our understanding a clear and fair definition. However, in order to avoid confusion we eliminated the term 'open' from the ms.

But at the JAM site, it is only one season which falls out of this pattern, the other fits perfectly (and it is unclear why see comment below). This should be specified.

With respect to the pattern we agree with the reviewer, but what matters in our interpretation is the ratio between organic carbon fluxes and primary production. At JAM this ratio is highest during the rainy season and in general it is higher at JAM than e.g. at WAST. The high ratio indicates a more efficient export of organic carbon into the deep sea. This is discussed in the ms and summarized in the abstract:
We calculated that a lithogenic matter content in aggregates and pellets enhances organic carbon flux rates on average by 45%, and by up to 62% at trap locations in the river-influenced regions of the Indian Ocean. Such a strong lithogenic matter ballast effect explains that organic carbon fluxes are higher in the low-productive South Java Sea compared to the high-productive western Arabian Sea.

The next sentence " At trap sites in the river-influenced northern and central Bay of Bengal and off South Java lithogenic matter was the main ballast material and its content strongly influenced organic carbon fluxes favoured by weakly pronounced variability of primary production at our trap locations in these regions." What does this mean "favoured by weakly pronounced variability of PP"? So if the variability of PP was strong, lithogenic matter would not favour organic carbon fluxes? This I did not see in the paper, so how can it go into the abstract?

Lithogenic matter favors organic carbon fluxes and we calculated its impact on the organic carbon flux. We changed the abstract accordingly:
To quantify the impact of lithogenic matter on the organic carbon flux, densities of the main ballast minerals, their flux rates and seawater properties were used to calculate sinking speeds of material intercepted by sediment traps. Sinking speeds in combination with satellite-derived export production rates allowed us to compute organic carbon fluxes. Flux calculations imply that lithogenic matter ballast increases organic carbon fluxes at all sampling sites in the Indian Ocean by enhancing sinking speeds and reducing the time of organic matter respiration in the water column. We calculated that a lithogenic matter content in aggregates and pellets enhances organic carbon flux rates on average by 45%, and by up to 62% at trap locations in the river-influenced regions of the Indian Ocean.

When lithogenic matter content hardly varies, primary production is the factor controlling the variability of organic carbon fluxes. This was clarified in the revised version.

Line 21 speaks of the "low productive Java Sea" but this is not borne out in the data where does this assertion come from?

The assertion is based on the satellite-derived primary production rates. We specified this in the revised abstract as follows:

"Such a strong lithogenic matter ballast effect explains that organic carbon fluxes are higher in the low-productive South Java Sea compared to the high-productive western Arabian Sea".

There are numerous typos and errors in the MS, particularly in the figure legends, that should be picked up.

The ms was checked by the coauthors to eliminate typos and improve the readability

Previous comment:

P5, line 26. What justification do they have for ignoring inter-annual differences in flux - just the *relative* standard deviation (not the standard deviation, as they say), compared to a general trapping efficiency (literature value), is doubtful reasoning. Especially in an area where inter-annual differences in the strength of the monsoon can be expected to cause corresponding flux differences, this needs to be expanded on. Though relative SD is "only" 17%, the ranges are large between 43 and 69 gC/m^2/yr (over 50% difference) at WAST for example. The authors may be missing important insights by ironing over inter-annual variations.

Revised manuscript: Authors move this section to the Results & Discussion (p 8, l 17-27). The paragraph where they discuss this does not convince. True, they have no estimates of PP in the individual years, and perhaps the temptation is to assume that mean annual values are a good proxy for what is happening at the sites. Maybe they are even right, but the argument does not hold up. We learn nothing by comparing 61% interannual differences (that could be due to differences in PP) to a 60% trapping efficiency estimate in a totally unrelated study, except that the numbers 60 and 61 are close to each other. The authors conclude " *However, the mean interannual variability was only 16.6 % implying that on the long-term run the reproducibility of the organic carbon fluxes measured by our deep moored traps was much better than the possible error range of 60% and thus the error of the calculated monthly, seasonal, and annual means used in the following discussion is much lower."* This is a tenuous statement.

Again, reading is laborious if one takes the authors literally. An example: *In order to estimate possible error ranges we calculated and compared annual mean organic carbon fluxes (Tab. 3).*

But this comparison is not useful to estimate "error ranges" (whatever that means) it is useful to estimate variability of flux!! Further, the table shows annual fluxes where they were measured for at least 150 days (less than half a year depending which season was not measured, the entire difference could potentially be accounted for by this). At the JAM site in 2003, only the period of high flux was measured (after which data are not available) so obviously the mean flux would be higher this doesn't show anything (lines 18 and 19).

We agree to the reviewer and calculated annual mean fluxes only when particle fluxes were measured for more than 255 days year^{-1} At JAM this reduced the interannual variability from 61 to 12.8%. The papers we cited are not unrelated. For instance, Yu et al. 2001 analyzed the trapping efficiency of our traps in the Arabian Sea showing that in comparison to methodical biases (such as changes in the trapping efficiency) the interannual variability is low.

In order to address these comments we changed the text as follows:

Radionuclide studies on samples collected during the first year of the sediment trap experiment in the

Arabian Sea revealed trapping efficiencies ranging between 0.89 and 1.17 at WAST and CAST; trapping efficiencies at EAST of 1.14 to 1.37 indicated an overtrapping (Yu et al., 2001). Such changes of the trapping efficiency may be a prime reason underlying the observed interannual variability of particle fluxes, which is generally low (Tab. 3).

4.2 Seasonality

The biases inherent in the method are too weak to mask the influence of monsoon-driven processes on organic fluxes on a seasonal time scale. In comparison to the interannual variability the sediment trap data showed a pronounced seasonality with enhanced fluxes during boreal summer in the Arabian Sea at JAM off South Java (Fig. 3 a).

Previous coment: P7 Sinking Speeds: Table 4 shows the values used for calculation and these are given in the text, but justifications are not forthcoming. Is the temperature of 10°C realistic? What is the temperature dependency of the results? Similarly, for salinity. The authors show in Fig. 2 that their traps were in a region of widely varying T & S, and indeed this is what characterises the Indian Ocean. So where are the limits of applicability of their calculations? Indeed, they vary density and keep the other variables constant, but perhaps it is density that should be constrained and the other variables altered. This needs to be better justified.

Author response: We have checked the influence of temperature and salinity and they were small. Seawater temperatures and salinity were extracted from the World Ocean Atlas 2013 for each trap site and are presented in Table 5.

Revised manuscript: Please present these calculations if you made them.

How does this help? Are "sea water temperatures" mean over the entire water column? Their contrast to the SST shows that large changes in temperature could indeed affect sinking speeds differently at different depths. If the authors tested this, it would be good to see the results.

We added a new figure (Fig. 5) showing temperature and salinity profiles as well as the calculated sinking speeds for each sampling site.

Results and Discussion: have been re-arranged.

4.1 I commented upon above.

4.2 is titled " Seasonality and Java in Comparison to the Western Arabian Sea" How can one compare a characteristic (seasonality) to a site (Western Arabian Sea?). We learn that the Arabian Sea and Bay of Bengal have more and less pronounced seasonality respectively, which is well known and understood (the literature is cited). The last paragraph states that " *Monthly mean satellite-derived primary production rates, which we selected for the trap sites and sediment trap data show a similar seasonality (Fig. 3 b,d)* But exactly this is negated in the last sentence of this paragraphs in which this "similar seasonality" is not seen at JAMS.

We changed this part as follows:

Similar to the organic carbon fluxes also the monthly mean satellite-derived primary production rates at the trap sites indicate a more pronounced seasonality at JAM and in the Arabian Sea than at the trap sites in the equatorial Indian Ocean and the Bay of Bengal (Fig. 3 b, d). This pattern agrees with the well-known concept of export production being driven by inputs of nutrients from the aphotic zone and external reservoirs (the atmosphere and the land) into the euphotic zone (Dugdale and Goering, 1967; Eppley and Peterson, 1979). But the data show that organic carbon fluxes are higher at JAM than at WAST, whereas primary production is lower at JAM than at WAST. Furthermore, low primary production at JAM corresponds with enhanced organic carbon fluxes in winter, which indicates a decoupling between primary production and organic carbon fluxes at JAM, which will be explored in more detail in the following.

4.3 tries to explain this discrepancy, but fails to provide more than rather confusing conjecture. The first merely states that the satellite data may be too weak to make this comparison in the first place. The second reasoning states that reconstruction of SST from foram shells correlated well with satellite-derived SST (but this SST was doubted previously due to cloud cover!). It is not clear in which depth the forams grew, at which temperatures, whether these varied seasonally etc. etc. so this argument is either accepted on good faith or not substantiated. I chose the latter.

Mohtadi et al. 2009 provided further details based on which we changed the text as follows:

$\delta^{18}O$ and Mg/Ca ratios are well-known seawater temperature and salinity proxies and they were measured in shells of Globigerinoides ruber sensu stricto (s.s.) and G. ruber sensu lato (s.l.) thriving in the surface mixed layer (Mohtadi et al., 2009). The time series $\delta^{18}O$ values and Mg/Ca ratios in trap material tracked satellite-derived sea surface temperatures and the relationship between Mg/Ca ratio and the satellite-derived sea surface temperature resembled those found in other regions, arguing against significant contributions of materials resuspended from sediments.

Given the generation times of forams, it is entirely possible (probable?) that freshly sedimented forams (bringing with them a load of organic matter from the sediment surface) resuspended at the shelf/slope could have been laterally transported to the deep traps, and bring with them this signal. Indeed this is the most likely explanation.
The JAM site is unlike all others - a continental margin site, and these are characterized by large amounts of lithogenic material being resuspended (often where the M2 internal tide impinges on the slope) and transported to deep traps. This lithogenic material could sweep large amounts of organics with them if this were the case, then the effects of lithogenics on sinking speed would not the be the causative factor for the pattern seen.
Here we disagree. On the one hand only freshly sedimented forams are resuspended and on the other hand large amounts of lithogenic material are being resuspended. If only freshly sedimented forams are resuspended from where comes the lithogenic matter? Resuspension of a large amount of lithogenic matter implies that also a large amount of sediments are resuspended. Sediments at this margin contain forams that lived in other areas and at different times. Input of such reworked shells into traps would have adversely affected the validation of the temperature transfer functions, which was not the case (see *Mohtadi et al., 2009).*

In the original manuscript, the authors even mention freshwater diatoms found in the traps that would, qualitatively, support the strong lateral transport hypothesis, but this is missing from the revised manuscript.
Since this supports our assumption that river-discharges influence the station the reference (Romero et al. 2009) was again included into the ms.

For the third conjecture, in the last paragraph, the authors use a 14% increase in lithogenic contribution in winter to explain the strong pattern seen between December and March (fluxes increase by 100% though PP stays constant). It seems extremely unlikely that this would be adequate in strength as a cause.
The increase was only 8% and refers to seasonal means given in Tab. 2. The 100% increase in fluxes seems to be obtained from Fig. 3 showing monthly means. The seasonal mean PP was 860 and 430 mg m^{-2} day^{-1} in summer and winter. The seasonal mean POC fluxes were 14.35 and 11.47 mg m^{-2} day^{-1}, which means that the PP decreased by 51% whereas POC flux decreased by 20%, only. This difference corresponds to an increase of the lithogenic matter content of 8%.

The alternate explanation, that laterally transported lithogenic and organic matter-rich material (possibly with a riverine source) reached the trap, is not explored.
Rixen et al (2006), which was cited, explored it. However, we addressed this issue in the ms as follows:
The high lithogenic matter content of 61% (Tab. 4) and the vicinity of the trap site JAM to the coast of Java (Fig. 1) on the other hand suggest that inputs of resuspended sediments and river discharges are a significant source of lithogenic matter and strongly influenced observed fluxes at JAM. Notably, a clear fingerprint of land-derived particulate matter are freshwater diatom frustules that were encountered in the trap during the winter wet season, albeit in low numbers (Romero et al., 2009). However, organic carbon-to-nitrogen ratios and stable carbon isotopic ratios of organic matter were in the range of marine plankton suggesting that inputs terrestrial organic matter were negligible (Rixen et al., 2006). From these indications we infer that the high lithogenic matter environment at JAM leads to a strong ballast effect and is the reason for higher organic carbon fluxes at JAM than at WAST, despite a much lower primary production at JAM than at WAST (Fig. 3).

Previous comment: 4.4. Primary production and organic carbon fluxes: This section made very confused reading (see detailed comments below). Besides comparing three models for calculating and extrapolating fluxes (equations 1,2 and 3), and finding that they differ widely, there is no clear message. What do we learn from this?

We agree with the reviewer in so far as results obtained from three often-used models differ widely and formulate this as a clear message. The exercise showed that the different model results cause large uncertainties. This clearly is an issue that needs to be resolved in the future. However, we contributed to this discussion by showing which model result correlates best with the trap data. We wrote in Chapter 4.6:

Independent of which equation we used to compute export production, the calculated organic carbon fluxes correlate with the observations (Fig. 9 b), but organic carbon fluxes obtained by using Eq.1 and 2 were higher and those obtained by using Eq. 3 were lower than the measured fluxes. The varying calculated organic carbon fluxes are a consequence of the different export production rates resulting from Eqs. 1 to 3 applied to satellite-derived primary production (see above). Equation 3 yielded the best agreement between measured and calculated fluxes and the highest correlation coefficient (0.931).

The main message, that lithogenic matter enhances POC flux is stated but not critically discussed.

The main aim of chapter 4.4 was to introduce the models and the associated problems as mentioned before, as well as to introduce the lithogenic matter ballast effect. The critical discussion is presented in chapters 4.5 and 4.6.

Revised manuscript: This comment carries forward to the revised manuscript

In conclusion, the paper has been improved to the extent that omissions have been conducted that shorten it. The basic weakness, that arguments are hard to follow and inconsistent, and that the manuscript makes difficult reading and thus burdens reader evaluation, remain. If the purpose of a scientific paper is to allow evaluation of data and argument, this one falls short. However, it still contains a good data set, which it would seem a shame not to publish. I leave it to the editor to make a decision on publication. Should it be accepted, there are numerous typos and errors in the MS, particularly in the figure legends, that should be picked up and a language editor should check the paper.

The Ballast Effect of Lithogenic Matter and its Influences on the Carbon Fluxes in the Indian Ocean

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Abstract. Data obtained from long-term sediment trap experiments in the Indian Ocean in conjunction with satellite observations illustrate the influence of primary production and the ballast effect on organic carbon flux into the deep sea. They suggest that primary production is the main control on spatial variability of organic carbon fluxes at most of our study sites in the Indian Ocean, except at sites influenced by river-discharges. At these sites the spatial variability of organic carbon flux is influenced by lithogenic matter content. To quantify the impact of lithogenic matter on the organic carbon flux, densities of the main ballast minerals, their flux rates and seawater properties were used to calculate sinking speeds of material intercepted by sediment traps. Sinking speeds in combination with satellite-derived export production rates allowed us to compute organic carbon fluxes. Flux calculations imply that lithogenic matter ballast increases organic carbon fluxes at all sampling sites in the Indian Ocean by enhancing sinking speeds and reducing the time of organic matter respiration in the water column. We calculated that a lithogenic matter content in aggregates and pellets enhances organic carbon flux rates on average by 45%, and by up to 62% at trap locations in the river-influenced regions of the Indian Ocean. Such a strong lithogenic matter ballast effect explains that organic carbon fluxes are higher in the low-productive South Java Sea compared to the high-productive western Arabian Sea. It also implies that land use changes and the associated enhanced transport of lithogenic matter from land into the ocean may significantly affect the CO_2 uptake of the organic carbon pump in the receiving ocean areas.

1 Introduction

Photosynthesis and the export of organic matter from the euphotic zone into the deep sea drive the organic carbon pump and are integral parts of the global carbon cycle (Volk and Hoffert, 1985). The CO_2 uptake in the ocean surface by phytoplankton and its transfer as sinking organic carbon through the thermocline and thus into the deep ocean is determined by available nutrients. The nutrients and CO_2 associated with sinking organic matter are regenerated during passage through the water

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column and these 'regenerated nutrients' comprise approximately 50% of the oceans´s nutrient inventory. The other half, so-called 'preformed nutrients' (Broecker et al., 1985), originate at high latitudes where light limited their complete utilisation in the biologically active zone (Duteil et al., 2012; Ito and Follows, 2005; Knox and McElroy, 1984; Sarmiento and Toggweiler, 1984; Siegenthaler and Wenk, 1984) before subduction.

The ratio between total (regenerated and preformed) nutrient input into the ocean's mixed layer and their export as organic matter across the thermocline is a measure of the CO_2 uptake efficiency by the organic carbon pump (DeVries et al., 2012). The efficiency is high in the subtropics and tropics where the ratio between preformed nutrient input and export as regenerated nutrients is close to one. In these regions the ballast effect modulates the efficiency of the organic carbon pump because the ballasting with lithogenic particles increases sinking speeds of aggregates and thus the water depth at which sinking organic matter is respired (e.g., Haake and Ittekkot, 1990; Ittekkot, 1993; Kwon et al., 2009). If organic matter is respired within the euphotic zone, the released CO_2 can immediately return into the atmosphere and nutrients are recycled. If it is respired in the deep sea, regenerated CO_2 and nutrients are injected into the ocean's long-term overturning circulation, where they can be stored for up to 1,500 years (De La Rocha and Passow, 2014; Heinze et al., 1991). Accordingly, a significant ballast effect strengthens the organic carbon pump by extending the mean residence time of regenerated nutrients and CO_2 (CO_2 sequestration time) in the ocean (DeVries et al., 2012).

The ballast effect operates by two processes: minerals, which cause the ballast effect, can (i) adsorb and/or integrate organic molecules onto and into their structure (Armstrong et al., 2002) and (ii) increase the sinking speed of particles in which organic matter is exported from the euphotic zone (Haake and Ittekkot, 1990; Hamm, 2002; Ramaswamy et al., 1991). The former protects organic matter against remineralization and the latter retards respiration in the water column.

Carbonate, biogenic opal and lithogenic matter are the main ballast minerals. Marine plankton produces carbonates and biogenic opal, whereas lithogenic matter is formed during weathering of rocks on land. Its input as dust and by rivers into the ocean is thus a steering mechanism linking the CO_2 uptake of the organic carbon pump directly to processes on land (Ittekkot and Haake, 1990).

There is conflicting evidence for the roles of primary production and the ballast effect, respectively, in organic matter export production in the literature. We adopt this term export production as corresponding to the organic carbon flux at a water-depth of 100 m and use the term 'organic carbon flux' for the organic carbon fluxes measured by sediment traps in the deep sea. Sediment trap experiments in the northern Indian Ocean have indicated that the Asian monsoon and its impacts on the nutrient supply into the euphotic zone (and thus primary production) primarily control organic carbon fluxes into the deep Arabian Sea and Bay of Bengal (Haake et al., 1993; Ittekkot et al., 1991; Nair et al., 1989; Rixen et al., 1996; Rixen et al., 2009). But additionally, eolian dust inputs and discharges from rivers appearedt to influence the ballast effect in these two basins (Ittekkot, 1993; Ittekkot and Haake, 1990). Similarly, an unusually high share of the organic matter exported from the euphotic zone reached the deep sea in the river-dominated Bay of Bengal, where high detrital inputs may cause a stronger ballast effect (Rao et al., 1994).

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A Multiple Linear Regression Analysis (MLR) of a global compilation of sediment trap data, including data from the Indian Ocean, surprisingly showed that primary production hardly affects organic carbon fluxes and that the ballast effect, dominated by carbonate minerals, controls the organic carbon export into the deep sea in the world's ocean (Klaas and Archer, 2002). This result was supported by Francois et al. (2002) who postulated that the contribution of lithogenic matter was too low to significantly contribute to the ballast effect, except in near-shore regions such as the Bay of Bengal. Based on an expanded global compilation of sediment trap data, a geographically weighted analysis identified both carbonate and lithogenic matter as the main ballast minerals in the Arabian Sea and the Bay of Bengal (Wilson et al., 2012), whereas another analysis of data from the Indian Ocean emphasised the role of biogenic opal as the main ballast mineral (Ragueneau et al., 2006). Thus, the role of primary production as the main driver of organic carbon fluxes is under scrutiny and all mineral components (lithogenic matter, carbonate and biogenic opal) have been identified as the 'main ballast material' in the Indian Ocean. To re-evaluate evidence and in an attempt to quantify the influence of primary production and the impact of individual ballast minerals on organic carbon fluxes in the Indian Ocean, we compiled data sets of sediment trap results (Fig. 1, Tab. 1) and applied the MLR technique to segregate regional patterns of dominant controls on organic carbon fluxes. Furthermore, densities of ballast minerals were compiled from the literature and used jointly with measured fluxes, satellite-derived export production rate estimates and water column properties obtained from the World Ocean Atlas 2013 (Locarnini et al., 2013; Zweng et al., 2013) to calculate sinking speeds and organic carbon fluxes. This new mechanistic approach allows us to quantify the strength of the lithogenic matter ballast effect.

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2. Study Area

The Asian monsoon strongly influences the northern Indian Ocean with its two semi-enclosed basins: the Arabian Sea and the Bay of Bengal. Sea-level pressure differences between the Asian landmass and the Indian Ocean drive the monsoon (Ramage, 1987, 1971). Following the pressure gradient and deflected by the Coriolis force, wind blows from the NE over the Arabian Sea and the Bay of Bengal in winter between December and February (Currie et al., 1973). In summer (June - September), the situation reverses. The heating of the Asian landmass leads to the formation of a strong atmospheric low which attracts and enforces the SE trade winds to cross the equator in the western Indian Ocean. They form a strong low-level jet (Findlater Jet) blowing from the SW over the Arabian Sea (Fig. 2a,b, Findlater, 1969; Findlater, 1977).

In the Arabian Sea, the positive wind stress curl west of the axis of the Findlater Jet causes upwelling, which is strongest along the coast of the Arabian Peninsula (Bauer et al., 1991; Luther and O'Brien, 1990; Ryther and Menzel, 1965; Sastry and D'Souza, 1972). Weaker upwelling systems also occur NE off Sri Lanka and along the SW coast of India (Sharma, 1978; Shetye et al., 1990; Wiggert et al., 2006) and these signals are carried by the Southwest Monsoon Current into the southern Bay of Bengal (Unger et al., 2003). Due to the northward movements of the SE trade wind systems and the associated reversal of the South Java Current an upwelling system emerges off South Java and Bali almost simultaneously with the development of the Findlater Jet in the Arabian Sea during the boreal summer (Susanto et al., 2001). Off Java and Bali this is

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actually the winter season, but in order to avoid confusion we refer the term 'summer' and 'winter' to the boreal summer and winter only.

The monsoon rains feed one of the world's largest river systems (Ganges-Brahmaputra-Meghna), which originates in the Himalayas and has its maximum discharge into the Bay of Bengal in summer (Ludwig et al., 1996; Milliman and Meade, 1983; Milliman et al., 1984; Subramanian et al., 1985). Unlike the Indian subcontinent, Indonesia has no major rivers because it comprises relatively small islands. Nevertheless, model studies suggest that the small Indonesian rivers contribute ~11% ($4.26 * 10^{12}$ m^3yr^{-1}) to the global freshwater discharge into the ocean (Syvitski et al., 2005). Due to the high freshwater water inputs, low salinity surface waters (salinity < 33) fringe the continental shelves and margins in the eastern Indian Ocean and the high salinity waters (salinity > 35) reflect the negative freshwater balance in the Arabian Sea (Fig. 2c, d).

Inputs of suspended sediments from the Ganges-Brahmaputra-Meghna (1060 Mt yr^{-1}) and Indonesian rivers (1630 Mt yr^{-1}) represent 80% and 20% of the suspended sediment inputs into the Indian and the world's ocean, respectively (Milliman and Farnsworth, 2011; Syvitski et al., 2005). Sediment discharge from the Indus into the Arabian Sea only amounts to about 10 Mt yr^{-1} (Milliman and Farnsworth, 2011) that are to a large extent trapped on the continental shelf and upper continental slope of the Indian margin due to the prevailing current regime (Ramaswamy et al., 1991). In the western part of the Arabian Sea, where the formation of High Salinity Arabian Sea Water (Rochford, 1966; Tchernia, 1980; Tegen and Fung, 1995) shows negligible freshwater inputs (Fig. 2 c, d), eolian dust inputs are the main sources of lithogenic matter (Clemens et al., 1991; Sirocko et al., 1993; Tegen and Fung, 1995).

3. Methods

3.1 Sediment Trap Data

Sediment trap experiments started in 1986 in the Arabian Sea and were expanded into the Bay of Bengal in 1987. The fieldwork ended around 1998, was briefly reinitiated in 2007 and 2008, and then aborted for safety reasons. The sediment trap moorings equipped with Mark 6 and 7 time-series sediment traps were deployed for periods of six months to one year with sampling intervals of mostly around 21 days. The sediment trap sites in the northern and central Bay of Bengal were shifted slightly southward in some years, so that the stations NBBT and CBBT were split into northern (NBBT-N, CBBT-N) and southern sites (NBBT-S, CBBT-S, Fig. 1, Tab. 1). Haake et al. (1993) and Rixen et al. (1996) describe the sample processing and the analysis of bulk components (organic carbon, carbonate, biogenic opal and lithogenic matter) in detail. Organic carbon fluxes (POC) multiplied by 1.8 yield organic matter fluxes (OM). The lithogenic matter fluxes represent the difference between total flux and fluxes of OM, carbonate and biogenic opal. Fluxes were used to calculate monthly (Fig. 3), seasonal (Tab. 2), annual (Tab. 3) and long-term annual means (Tab. 3, 4). The seasons considered were summer (June - September), winter (January - April) and transition periods (May and October to December). Annual means were calculated only when particle fluxes were measured for more than 255 days $year^{-1}$ (Tab. 3). Since our record at station NEAST covers only one season, we calculated a seasonal mean (Tab. 2), but no annual mean.

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3.2 Satellite Data

Monthly mean wind speeds and salinity data were derived from the Scatterometer Climatology of Ocean Winds (Risien and Chelton, 2008) and the Soil Moisture and Ocean Salinity (SMOS) satellite mission, respectively (Fig. 2a-d). The SMOS data covering the period between 2010 and 2012 were downloaded from ftp://ftp.icdc.zmaw.de/smos_sss/. Monthly mean satellite-derived sea surface temperatures (SST, Smith et al., 2008) were obtained from ftp://ftp.emc.ncep.noaa.gov/cmb/sst/oimonth_v2/ASCII_UPDATE. Primary production rates (PP, Fig. 2 e, f) derived from the Vertically Generalized Production Model (VGPM, Behrenfeld and Falkowski, 1997) were downloaded from http://www.science.oregonstate.edu/ocean.productivity and averaged at around 1 degree around the trap location, as were the SST data.

Equations 1 - 3 introduced by Eppley and Peterson (1979), Law et al. (2000) and Henson et al. (2011) were used to convert primary into export production (POC_{Export}).

$$E: POC_{Export} = \begin{matrix} 0.0025 \cdot PP^2 \rightarrow PP < 200 \\ 0.5 \cdot PP \rightarrow PP > 200 \end{matrix} \quad (1)$$

$$L: POC_{Export} = (-0.02 \cdot SST + 0.63) \cdot PP \quad (2)$$

$$H: POC_{Export} = 0.23 \cdot exp^{(-0.08 \cdot SST)} \cdot PP \quad (3)$$

We applied Eqs. 1 - 3 to the satellite-derived primary production rates to calculate export production. Eppley and Peterson (1979) suggested two different equations for PP less than and more than 200 g m^{-2} $year^{-1}$. The monthly mean primary and export production rates covering the period between 2002 and 2015 were used to calculate monthly (Fig. 3), seasonal (Tab. 2) and long-term annual means (Tab. 5).

3.3 Multiple Linear Regression Analysis (MLR)

A Multiple Linear Regression Analysis was applied to calculate carrying coefficients (f). Here, we used the OLS regression analysis included in the Python module *statsmodels*:

$$F_{POC}\left[\frac{g}{m^2 \cdot year}\right] = (f_{Lith.} \cdot F_{Lith.}) + (f_{Opal} \cdot F_{Opal}) + (f_{Carb} \cdot F_{Carb.}) \quad (4)$$

(F) represents fluxes of respective bulk components lithogenic matter (Lith.), biogenic opal (Opal) and carbonate (Carb.). In order to estimate the relative importance of individual ballast minerals (RIB) for the POC flux (F_{POC}), their contribution to the predicted POC flux was calculated.

$$RIB_i[\%] = \frac{100}{F_{POC}} \cdot (f_i \cdot F_i) \quad (5)$$

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where (i) indicates the different ballast minerals.

3.4 Sinking Speed

The influence of the individual ballast minerals can also be derived from a more mechanistic approach by quantifying their contribution to the density of the solids (ρ_{solids}):

$$\rho_{solids} = \frac{(Lith\%\cdot D_{lith})+(OM\%\cdot D_{OM})+(Opal\%\cdot D_{Opal})+(Carb.\%\cdot D_{Carb.})}{100} \quad (6)$$

Lith%, OM (=POC*1.8)%, Opal% and Carb% are the percentage of the respective ballast minerals in the sinking particles collected in the sediment traps and (D) represents their density in g cm^{-3}.

Densities of the bulk component show a wide range and fall below those of their crystalline analogues (Fig. 4). For example, the density of proteins varies between 1.22 to 1.47 g cm^{-3}, whereas the density of organic matter in phytoplankton comprising > 80% of amino acids varies between 1.03 and 1.1 g cm^{-3} (Lee et al., 2004; Logan and Hunt, 1987; Miklasz and Denny, 2010; Quillin and Matthews, 2000). With 0.7 – 0.84 g cm^{-3}, the density of transparent exopolymers (TEP) – which play an essential role for the formation of marine snow – is even below that of seawater (Azetsu-Scott et al., 2004). Other carbohydrates such as cellulose have a density of 1.5 g cm^{-3}. The density of calcite – the most common calcium carbonate mineral in the pelagic ocean – is 2.71 g cm^{-3} (Mottana et al., 1978). In turn, coccolithophores and foraminifera tests reveal densities of only 1.55 g cm^{-3} (page 71, Winter and Siesser, 1994) and up to 1.7 g cm^{-3} (Schiebel et al., 2007; Schiebel and Hemleben, 2000). In contrast to opal – which is a hydrous silicon oxide and of density between 1.9 to 2.5 g cm^{-3} – the density of diatom frustules (biogenic opal) varies between 1.46 and 2.0 g cm^{-3} (Csögör et al., 1999; DeMaster, 2003).

The density of lithogenic matter depends on its mineral composition. Clay minerals change their density by adsorbing water, which is most pronounced within the group of smectite. Their density decreases from 2.72 to 1.4 g cm^{-3} during hydration (Osipov, 2012), whereas hydration hardly affects the density of illite, which decreases from 2.75 to 2.72 g cm^{-3}. At our trap sites, illite and quartz dominate lithogenic matter (Ramaswamy et al., 1991; Ramaswamy et al., 1997). Since the density of quartz is 2.65 g cm^{-3}, we assumed a density of 2.70 ±0.05g cm^{-3} for lithogenic matter at our trap sites. Accordingly, we used a density of 2.70 ±0.05, 0.9 ±0.2, 1.73 ±0.27, and 1.63 ±0.08 for lithogenic matter, organic matter, biogenic opal and carbonate, respectively to calculate densities of the solids and sinking speeds of particles (Tab. 6).

The density of solids is the term describing the effect of mineral particles on the sinking speed of particles in Stokes's law. Stokes's law derived from the Navier-Stokes equation is a commonly-used parameterisation for calculating the sinking velocity (U) of particles (e.g., Engel et al., 2009; Lal and Lerman, 1975; McCave, 1975; Miklasz and Denny, 2010):

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$$U = \frac{(2 \cdot g \cdot \Delta\rho \cdot radius^2)}{9\eta} \quad (7)$$

(g) is the gravitational acceleration and (radius) defines the radius of the sinking particle. (η) is the viscosity and (Δ ρ) represents the excess density of particles over water or – expressed in other words – the difference between the density of the particle ($\rho_{particle}$) and seawater ($\rho_{seawater}$).

$$\Delta\rho = \rho_{particle} - \rho_{seawater} \quad (8)$$

The density of a sinking particle results from its pore water content and the density of the solids:

$$\rho_{particle} = (porosity \cdot \rho_{water}) + (1 - porosity) \cdot \rho_{solids} \quad (9)$$

Sinking speed (U) can be used to estimate the organic carbon flux (POC) at trap depth (z) according to Equation 10 introduced by Banse (1990):

$$POC(z) = POC_{Export} \cdot e^{\left[\frac{-\lambda \cdot (z - depth\ of\ the\ euphotic\ zone)}{sinking\ speed}\right]} \quad (10)$$

(λ) is the POC-specific respiration rate and (POC_{Export}) is the export production. (λ) was assumed to vary in a relatively narrow range (0.106 ± 0.028 day^{-1} (Iversen and Ploug, 2010; Ploug and Grossart, 2000), whereas more recent studies suggest that λ decreases with decreasing temperatures (Iversen and Ploug, 2013; Marsay et al., 2015). Direct field observations are scarce (Laufkötter et al., 2017) but *in-situ* incubation experiments carried out at a water depth of < 500 m indicate respiration rates of 0.4 ± 0.1 and 0.01± 0.02 day^{-1} in the subtropical North Atlantic Ocean and the Southern Ocean, respectively (McDonnell et al., 2015). We selected a λ of 0.106 day^{-1}, which is well within this range.

The viscosity of the fluid (η) and the density of sea water (ρ_{water}) were calculated as a function of sea water temperature and salinity by using the Python routines *gsw* (Gibbs SeaWater) and *iapws* (International Association for the Properties of Water and Steam) (IOC et al., 2010; Wagner and Pruß, 2002). Seawater temperature and salinity were selected from the World Ocean Atlas 2013 (Locarnini et al., 2013; Zweng et al., 2013) for each trap site (Fig. 5a,b) and averaged between water depths of 100 and 1500 m (Tab. 5). At our sediment trap sites, the porosity of particles and the radius are unknown. Based on results derived from other studies, we assume a porosity of 0.917 (Logan and Hunt, 1987).

The equivalent spherical diameters (ESD) of sinking particles cover a wide size spectrum ranging mostly between 0.01 and < 5 mm (Guidi et al., 2009; Iversen et al., 2010). Diameters of particles formed in rolling tanks often exceed 1 mm, reached ESDs of > 1 cm and resemble in size marine snow collected by scuba divers in the surface water of the ocean that have ESDs

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of up to 7.5 cm (Alldredge and Gotschalk, 1988; Engel et al., 2009). An ESD of 0.1 mm is a commonly-considered threshold dividing small and large particles (Durkin et al., 2015; Guidi et al., 2009). We selected an ESD of 0.15 mm to calculate sinking speeds (Tab. 6, Fig. 5c).

4. Results and Discussion

4.1 Interannual variability

The interannual variability of particle fluxes was largest at EAST (Tab. 3). At this site we intercepted particle fluxes over periods of > 255 days per year during three years. In 1989 and 1991 fluxes hardly deviate from each other, but total fluxes dropped by 40% in 1993. In contrast to EAST, where our record covers only three years, the record of particle fluxes at four sites in the northern Indian Ocean extends over a period of five and more years. Two of theses sites were in the Arabian Sea (WAST and CAST) and two were in the Bay of Bengal (NBBT-N and CBBT-N). Among these sites the annual mean fluxes revealed a standard deviation of < 18.3%.

Sediment traps are the only and thus intensively used tool to measure the seasonal and interannual variability of particle fluxes in the ocean (Turner, 2015), but hydrodynamic, biological and chemical processes bias the accuracy of sediment trap measurements (e.g. Antia, 2005; Buesseler et al., 2007). Since current velocities decrease with depth and zooplankton migration is restricted to water depth < 900 m particle fluxes measured at water depth > 1500 m are generally considered as most reliable (Bianchi et al., 2013; Honjo et al., 2008). Nevertheless, there are indications that also deep-moored traps can undertrap organic matter fluxes by 60% (Buesseler et al., 2007; Buesseler et al., 1992; Usbeck et al., 2003; Yu et al., 2001). Radionuclide studies on samples collected during the first year of the sediment trap experiment in the Arabian Sea revealed trapping efficiencies ranging between 0.89 and 1.17 at WAST and CAST; trapping efficiencies at EAST of 1.14 to 1.37 indicated an overtrapping (Yu et al., 2001). Such changes of the trapping efficiency may be a prime reason underlying the observed interannual variability of particle fluxes, which is generally low.

4.2 Seasonality

The biases inherent in the method are too weak to mask the influence of monsoon-driven processes on organic fluxes on a seasonal time scale. In comparison to the interannual variability the sediment trap data showed a pronounced seasonality with enhanced fluxes during boreal summer in the Arabian Sea at JAM off South Java (Fig. 3 a). Between May and August/September organic carbon fluxes increased from approximately 7 and 10 mg m^{-2} day^{-1} to about 24 and 26 mg m^{-2} day^{-1}. This represents an increase of about 240% and 160% at stations WAST and JAM, respectively, and exceeds estimated impacts of a changing trapping efficiency on the organic carbon fluxes. This also applies to the other sites in the Arabian Sea where organic carbon fluxes increased by about 100% (from ~ 6 to ~12 mg m^{-2} day^{-1}) between May and August. However, in the Arabian Sea winter peaks were less pronounced compared to summer maxima, except at the trap site NEAST (Fig. 3a). Although the record at this site covered not even a full year, it recorded an increase in organic carbon fluxes by 160% from

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10 to 26 mg m^{-2} day^{-1} between November and March, suggesting a seasonal response of organic carbon fluxes to the winter monsoon that weakened towards the south and southwest. In the Bay of Bengal and at EIOT in the equatorial Indian Ocean the seasonality of organic carbon fluxes was weaker than in the Arabian Sea and specific responses of the organic carbon fluxes to summer and winter monsoon forcing are lacking (Fig. 3 c). Importantly, however, the seasonality of organic carbon fluxes in the Arabian Sea and at JAM (as well as the weak seasonality in the Bay of Bengal) reflect impacts of the monsoons on surface ocean processes (e.g., Ittekkot et al., 1991; Rixen et al., 2009).

The monsoon is thought to cause the seasonality through its impact on the physical nutrient supply mechanisms, such as upwelling, vertical mixing, and river discharges into the Bay of Bengal. Riverine nutrient discharges are assumed to increase organic carbon fluxes within river plumes near the coast, but after the consumption of nutrients within the river plume nutrient-depleted freshwater forms a buoyant low salinity surface layer in the open Bay of Bengal (Kumar et al., 1996). This increases stratification in the surface ocean and reduces nutrient inputs during mixed-layer deepening in summer and winter, which in turn weakens the seasonality of organic carbon fluxes at trap sites in the Bay of Bengal. The same occurs in the winter rainy season off South Java, but here riverine nutrient inputs increase organic carbon fluxes, because the trap site JAM is located close to the coast (Rixen et al., 2006).

Monthly mean satellite-derived primary production rates at the trap sites indicate a more pronounced seasonality at JAM and in the Arabian Sea than at the trap sites in the equatorial Indian Ocean and the Bay of Bengal (Fig. 3 b, d). This pattern agrees with the well-known concept of export production being driven by inputs of nutrients from the aphotic zone and external reservoirs (the atmosphere and the land) into the euphotic zone (Dugdale and Goering, 1967; Eppley and Peterson, 1979). But the data show that organic carbon fluxes are higher at JAM than at WAST, whereas primary production is lower at JAM than at WAST. Furthermore, low primary production at JAM corresponds with enhanced organic carbon fluxes in winter, which indicates a decoupling between primary production and organic carbon fluxes at JAM, which will be explored in more detail in the following.

4.3 The Java Mooring (JAM)

The sediment trap data at site JAM overlap temporally with satellite observation of primary production so that these records can directly be compared (Fig. 6). This comparison shows that high organic carbon fluxes during the upwelling season in summer 2002 corresponded to high primary production rates, but this was not the case during the rainy season in winter 2002/2003. The ratio between organic carbon fluxes and primary production was enhanced in winter (Figs. 3, 6) and corresponded to an increase of the lithogenic matter content by about 8% between summer and winter (Tab. 1). There are several possible explanations for these patterns. A dense cloud cover shades the Indonesian seas from space observations and biases satellite observations of primary production especially in winter (Hendiarti et al., 2004). On the other hand, enhanced inputs of sediments from land, and resuspension of shelf and upper slope sediments during the rainy season in winter as compared to the upwelling season in summer provide lithogenic matter to amplify the ballast effect and cause a decoupling of satellite-derived primary production rates and organic carbon fluxes.

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An influence of resuspended sediments has been dismissed on the basis of stable oxygen isotopes ($\delta^{18}O$) and Mg/Ca ratios of foraminifera shells collected by the JAM trap. $\delta^{18}O$ and Mg/Ca ratios are well-known seawater temperature and salinity proxies and they were measured in shells of *Globigerinoides ruber sensu stricto* (s.s.) and *G. ruber sensu lato* (s.l.) thriving in the surface mixed layer (Mohtadi et al., 2009). The time series $\delta^{18}O$ values and Mg/Ca ratios in trap material tracked satellite-derived sea surface temperatures and the relationship between Mg/Ca ratio and the satellite-derived sea surface temperature resembled those found in other regions, arguing against significant contributions of materials resuspended from sediments.

The high lithogenic matter content of 61% (Tab. 4) and the vicinity of the trap site JAM to the coast of Java (Fig. 1) on the other hand suggest that inputs of resuspended sediments and river discharges are a significant source of lithogenic matter during winter and strongly influenced observed fluxes at JAM. Notably, a clear fingerprint of land-derived particulate matter are freshwater diatom frustules that were encountered in the trap during the winter wet season, albeit in low numbers. From these indications we infer that the high lithogenic matter environment at JAM leads to a strong ballast effect and is the reason for higher organic carbon fluxes at JAM than at WAST, despite a much lower primary production at JAM than at WAST (Fig. 3).

4.4 Primary Production and Organic Carbon Fluxes

To distinguish the roles of primary production and the ballast effect on the organic carbon flux, seasonal means (Tab. 2) were used to calculate transfer efficiency (T_{eff}) of organic carbon. This defines the ratio between organic carbon fluxes measured by sediment traps and export production and expresses the fraction of export production which reaches the deep sea (Francois et al., 2002). To calculate T_{eff} we converted primary production into export production by using Eqs. 1 to 3. The results between the three equations differed. The lowest and highest export production rates were obtained by using Eq. 3 (8 – 49 mg m^{-2} day^{-1}) and Eq. 1 (178 - 639 mg m^{-2} day^{-1}), respectively. Export production is difficult to quantify in the field and constitutes a highly uncertain element in the marine carbon cycle. The wide range of estimates of global mean export production (1.8 - 27.5 10^{15} g C yr^{-1}) reflects this uncertainty (del Giorgio and Duarte, 2002; Honjo et al., 2008; Lutz et al., 2007). Since we cannot resolve this issue and have no data to validate the calculated export production we used results obtained from all three equations to compute export production rates and T_{eff} (Fig. 7).

Francois et al. (2002) calculated T_{eff} by using Eq. 2 and a global compilation of sediment trap data, which contained also data from the Arabian Sea and the Bay of Bengal. Their results indicated that 9.6 ±4.9% and 16±2.4% of the exported organic carbon arrives in the sediment traps in the Arabian Sea and the Bay of Bengal. Using Eq. 2 as Francois et al. (2002), our annual mean data suggest that 16.5 ±5% and 46.5±5% of the exported organic matter reach the traps, respectively. Different SST values used to calculate export production mainly cause this deviation because Eq. 2 is extremely sensitive to temperature changes. SSTs obtained from Smith et al. (2008) were approximately 0.6° higher than those used by Francois et al. (2002). But even with these different SST values the resulting shifts in T_{eff} using Eq. 2 are small in comparison to the spread of estimates of all three equations. On average 6±3% (Eq.1), 35±19%, (Eq. 2), or 56±22% (Eq.3) of the export

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production reaches the sediment traps.

Independent of the equation used, the calculated export production correlates with T_{eff}, and T_{eff} increases with decreasing export production (Fig. 7). Francois et al. (2002) explained this with a more labile quality of organic matter exported when f-ratios (=export/primary production) are high. A high f-ratio indicates a low recycling efficiency of organic matter in the euphotic zone and thus a reduced transfer of organic matter to higher trophic levels. The low recycling efficiency favours the export of more labile organic matter in marine snow and the reduced transfer of organic matter to higher trophic levels reduces the formation of fast-sinking zooplankton faecal pellets. More labile organic matter is exported in slower-sinking marine snow, which in turn favours respiration and lowers T_{eff}.

If we divide our data into two groups, characterized by a lithogenic matter content of < 25% and > 25%, the group with a lithogenic matter content > 25% has generally higher T_{eff} at similar export production rates (Fig. 7). This suggests that the lithogenic content increases T_{eff} if lithogenic matter content exceeds 25%. This is the case in samples collected in the river-dominated northern and central Bay of Bengal and at JAM. In winter T_{eff} at JAM even exceeds 100% if Eq. 3 is used to calculate export production. This is unrealistic as it means that organic carbon fluxes measured by the trap exceed the calculated export production, but it points towards the strong lithogenic matter ballast effect at site JAM in winter.

4.5 Carbonate versus Lithogenic Ballast

Analysis by MLR is an approach to study the relative importance of different ballast minerals. It was applied here to test the assumption that lithogenic matter is the main ballast mineral in river-influenced regions and to investigate the roles of individual ballast minerals on organic carbon fluxes at the other trap locations in the Indian Ocean. For this investigation we included data obtained from six sediment traps deployed at water depths of > 2220 m in the western Arabian Sea off Oman during the US JGOFS program in 1994/95 at sites MS2-5 (Fig. 1, Honjo et al., 1999). Applied to annual means, the MLR implies that the highest carrying coefficients are associated with biogenic opal, followed by those of carbonate (Tab. 7). This matches results obtained by Ragueneau et al. (2006) and disagrees with those obtained from the geographically weighted analyses, which identified carbonate and lithogenic matter as the main ballast minerals in the Arabian Sea and the Bay of Bengals (Wilson et al., 2012).

To discern regional differences within the Indian Ocean, the MLR was furthermore conducted on data of bulk composition of sinking particles collected in the individual sampling cups at each sediment trap site (Tab. 7). This revealed that on average the highest carrying coefficients are associated with lithogenic matter. Weighted by multiplying the carrying coefficients with the associated flux (RIB) indicates that lithogenic matter ballast contributes on average 43 ±19% to the predicted organic carbon fluxes (Tab. 8), but with regional differences. At WAST the analysis suggests that carbonate is the main ballast mineral and , in contrast to our previous inference - also at JAM, which is surprising considering the low carbonate and the high lithogenic matter content in samples from these two sites (Tab. 4, 5). A correlation analysis of organic carbon fluxes with the content of the individual ballast materials suggests a threshold of 25% beyond which lithogenic matter content correlates with organic carbon fluxes measured in the Indian Ocean (Fig. 8a). Below this threshold

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in lithogenic matter content, organic carbon fluxes correlate best with carbonate fluxes and vary independent of lithogenic matter concentrations (Fig. 8b). This corroborates the role of lithogenic matter as the dominant ballast material in river-influenced regions, whereas carbonate is the main ballast mineral in the open Indian Ocean (Francois et al., 2002). The correlation between carbonate and organic carbon fluxes observed here is very likely a consequence of a joint production than of the ballast effect. For instance, in the western Arabian Sea peak fluxes of pelagic foraminifera coincide with upwelling-driven diatom blooms (Haake et al., 1993). Foraminifera tests are incorporated into and weight sinking particles, but due to their size also sink individually at velocities of several hundred-metres day^{-1} (Schiebel, 2002; Schiebel and Hemleben, 2005; Schmidt et al., 2014). This contrasts with lithogenic matter that mostly consists of clay minerals (Ramaswamy et al., 1991) that are too small to sink on their own (Honjo, 1976; McCave, 1975; Rex and Goldberg, 1958). Clay minerals are therefore transferred into the deep sea mainly by incorporation into aggregates and faecal pellets, implying that their effect as ballast should be particularly strong in ocean areas rich in alumosilicate detritus that enhances the sinking velocity of aggregates and marine snow.

4.6 Sinking Speeds and organic carbon fluxes

An important effect of ballast is to increase the specific density of sinking materials and accelerate sinking velocities. Eqs. 6 – 9 were used to calculate sinking speeds based on the composition of the sinking material and the respective densities of the bulk components (Tab. 6). The average calculated sinking speed is 224±33 m day^{-1} and agrees with sinking speeds of > 214 m day^{-1} calculated from the time lag of about 14 days between the onset of upwelling and the associated increase of organic fluxes at water depth of about 3000 m in the Arabian Sea (Rixen et al., 1996). Furthermore, it agrees with sinking speeds (230 ±72 m day^{-1}) obtained from the US JGOFS sediment trap experiment in the Arabian Sea (Berelson, 2001), lending credence to the values of sinking velocities (Tab. 6). The high mineral-specific density of lithogenic matter is a first-order influence on sinking speeds (Fig. 9a).

The calculated sinking speeds and satellite-derived export production permit to calculate organic carbon fluxes (Eq. 10). Independent of which equation we used to compute export production, the calculated organic carbon fluxes correlate with the observations (Fig. 9 b), but organic carbon fluxes obtained by using Eq.1 and 2 were higher and those obtained by using Eq. 3 were lower than the measured fluxes. The varying calculated organic carbon fluxes are a consequence of the different export production rates resulting from Eqs. 1 to 3 applied to satellite-derived primary production (see above). Equation 3 yielded the best agreement between measured and calculated fluxes and the highest correlation coefficient (0.931). The agreement can even be improved by changing the constant in Eq.3 from 0.23 to 0.37 , which would imply that Eq. 3 underestimates export production in the Arabian Sea (Fig. 9c). This modification accounts for an underestimated primary and export production and/or a neglected protection of organic matter due to which we underestimate the strength of the ballast effect in our calculations.

To disentangle the roles of primary production and the ballast effect on organic carbon fluxes we recalculated organic carbon fluxes by using the modified Eq. 3 but instead of the speeds derived from the seawater properties and densities of the solids

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we used a constant sinking speed of 224 m day^{-1}. Therewith organic carbon fluxes were calculated as function of primary and export production, only (Eq. 10). The resulting correlation coefficient was 0.926, for calculated and observed data obtained from stations at which the lithogenic matter content of sinking material was < 25% (Fig. 10). This correlation coefficient was almost as high as the one obtained from the correlation between measured fluxes and those derived from the site-specific sinking speeds (0.931, Fig. 9c). Accordingly, the adjustment of sinking speeds to differences in particulate matter composition and local seawater properties hardly improved the correlation between calculated and measured fluxes and primary production is assumed to control the spatial variability of organic carbon fluxes at these sampling sites. At sites characterized by a lithogenic matter content > 25% measured organic carbon fluxes and those derived from a constant sinking speed of 224 m day^{-1} are also correlated (Fig. 10). Since calculated organic carbon fluxes were significantly lower than measured fluxes it is suggested that higher sinking speeds induced by lithogenic matter ballast effect determine organic carbon fluxes at these sites.

Eqs. 6 – 9 can be used to estimate the lithogenic matter effect on sinking speed when the lithogenic matter flux is set to zero and the contribution of the other ballast minerals to the remaining total flux (total flux - lithogenic matter flux) is recalculated. The difference between sinking speeds derived from the density of solids with and without considering lithogenic matter content (Δ Sinking Speed) reflects the impact of lithogenic matter on the sinking speeds and the strength of the lithogenic matter ballast effect (Fig. 11a). The strength of the lithogenic matter ballast effect increases with an increasing lithogenic matter content (Fig. 11b). In the absence of lithogenic matter the mean sinking speed is 147 ±5 m day^{-1}, which implies that on average lithogenic matter enhances the sinking speed by 52% from 147 to 224 m day^{-1} (Fig. 11a).

The impact of the lithogenic matter ballast effect on the organic carbon fluxes can be estimated by applying the reduced sinking speeds to Eq. 10 in addition to export production derived from primary production and the modified Eq. 3. In this case the mean calculated organic carbon fluxes are lower by 45% than the one calculated by considering the lithogenic matter ballast effect on the sinking speeds. The difference between organic carbon fluxes calculated by using sinking speeds derived from the density of solids with and without considering lithogenic matter defines 'Δ POC flux' which in general increases with an increasing lithogenic matter ballast effect ('Δ Sinking Speeds', Fig. 11c). At site JAM the absence of lithogenic ballast reduces the organic carbon flux by 62% which implies, vice versa, that the weighting with silicate strongly enhances organic carbon fluxes at JAM. This pronounced influence of lithogenic ballast is also the reason for higher measured organic carbon flux via a more rapid transfer through the water column at JAM than at WAST, although the WAST site is far more productive.

This indicates that lithogenic matter ballast is an important factor enhancing organic carbon fluxes at all sites in the Indian Ocean. Such a strong lithogenic matter ballast effect emphasizes the role of land use changes on the residence time of regenerated CO_2 and the associated CO_2 uptake efficiency of the organic carbon pump. Considering that the Neolithic revolution was accompanied by a twenty-fold increase of erosion in the wake of deforestation and the expansion of agriculture (Neil, 2014), humans must have increased the ballast effect and the CO_2 uptake of the organic carbon pump particularly in regions under river influence since thousands of years.

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5. Conclusions

The evaluation of data from sediment trap time-series in conjunction with satellite-derived observations suggests that at those sites characterized by low lithogenic matter contents (< 25%) primary production is the dominant control of the spatial variability of organic carbon fluxes into the deep ocean. A pronounced lithogenic matter ballast effect overrides primary production as the main influence on sinking organic carbon fluxes in ocean areas under river influence. However, the lithogenic matter ballast effect strongly enhances the amount of organic carbon reaching the deep ocean at all sampling sites in the Indian Ocean. Calculated sinking speeds and organic carbon fluxes indicate that the lithogenic matter ballast effect increased the mean sinking speeds by 52% and the mean calculated organic carbon flux by 45%. Due to the high lithogenic matter content the lithogenic matter ballast effect even enhanced organic carbon fluxes by > 62% off South Java so that organic carbon fluxes are higher in the low-productive South Java Sea compared to the high-productive western Arabian Sea upwelling area. This implies that land uses changes affect the CO_2 uptake of the organic carbon pump by increasing lithogenic matter inputs into the ocean.

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Captions

Figure 1: Bathymetric chart of the northern Indian Ocean and the adjacent land mass. Data were obtained from http://Ingrid.ldgo. Columbia.edu/SOURCE/WORLDBATH. White circles show the sediment trap sites operated by the joint Indo/German and Indonesian German projects (see Tab. 1). The black circles represent the US JGOFS sediment trap site M2 to M5 (Honjo et al., 1999; Lee et al., 1998).

Figure 2. Monthly mean wind speeds (a, b), derived from the Scatterometer Climatology of Ocean Winds (Risien and Chelton, 2008) indicating the Findlater Jet during the summer (August) in the Arabian Sea. Monthly mean sea surface salinities (c, d) derived from the Soil Moisture and Ocean Salinity (SMOS) satellite mission. Monthly mean primary production rates (Behrenfeld and Falkowski, 1997) covering the periods between 2002 and 2014 (e, f). The black circles show the sediment trap sites (Fig. 1, Tab. 1).

Figure 3: Monthly mean organic carbon fluxes (POC) obtained from our sediment trap experiments in the Arabian Sea (a) and the Bay of Bengal (c) as well as monthly mean primary production rates (Behrenfeld and Falkowski, 1997) selected for the sediment trap sites (b, d). The sediment trap data were normalized to a water depth of 2000 m by using the equation introduced by Rixen et al. (2002).

Figure 4: Densities of bulk components including quartz and illite as representatives of lithogenic matter (red lines, and circle). Black circles and lines indicate the densities of crystalline analogues and of cellulose as an example of a carbohydrate. The data were compiled from the literature and the references are given in the text. The grey area shows the density range of seawater.

Figure 5: Sea water temperature (a) and salinity profiles (b) selected from the World Ocean Atlas 2013 for the trap site and (c) speed of sinking material derived from the sea water properties (Eqs. 7 - 9) and the density of the solid (see Eq. 6). The grey bar indicates water-depth < 100 m. Black, red and blue lines represent the trap site JAM, as well as the trap sites in the Bay of Bengal and the Arabian Sea.

Figure 6: Organics carbon fluxes measure at JAM and the primary production rates selected for the JAM site.

Figure 7: T_{eff} versus export production rates derived from equation 1 (a), 2 (b) and 3 (c). The red circle indicate samples associated with lithogenic matter content < 25%.

Figure 8: Organic carbon fluxes (POC) versus lithogenic matter content (a) and carbonate flux (b). The red and black circle indicate trap sites at which the annual mean lithogenic matter content is < and > 25%, respectively.

Figure 9: (a) Annual mean lithogenic matter content at the trap sites in the Indian Ocean versus sinking speeds derived from the density of the solids (Eqs. 6 - 9) including the regression equation and line. The red circle indicates sinking speeds derived from the US JGOFS sediment trap sites in the western Arabian Sea (Berelson, 2001) and the blue circle represents sinking speeds derived from the density of the solids by setting the lithogenic matter flux to zero. (b) Annual mean organic carbon fluxes determined at the sediment trap sites versus organic carbon fluxes calculated by using Eq.10 and sinking speed shown in figure 8 a. The export production was derived from Eq.1 (red circles), 2 (blue circles), and 3 (black circles). The red colour shows the regression equation and line obtained from the correlation between the calculated and measured fluxes whereas the respective export production used to calculate the organic carbon flux was derived from Eq.1. The black line indicates the 1:1 line (c) Calculated versus measured fluxes as in (b) but the modified Eq.3 was used to calculate the required export production. The errors bars indicate the interannual variability of the measured fluxes and the range caused the variability of the sinking speeds used to calculate the organic carbon flux.

Figure 10: Calculated versus measured annual mean organic carbon fluxes. In addition to export production derived from primary production and the modified Eq. 3 a constant sinking speed of 224 m day^{-1} was used to calculate organic carbon fluxes. Black and red circles indicate data obtained at those sites characterized by low (<25%) and high lithogenic matter content (> 25%).

Figure 11: (a) Annual mean lithogenic matter content at the trap sites in the Indian Ocean versus sinking speeds derived from the density of the solids and sea water properties (black circles) including the regression equation and line as show in Figure 9a but without error bars. The red circles indicate sinking speeds derived from the density of the solids by setting the lithogenic matter flux to zero. This data were plotted versus the original lithogenic matter content to illustrate the differences between sinking speeds calculated with and without considering the lithogenic matter flux (Δ Sinking Speed). The blue circle represents mean sinking speeds derived from the density of the solids by setting the lithogenic matter flux to zero. (It represents the average of the data indicated by the red circles). (b) 'Δ Sinking Speed' versus the annual mean lithogenic matter content at the trap sites in the Indian Ocean including regression equation and line. (c) 'Δ POC flux' versus 'Δ Sinking Speed'. Δ POC flux is the difference between organic carbon fluxes derived from primary production and the modified Eq. 3 and sinking speeds derived from the density of solids with (POC1) and without considering lithogenic matter content (POC2). It is expressed as percentile deviation of the difference (POC1 – POC2) from the organic carbon fluxes calculated based on the lithogenic matter contents (POC1). Positive values indicate that POC1 is larger than POC2.

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The increase of organic carbon flux indicates the strength of the lithogenic matter ballast effect, which based on our calculations,

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a at trap sites revealing a lithogenic matter content of 12 to 22%. Due to an enhanced lithogenic matter content of 25 to 61% a stronger lithogenic matter ballast effect increased calculated organic carbon fluxes enhanceraises organic carbon fluxes

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Such a strong lithogenic matter ballast effect explains high measured observed organic carbon fluxes in the - compared to the western Arabian Sea - low-productive South Java Sea.

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A Multiple Linear Regression Analysis (MLR) using a global compilation of sediment trap data, including data from the Indian Ocean, showed that primary production hardly affects organic carbon fluxes and that carbonate is the main ballast mineral controlling the organic carbon export into the deep sea in the world's ocean (Klaas and Archer, 2002).

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and could be regarded as a measure for the reproducibility of sediment trap data

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and could be regarded as a measure for the reproducibility of sediment trap data

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and winter, respectively

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and winter, respectively

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and winter, respectively

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and winter, respectively

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. Accordingly, also

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. Accordingly, also

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thus, impacts

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Page 9: [26] Comment [2] **Birgit Gaye** **15/11/18 08:54**

In der Einleitung hattest Du gesagt, dass Winter für boreal steht. Hier benutzt Du es für südlichen Winter. Alternativ kannst Du es ja dazu schreiben.

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during the

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during the

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are assumed to

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are assumed to

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as the sediment trap data

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as the sediment trap data

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During this time low primary production rates accompanied high organic carbon fluxes.

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this discrepancy

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this discrepancy

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, which is stronger

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than during the upwelling season in summer and could explain the

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than during the upwelling season in summer and could explain the

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This also helps to estimate the reliability of satellite data and the contribution of resuspended sediments to the measured fluxes.

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This verifies the application paleo-temperature functions used to convert Mg/Ca ratios measured in *G. ruber* shells, which were preserved in marine sediments into seawater temperature. Since seawater temperatures vary temporally and spatially the link between proxies derived from foram shells and satellite data obtained at the trap site during the lifetime of forams indicate the reliability of at least satellite-derived sea surface temperatures. Furthermore, it

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This is a strong argument against a significant input of resuspended sediments as this they would contains foram shells deposited at other times and sites disturbing the link between $\delta^{18}O$, Mg/Ca ratios, and sea water temperatures.

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compared to other sites in the Indian Ocean

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compared to other sites in the Indian Ocean

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could be an alternative and/or additional

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could be an alternative and/or additional

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could be an alternative and/or additional

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However, resuspension of sediments supplying large amounts of lithogenic matter and no *G. ruber* shells are difficult to imagine, as they are as lithogenic matter a component of marine sediments. Nevertheless, it cannot be ruled out that a lateral turbidity flow across shelf and slope sediments reached the trap and a density fractionation separated lithogenic matter from foram shells during the transport of the resuspended sediments. As suggest in our previous study (Rixen et al., 2006) river discharges could be an alternative and/or additional source of lithogenic matter, which incorporated into particles sinks along with foram shells form surface ocean into the deep sea

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Considering that the numerous small Indonesian rivers contribute 13% to the global riverine sediment discharge into the ocean (Syvitski et al., 2005) t

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(Romero et al., 2008). Since organic carbon-to-nitrogen ratios and stable carbon isotopic ratios of organic matter were in the range of marine plankton it was suggested that impacts of resuspended sediments and terrestrial organic matter were negligible at JAM (Rixen et al., 2006).

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explaining

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explaining

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was much lower

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was much lower

Page 10: [53] Deleted **Dr. Tim Rixen** **21/11/18 18:52**

. Muss das hier angesprochen werden? but it poses also the question whether this increase in the lithogenic matter content could be sufficient to explain the low ratio between primary production and organic carbon

flux observed at JAM in winter 2002/2003.

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The compared to WAST higher ratio between organic carbon fluxes and primary production was most pronouncedenhanced in winter when high organic carbon fluxes occurred in association with low primary production (Fig. 3, 6). A stronger lithogenic matter ballast effects in winter agrees with anis indicated by an increase of the lithogenic matter content by about 8% between summer and winter (Tab. 1) but it poses also the question whether such anthis increase in the lithogenic matter content could be sufficeient to explain the low ratio between primary production and organic carbon flux as observed at JAM in winter 2002/2003.

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In an attempt to further estimate

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This indicates that

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Das verstehe ich nicht. Fig. 7 zeigt doch eine Antikorrelation?

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at our sites

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another and often-used

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another and often-used

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In order to investigate

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To gain more clarity we correlated

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This is obvious in blooms dominated by coccolithophorids, as well as in those dominated by non-calcifying phytoplankton when e.g. calcifying grazers such as pelagic foraminifera prevail.

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This is obvious in blooms dominated by coccolithophorids, as well as in those dominated by non-calcifying phytoplankton when e.g. calcifying grazers such as pelagic foraminifera prevail.

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This is obvious in blooms dominated by coccolithophorids, as well as in those dominated by non-calcifying phytoplankton when e.g. calcifying grazers such as pelagic foraminifera prevail.

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This is obvious in blooms dominated by coccolithophorids, as well as in those dominated by non-calcifying phytoplankton when e.g. calcifying grazers such as pelagic foraminifera prevail.

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In contrast to carbonate

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organic particles

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This is another meansa complementary approach addition to satellite-derived export production rates allowed us to computinge organic carbon fluxes (Eq. 10) . in addition to satellite-derived export production rate estimatess, but requires verification.. The reliability of the approach will be tested by comparing calculated sinking speeds with literature values and by comparing calculated and measured organic carbon fluxes. Subsequently, this approach will be used to quantify the impact of the individual ballast minerals on sinking speeds and organic carbon fluxes., which in turn indicates the strength of the ballast effect.

To calculate the density of the solids (ρ_{solids}, Eq. 6) and the resulting sinking speed of particles (Eqs. 7- 9), the densities of bulk components were compiled from the literature

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The high mineral-specific density of lithogenic matter its content mainly controlsis a first-order influence on sinking speeds as indicated by the correlation between lithogenic matter content and sinking speed (Fig. 9a).

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when changing the constant in Eq.3 from 0.23 to 0.40 [1]

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Muss man hier schreiben warum man das machen kann?

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The resulting correlation between the calculated and measured fluxes further indicates the reliability of the approach – das zeigt nur, dass man die Gleichung an alles anpassen kann, oder? Gibt es einen Grund weshalb die Konstante 0.4 sein sollte?.

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conducted a numerical experiment in whichwhether we used a constant sinking speed

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affected the flux rates to calculate organic carbon fluxes. Sinking speeds and thus the ballast effect would be negligible if the results obtained by using a constant sinking speed are as good as comparable with the one results obtained by sinking speeds derived from seawater properties and the densities of the solids at each site. unverständlich

We used the mModified Eq. 3 is also suited to calculate the required export production needed to match the observed fluxes in traps. For this and . selected a constant sinking speed of 206.5 (aus irgendeinem überzeugenden Grund? weil es dann past?) m day^{-1} to calculate organic carbonwas adopted fluxes in a first step (Eq. 10). Organic carbon fluxes derived with a constant of 0.4 and constant sinking speed in Eq. 10 At at sampling sites characterized by a lithogenic matter content < 25% organic carbon fluxes derived from the constant and calculated sinking speed hardly deviate from each otherare very similar. In contrast, at the sites in river-influenced regions of the Indian Ocean, organic carbon fluxes computed with a constant sinking speed of 206.56 m day^{-1} are on average by 20% and at JAM by even 35% lower as than the observed onefluxes (meinst Du das?) derived from the calculated sinking speeds. This implies that sSinking speeds and thus the ballast effect isclearly are a factor which influences the spatial variability ofimpacts on organic carbon fluxes at those sites in the river-influenced regions of the Indian Ocean, where suspended alumosilicate detritus is abundant due to river influence. At the other sites outside of river influence their effectthe net impact of the ballast effect on the spatial variability of fluxes appears to be negligible small and primary and export production are the major processes controllingcontrols on the spatial variability of organic carbon fluxes (Fig. 8a – Du solltest die Reihenfolge in Abb. 8 umdrehen!)). This in turn indicates that aimplicates joint production rather than the carbonate ballast effect causeind the correlation between carbonate and organic carbon fluxes at these sites. as shown in figure 8b.

Primary production and the lithogenic matter content of the sinking matter explain the results obtained from our constant sinking speed experiment. At sites in river-influenced regions of the Indian Ocean lithogenic matter contents varyies between 25 and 61% and exceed the variability range of lithogenic matter content

at the other sites where it varies only (between 12 and 21%) (Fig. 8b a). Vice versaOn the other hand, the variability range of primary production is smaller in the river-influenced regions of the Indian Ocean where it ranged betweenwith a range of(0.31 and 0.53 g m^{-2} day^{-1}) as than at the other sites (with a range of (0.31 - 1.15 g m^{-2} day^{-1},) (Tab. 5). Accordingly, the factor revealing thelithogenic matter flux which leads to the larger variability of fluxes also controls the spatial variability of organic carbon fluxes at our sampling site in the Indian Ocean. Rivers Thus, rivers seem to play an important role because they supply lithogenic matter on the one hand to fuel the ballast effect, and because they additionally lower the variability of primary production by forming a buoyant low salinity surface layer depleted in nutrientsas mentioned before.

In order to quantify the impact of tThe

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ballast

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The result (Fig. 9a) impliesy that the absence of lithogenic matter would have reduced the mean sinking speed decelerates from 224 ± 33 to 147 ±5 m day^{-1} (Fig. 9a) in the absence of lithogenic matter and and the resulting mean calculated organic carbon fluxes would beare lower by 501% at sites in the river-influenced regions of the Indian Ocean. At site JAM the absence of lithogenic ballast would have reducesd the organic carbon flux even by even 602%. Vice versa thisand implies that the lithogenic matter ballast effectweighting with silicate detritus increases themore than doubles organic carbon fluxes at JAMby 62%. This pronounced influence of lithogenic ballast is also the reason , which explains the compared to WAST higherfor higher measured organic carbon flux via a more rapid transfer through the water column at JAM than at JAMWAST, although the WAST site is far more productive.

Due to the lower lithogenic matter content the absence of lithogenic matter reduced the calculated organic carbon flux by 41% at sites. characterized by a Where lithogenic matter content of sediment trap material is < 25% in areas outside river influence, the simulated absence of lithogenic matter (as above) reduced the calculated organic carbon flux by approximately 40%.

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and the estimated of an up to

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organic carbon

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organic carbon

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Acknowledgments

First of all, we would like to thank all of the scientists, technicians, officers and their crews of the numerous research vessels used during our studies in the Indian Ocean. We would specifically like to express our gratitude to the Federal German Ministry for Education, Science, Research and Technology (BMBF, Bonn ref. no. 03F0463A), the Council of Scientific and Industrial Research (CSIR, New Delhi), the Ministry of Earth Sciences (MOES, New Delhi), and the Agency for the Assessment and Application of Technology (BPPT), Jakarta, Indonesia for financial support. P. Wessels and W.H.F Smith are acknowledged for providing the generic mapping tools (GMT).

Table 1. Number of station, trap ID, station name, position, water-depth, trap depth, seawater temperature and salinity.

No.	Trap ID	Name	Lat.	Lon.	W-Depth	T-Depth
			[°N]	[°N]	[m]	[m]
1	WAST	Western Arabian Sea Trap Station	16.26	60.58	4032	3017
2	CAST	Central Arabian Sea Trap Station	14.51	64.72	3920	2944
3	EAST	Eastern Arabian Sea Trap Station	15.57	68.73	3791	2870
4	NEAST	Northeastern Arabian Sea Trap Station	16.93	67.84	3545	3039
5	SAST	Southern Arabian Sea Trap Station	11.60	66.08	4243	3032
6	EIOT	Equatorial Indian Ocean Trap Station	3.56	77.78	3400	2374
7	NBBT-N	Northern Bay of Bengal Trap Station – North	17.42	89.65	2267	1889
8	NBBT-S	Northern Bay of Bengal Trap Station – South	15.48	89.45	2709	2172
9	CBBT-N	Central Bay of Bengal Trap Station – North	13.14	84.41	3266	2261
10	CBBT-S	Central Bay of Bengal Trap Station – South	11.03	84.43	3462	2527
11	SBBT	Southern Bay of Bengal Trap Station	5.09	87.26	3995	2976
12	JAM	Java Mooring	-8.28	108.02	3250	2456

Table 2. Trap ID, season, seasonal averaged primary production, sea surface temperature, organic carbon flux and lithogenic matter content.

Trap ID	Season	PP [g m^{-2} day^{-1}]	SST [°C]	POC [mg m^{-2} day^{-1}]	Lith. Matter [%]
WAST	summer	1.28	25.60	11.69	14.46
WAST	winter	0.79	26.32	7.50	15.39
WAST	transition	0.49	27.90	6.48	13.04
CAST	summer	1.11	26.76	6.95	16.73
CAST	winter	0.70	26.93	6.41	14.55
CAST	transition	0.42	28.32	5.52	15.85
EAST	summer	0.57	27.56	6.82	21.39
EAST	winter	0.46	27.41	5.28	19.91
EAST	transition	0.30	28.63	5.05	21.97
SAST	summer	0.56	27.78	6.65	14.21
SAST	winter	0.34	27.98	6.46	15.75
SAST	transition	0.30	28.75	3.91	14.87
SBBT	summer	0.39	28.39	7.91	15.04
SBBT	winter	0.27	29.00	5.34	17.48
SBBT	transition	0.29	28.85	5.29	15.27
EIOT	summer	0.38	28.75	4.55	10.13
EIOT	winter	0.27	29.06	3.90	18.50
EIOT	transition	0.34	28.92	4.07	11.65
CBBT-N	summer	0.31	28.98	8.03	38.90
CBBT-N	winter	0.32	27.90	8.00	36.14
CBBT-N	transition	0.29	28.92	7.64	44.89
CBBT-S	summer	0.35	28.95	5.13	24.33
CBBT-S	winter	0.30	28.16	5.15	32.45
CBBT-S	transition	0.30	28.97	6.19	21.99
NBBT-N	summer	0.39	28.82	9.74	41.99
NBBT-N	winter	0.34	27.15	7.05	38.06
NBBT-N	transition	0.29	28.80	6.92	38.98
NBBT-S	summer	0.34	28.73	5.91	32.39
NBBT-S	winter	0.30	27.53	6.03	33.49
NBBT	transition	0.27	28.93	6.17	32.76
JAM	summer	0.86	27.09	14.35	60.48
JAM	winter	0.31	29.08	11.47	68.09
JAM	transition	0.49	28.48	11.75	60.36
NEAST	transition	0.33	28.13	8.80	29.82

Table 3. Annual mean total fluxes measured at the trap sites during the years from 1987 to 2002 in the g C m^{-2} $year^{-1}$ including the mean and the standard deviation as well as the number of years (no) in which particle fluxes were measured for more than 255 days $year^{-1}$. For calculating the long-term average data obtained in years in which fluxes were measured for less than 255 day were omitted.

Trap ID	87	88	89	90	91	92	93	94	95	96	97	98	1	2	Mean	Std.	No.
	[g C m^{-2} $year^{-1}$]															[%]	
WAST	43.0	53.6		66.0	50.6	48.5		52.9	58.6		69.2				55.3	16.0	8
CAST	34.4	40.7					35.0	40.3		40.0					38.1	8.2	5
EAST			39.0		37.5		23.3								33.3	26.1	3
SAST																	
EIOT										21.3					21.3		1
NBBT-N		53.2	50.2					53.4		47.5	38.9	46.1			48.2	11.3	6
NBBT-S					33.4	34.0									33.7	1.3	2
CBBT-N		43.5	56.7	66.4	60.7		44.8								54.4	18.3	5
CBBT-S						34.8									34.8		1
SBBT		39.9			37.3		37.2	42.3							39.9	6.2	4
JAM													101.8	122.1	112.0	12.8	2

Table 4. Trap ID, mean bulk fluxes including standard deviation (std) and contents. In contrast to averages presented in Tab. 3 all data including the one measured in years in which fluxes were measured for less than 255 day were used to calculate mean values and the standard deviations shown in this table.

Trap ID	POC	std	Carb.	std	Opal	std	Lith.	std	POC	Carb.	Opal	Lith.
	[g m^{-2} $year^{-1}$]								[%]			
WAST	3.1	0.4	29.0	3.5	13.1	3.9	7.9	1.5	5.6	52.3	23.5	14.2
CAST	2.3	0.2	22.4	1.3	4.8	0.4	5.9	0.8	6.1	60.1	12.9	15.9
EAST	2.1	0.3	17.9	2.1	5.4	1.1	7.3	1.1	6.1	52.2	15.8	21.1
SAST	2.3	0.0	27.1	0.0	6.0	0.0	6.5	0.0	5.2	62.0	13.6	15.0
EIOT	1.5	0.3	16.4	3.1	5.2	1.3	3.6	0.9	5.4	58.7	18.7	12.8
NBBT-N	2.9	0.3	13.3	1.9	10.4	0.7	18.8	3.9	6.1	27.9	21.8	39.5
NBBT-S	2.2	0.0	11.0	0.4	7.7	0.4	11.1	0.3	6.5	32.5	22.9	32.9
CBBT-N	2.9	0.3	15.5	1.0	11.7	2.3	21.9	5.9	5.3	28.5	21.6	40.3
CBBT-S	2.0	0.0	13.4	0.0	8.9	0.0	9.0	0.0	5.7	38.4	25.6	25.7
SBBT	2.3	0.3	20.0	1.8	9.8	1.5	6.1	1.4	5.6	50.0	24.6	15.3
JAM	4.8	0.6	15.1	2.5	31.3	15.6	86.6	23.9	3.4	10.7	22.1	61.1

Table 5. Trap ID, annual mean primary production (PP) and sea surface temperature (SST) as well as seawater temperature (Temp) and salinity. Temp and salinity were selected for trap sites from the World Ocean Atlas 2013 and averaged between water-depth of 100 and 1500 m. Density and viscosity were calculate by using Temp and salinity, considering a water-depth of 800 m. Python routines 'gsw' and iapws were used for these calculations. In addition to our trap site also data for the US JGFOS trap site MS2-5 were selected. Figure 1 shows the location of these sites.

Station ID	PP	SST	Temp.	Salinity	Density	Viscosity
	[g m^{-2} day^{-1}]	[°C]	[°C]		[g cm^{-3}]	[kg m^{-1} s^{-1}]
WAST	0.79	26.93	11.48	35.49	1.030511	0.001217
CAST	0.69	27.57	11.22	35.43	1.030517	0.001225
EAST	0.42	28.07	11.11	35.42	1.030529	0.001229
SAST	0.38	28.38	10.63	35.29	1.030525	0.001244
NEAST	0.49	27.81	11.32	35.47	1.030527	0.001222
EIOT	0.33	29.05	9.34	35.01	1.030555	0.001287
NBBT-N	0.33	28.25	9.42	34.96	1.030505	0.001285
NBBT-S	0.30	28.43	9.42	34.96	1.030505	0.001285
CBBT-N	0.31	28.57	9.38	34.96	1.030510	0.001286
CBBT-S	0.31	28.70	9.36	34.98	1.030526	0.001286
SBBT	0.31	28.91	9.33	34.99	1.030542	0.001288
JAM	0.53	28.33	8.25	34.69	1.030496	0.001326
MS2	1.15	26.48	11.53	35.52	1.030523	0.001215
MS3	0.97	26.60	11.56	35.52	1.030518	0.001214
MS4	0.74	27.11	11.35	35.45	1.030509	0.001221
MS5	0.32	28.43	10.32	35.22	1.030529	0.001254

Table 6. Values used to calculate sinking speeds (Eqs.6 - 9). Densities of the bulk components were obtained from the literature.

	Value	Unit
POC-specific respiration rate (λ)	0.106	day^{-1}
Porosity	0.917	
Radius	0.150	mm
Density of the ballast material		
OM	0.90 ±0.20	g cm^{-3}
Opal	1.73 ±0.27	g cm^{-3}
Carb.	1.63 ±0.08	g cm^{-3}
Lith.	2.70 ±0.05	g cm^{-3}

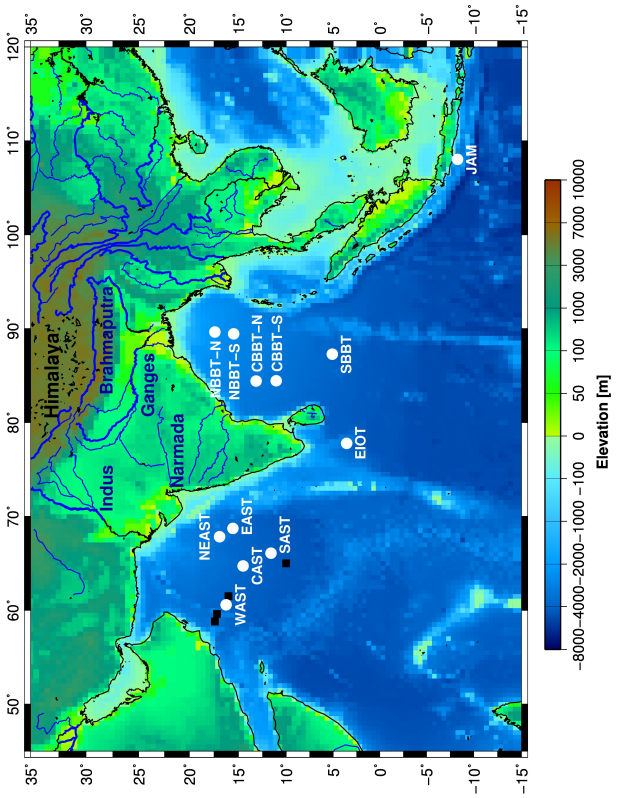
Table 7. Carrying coefficients derived from the MLR applied to data measured at the trap sites (Trap ID) including the mean. 'No.' indicates the number of data used for the analysis. A-Trap shows the carrying coefficients derived by applying the MLR to the annual mean sediment data obtained from our sites (No. = 11) and including the US JGOFS data (No. = 17). CA-Trap shows carrying coefficients obtained from all annual means (our and US JGOFS data) including a constant term to Ep. 4.

Trap ID	$CaCO_3$	Std.	P val.	Opal	Std.	P val.	Lith.	Std.	P val.	r^2	No.
WAST	0.044	0.007	0.000	0.046	0.007	0.000	0.132	0.018	0.000	0.958	142
CAST	0.018	0.007	0.008	0.198	0.032	0.000	0.120	0.026	0.000	0.955	88
EAST	0.033	0.007	0.000	0.124	0.020	0.000	0.108	0.014	0.000	0.970	115
SAST	0.011	0.004	0.034	0.049	0.028	0.111	0.256	0.029	0.000	0.998	13
EIOT	0.031	0.008	0.000	0.035	0.034	0.303	0.227	0.029	0.000	0.963	39
NBBT-N	0.090	0.011	0.000	0.070	0.015	0.000	0.046	0.005	0.000	0.973	88
NBBT-S	-0.022	0.031	0.480	0.139	0.048	0.008	0.126	0.023	0.000	0.964	26
CBBT-N	0.096	0.008	0.000	0.057	0.012	0.000	0.033	0.005	0.000	0.972	78
CBBT-S	0.017	0.019	0.372	0.078	0.025	0.011	0.115	0.028	0.002	0.982	13
SBBT	0.041	0.006	0.000	0.073	0.011	0.000	0.115	0.014	0.000	0.960	99
JAM	0.128	0.026	0.000	0.034	0.013	0.010	0.022	0.005	0.000	0.943	54
Mean	0.044	0.012		0.082	0.022		0.118	0.018			
A-Trap	0.067	0.018	0.006	0.113	0.062	0.105	0.006	0.021	0.761	0.983	11
A-Trap	0.073	0.013	0.000	0.116	0.046	0.024	0.004	0.015	0.789	0.989	17
CA-Trap	0.066	0.018	0.002	0.120	0.048	0.026	0.002	0.016	0.913	0.922	17

Table 8. Contribution of the individual ballast minerals to the predicted POC flux (RIB see Eq. 5)

Trap	$CaCO_3$	Opal	Lith.
WAST	47.0	17.8	35.1
CAST	21.1	46.2	32.7
EAST	31.0	30.9	38.1
SAST	13.4	12.8	73.8
EIOT	37.0	11.8	51.2
NBBT-N	42.8	24.5	32.7
NBBT-S	-11.9	51.6	60.4
CBBT-N	55.2	21.4	23.4
CBBT-S	12.0	34.7	53.2
SBBT	36.0	30.9	33.1
JAM	41.1	19.1	39.7
Mean	29.5	27.4	43.0

Figure 1


Himalaya
Brahmaputra
Ganges
Narmada
Indus
NBBT–N
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CBBT–N
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Elevation [m]
−8000 −4000 −2000 −1000 −100 0 50 100 1000 3000 7000 10000

Figure 2

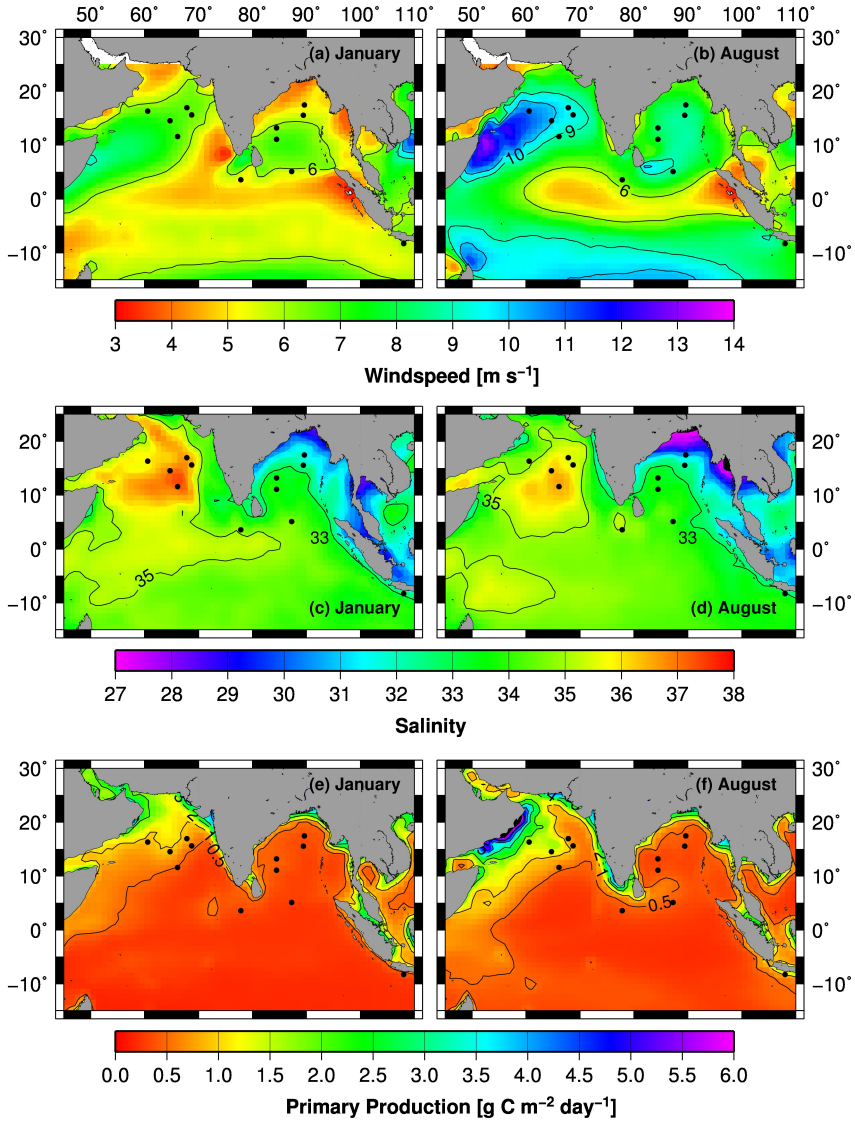
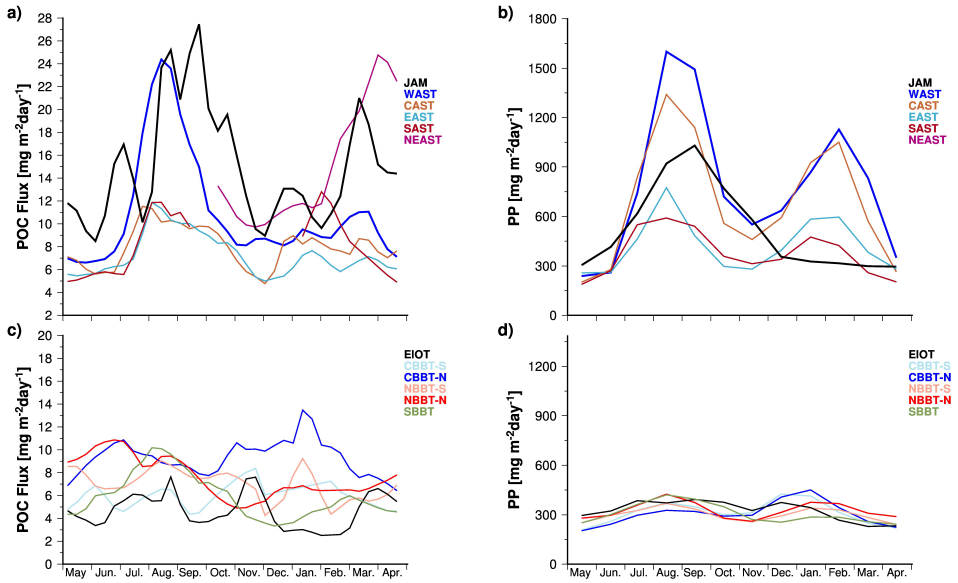

50° 60° 70° 80° 90° 100° 110°
30° 20° 10° 0° −10°
(a) January
(b) August
6
9
10
3 4 5 6 7 8 9 10 11 12 13 14
Windspeed [m s−1]
(c) January
(d) August
33
35
27 28 29 30 31 32 33 34 35 36 37 38
Salinity
(e) January
(f) August
0.5
1
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Primary Production [g C m−2 day−1]

Figure 3


a)
POC Flux [mg m-2day-1]
JAM
WAST
CAST
EAST
SAST
NEAST
b)
PP [mg m-2day-1]
JAM
WAST
CAST
EAST
SAST
NEAST
c)
POC Flux [mg m-2day-1]
EIOT
CWBT-S
CBBT-N
NBBT-S
NBBT-N
SBBT
d)
PP [mg m-2day-1]
EIOT
CWBT-S
CBBT-N
NBBT-S
NBBT-N
SBBT
May
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Apr.

5

Figure 4

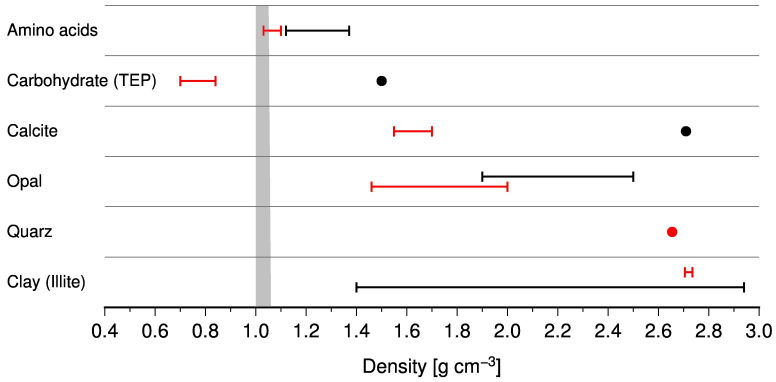

Amino acids
Carbohydrate (TEP)
Calcite
Opal
Quarz
Clay (Illite)
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
Density [g cm−3]

Figure 5

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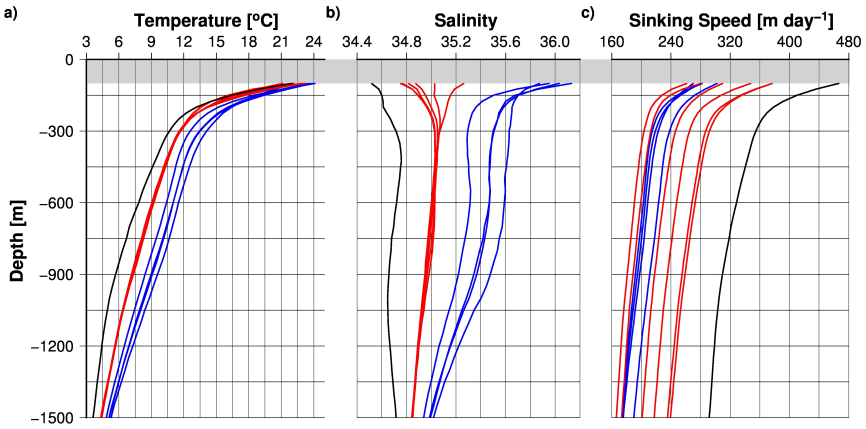
Moved (insertion) [1]



5

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Moved up [1]: <*sp*>Figure 5

Figure 6

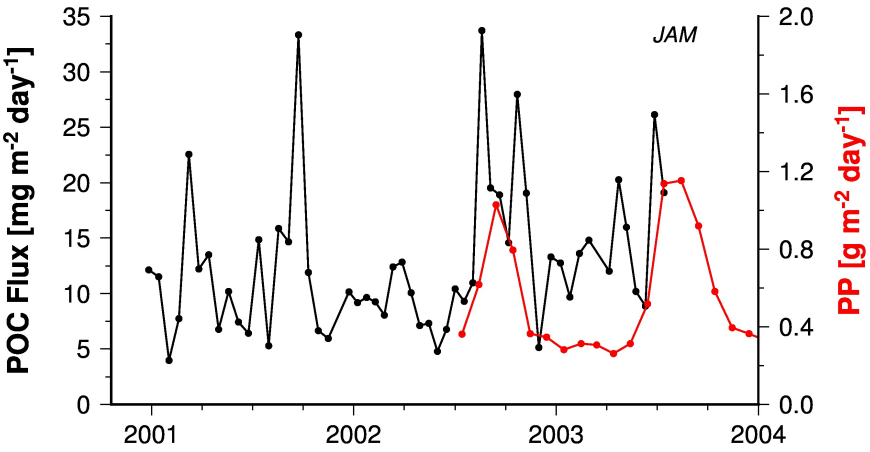

JAM
POC Flux [mg m-2 day-1]
PP [g m-2 day-1]
35
30
25
20
15
10
5
0
2.0
1.6
1.2
0.8
0.4
0.0
2001
2002
2003
2004

Figure 7

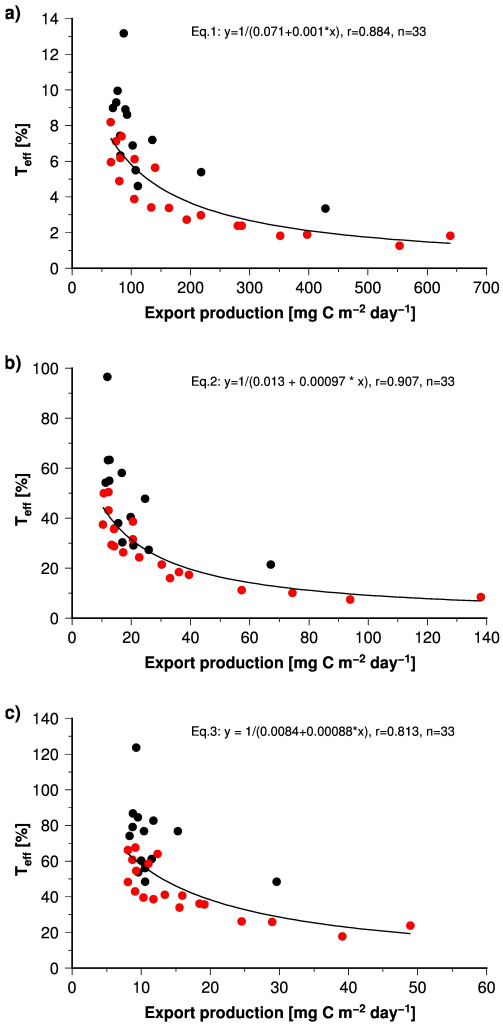
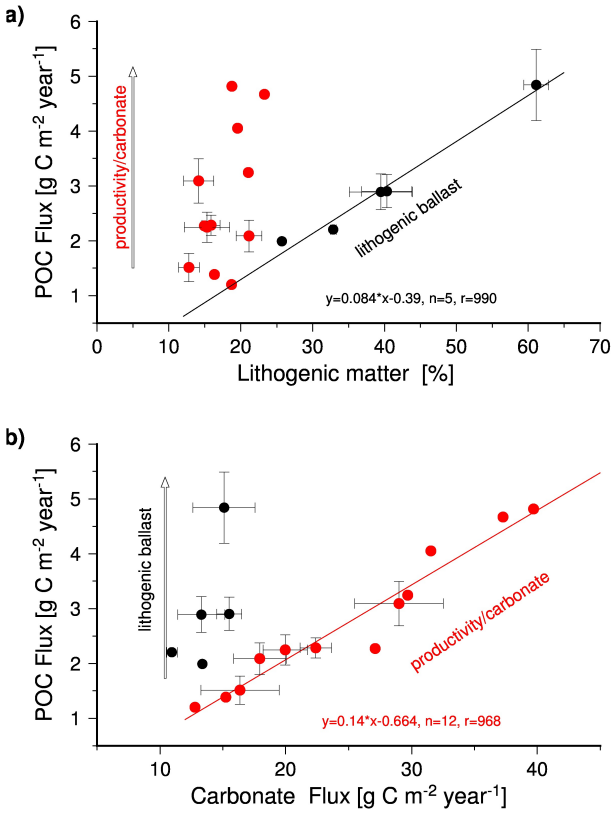
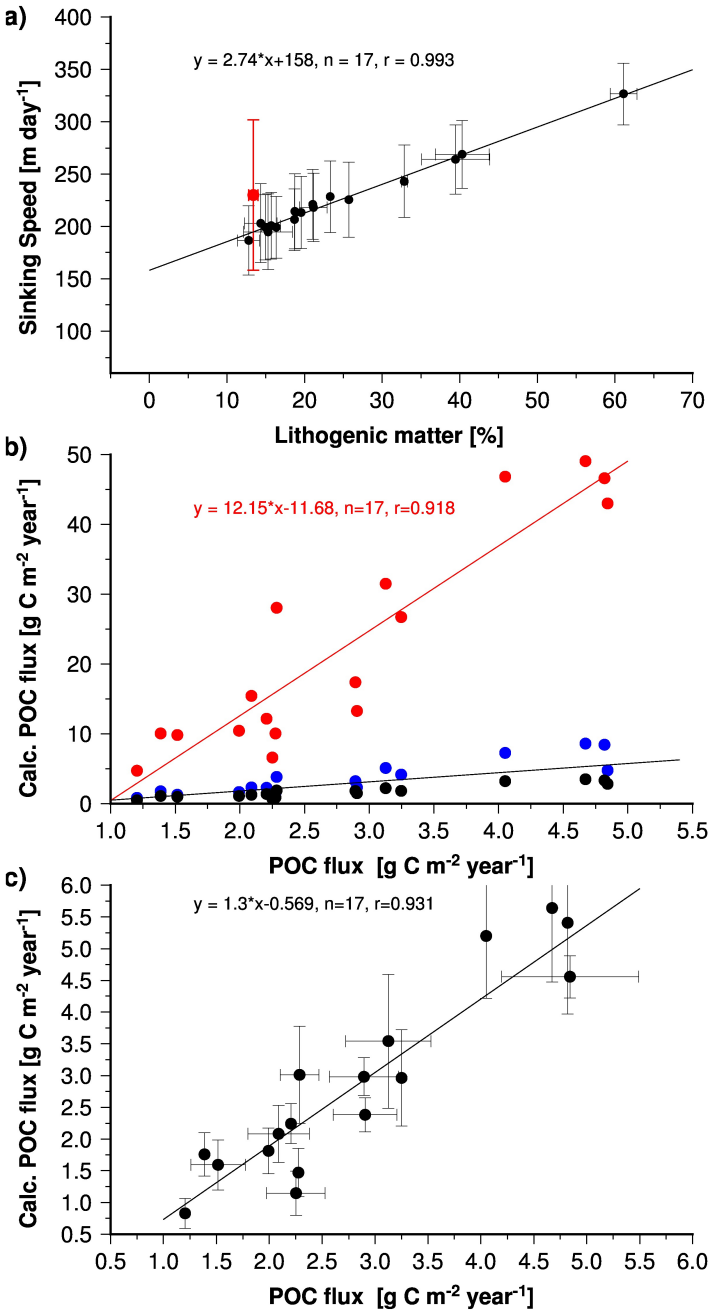

a)
Eq.1: y=1/(0.071+0.001*x), r=0.884, n=33
T_eff [%]
Export production [mg C m⁻² day⁻¹]
b)
Eq.2: y=1/(0.013 + 0.00097 * x), r=0.907, n=33
T_eff [%]
Export production [mg C m⁻² day⁻¹]
c)
Eq.3: y = 1/(0.0084+0.00088*x), r=0.813, n=33
T_eff [%]
Export production [mg C m⁻² day⁻¹]

Figure 8


a)
POC Flux [g C m-2 year-1]
productivity/carbonate
lithogenic ballast
y=0.084*x-0.39, n=5, r=990
Lithogenic matter [%]
b)
POC Flux [g C m-2 year-1]
lithogenic ballast
productivity/carbonate
y=0.14*x-0.664, n=12, r=968
Carbonate Flux [g C m-2 year-1]

5

Figure 9


a)
y = 2.74*x+158, n = 17, r = 0.993
Sinking Speed [m day-1]
Lithogenic matter [%]
b)
y = 12.15*x-11.68, n=17, r=0.918
Calc. POC flux [g C m-2 year-1]
POC flux [g C m-2 year-1]
c)
y = 1.3*x-0.569, n=17, r=0.931
Calc. POC flux [g C m-2 year-1]
POC flux [g C m-2 year-1]

5

15

Figure 10

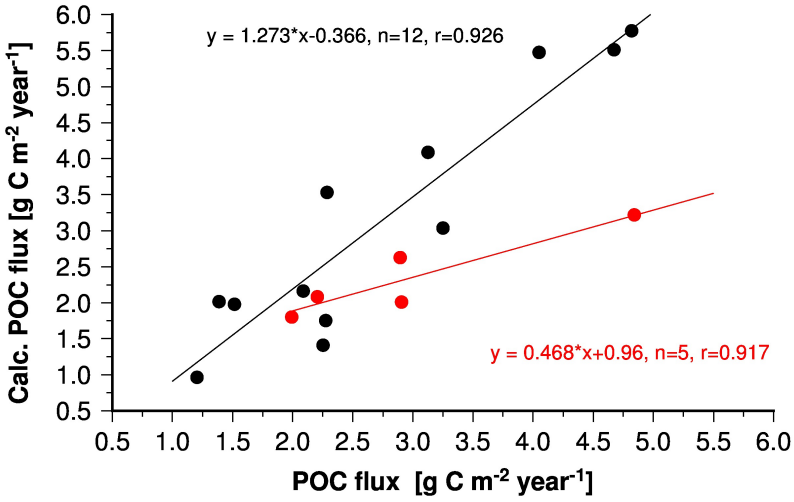
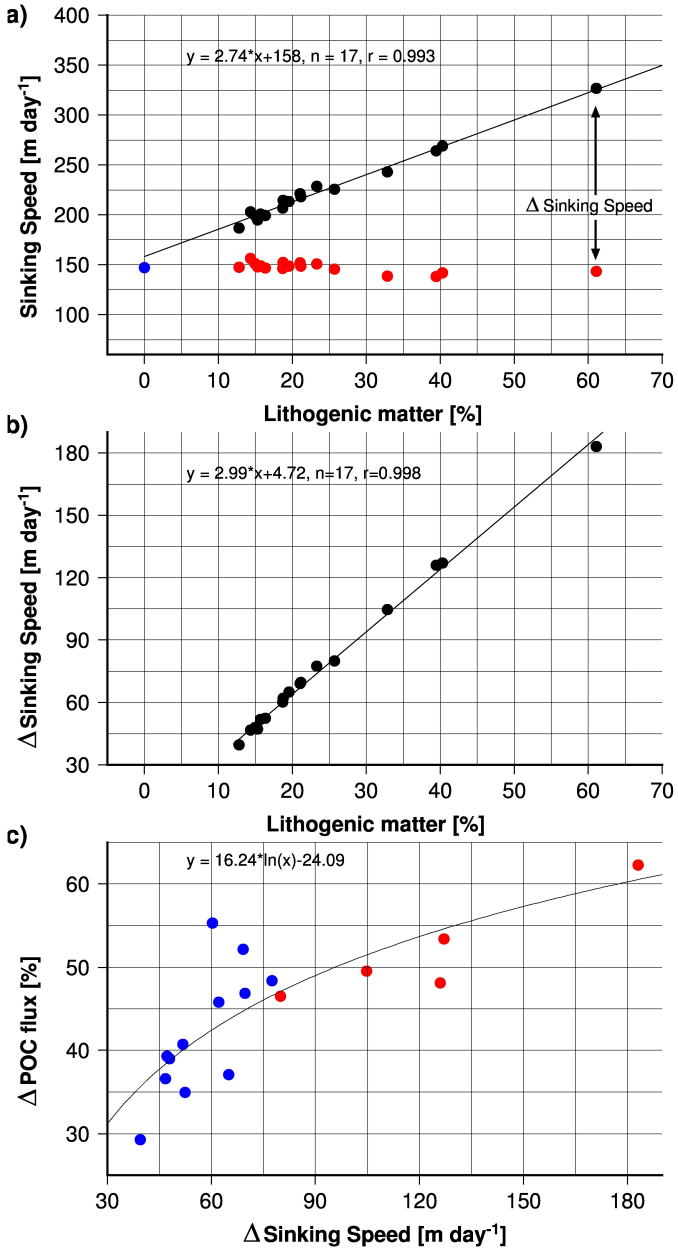

y = 1.273*x-0.366, n=12, r=0.926
y = 0.468*x+0.96, n=5, r=0.917
Calc. POC flux [g C m-2 year-1]
POC flux [g C m-2 year-1]
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0

Figure 11



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