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ENSO-driven carbon see saw in the Indo-Pacific

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[1] The sediment trap experiments have been carried out during the 2001/2002 El Niño/La Niña transition in the monsoon-driven and freshwater influenced upwelling system off South Java. The results indicate that enhanced precipitation rates and associated river discharges increase the CO_2-uptake of the biological pump by increasing the organic carbon export and reducing the carbonate precipitation. The freshwater, furthermore, forms a buoyant low salinity surface layer that caps off the nutrient and CO_2-rich subsurface waters which shortens the upwelling season during wet La Niña conditions. A reduced capping-effect during dryer El Niño conditions strengthens the upwelling and as shown by our model results increase CO_2 emission into the atmosphere along the freshwater influenced continental margins in SE Asia. By contrast El Niño weakens upwelling and reduces the CO_2 emission in the equatorial Pacific Ocean. **Citation:** Rixen, T., V. Ittekkot, B. Herunadi, P. Wetzel, E. Maier-Reimer, and B. Gaye-Haake (2006), ENSO-driven carbon see saw in the Indo-Pacific, *Geophys. Res. Lett.*, *33*, L07606, doi:10.1029/2005GL024965.

1. Introduction

[2] Marine organism influence the CO_2 concentration in the atmosphere via the organic carbon and the carbonate counter pumps together referred to as the biological pump [*Volk and Hoffert*, 1985]. Since the organic carbon pump favours and the carbonate counter pump lowers the marine uptake of atmospheric CO_2 the ratio between particulate organic carbon (POC) and carbonate carbon (PIC) known as the 'rain ratio' has suggested to be an indicator for the CO_2 uptake efficiency of the biological pump [*Berger and Keir*, 1984]. Data-based estimates of rain ratios are scarce and range between 3.3 and 12.5 [*Sarmiento et al.*, 2002, and references therein]. Sediment traps which are at present the only tools intercepting sinking particles in the water column show that POC/PIC ratios vary between 1.05 and 0.50 in the deep ocean (water-depth > 1000 m) at lower latitudes [*Klaas and Archer*, 2002]. This relatively low variation has been explained by the ballast-effect exerted by carbonates in sinking particles [*Armstrong et al.*, 2002; *Klaas and Archer*, 2002]. A decreased contribution of carbonate (ballast-effect) can increase the decomposition of organic matter by lowering the sinking speed and thus enhance the residence time of particles in the water column. Accordingly, a lower carbonate export associated with an enhanced decomposition of organic matter could result in POC/PIC ratio similar to one caused by an enhanced export of carbonate and a lower remineralization of organic matter. In order to study the carbon export from the surface into the deep sea and possible links to the CO_2 emission into the atmosphere sediment trap experiments and hydrographic surveys have been carried out off South Java, Indonesia and results obtained have been evaluated with a model. The sediment trap had been deployed at water depths of approximately 2200 m (8°17.5′S, 108°2.0′E) between November, 2000 and November 2002. Sampling intervalls varied between 16 and 18 days; sample processing and anaylitcal methods are described elsewhere [*Haake et al.*, 1993; *Jennerjahn et al.*, 2004].

2. Study Area

[3] Indonesia experiences some of the highest rates of precipitation in the world and contributes 20 to 25% to the global riverine sediment discharge [*Milliman et al.*, 1999]. Rainfall is strongly influenced by the Asian monsoon and the climate anomaly El Niño Southern Oscillation (ENSO). Its two well-known extremes, El Niño and La Niña causes a decrease and an increase, respectively, of the precipitation rates over Indonesia [*Ropelewski and Halpert*, 1987]. Monsoon-driven seasonally changing wind directions from SE to NW force the reversal of the South Java Current [*Quadfasel and Cresswell*, 1992] and lead to a dry season (June–October; SE monsoon) and a rainy season (December–April; NW monsoon) with the latter characterized by increased river discharges from Java by a factor of ∼12 [*Jennerjahn et al.*, 2004]. Ekman induced upwelling of cold, nutrient-enriched subsurface water occurs along the coast off South Java during the SE monsoon [*Susanto et al.*, 2001, Figure 1].

3. Results and Discussions

[4] The sediment trap results reflect the monsoon-caused seasonality with enhanced particulate organic carbon (POC) fluxes at the end of the NW and during SE monsoon (Figure 1). Enhanced POC fluxes at the end of the NW monsoon in March/April seem to be related to phytoplankton blooms triggered by increased riverine nutrient discharges following the rainy season as revealed by SeaWiFS data in the Java Sea [*Hendiarti et al.*, 2004]. The high SE monsoon POC fluxes are caused by an enhanced primary production driven by upwelling of cold and nutrient-enriched water as indicated by satellite-derived sea surface temperatures (SST). Due to the often observed dominance of diatoms in river-influenced areas [*Jennerjahn et al.*, 2004] and coastal upwelling systems [*Haake et al.*, 1993] the mean

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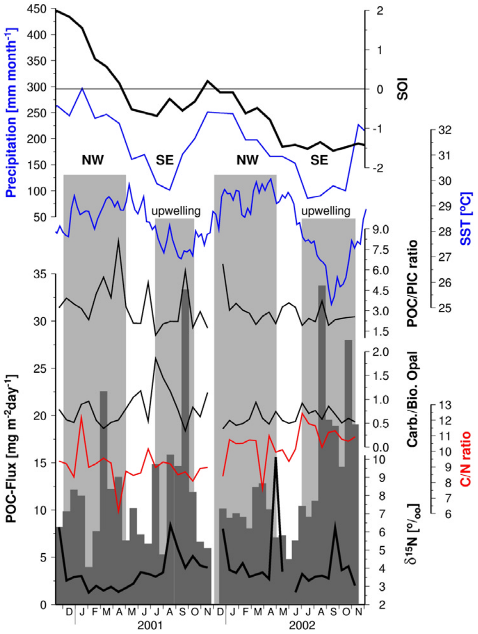

Figure 1. Organic carbon fluxes (bars), δ^{15}N values, C/N, carbonate/biogenic opal, and POC/PIC ratios of sinking matter collected at the sediment trap site. Data gap within the δ^{15}N record of 2002 is caused by the lack of material. Weekly averaged sea surface temperatures [*Reynolds and Smith*, 1994] have been selected for the sampling site. The continental precipitation rates averaged over Indonesia were obtained from the Global Precipitation Climatology Center (www.dwd.de/en/FundE/Klima/KLIS/int/GPCC/) and the Southern Oscillation Index (SOI) from NOAA Climate Prediction Center (www.cpc.ncep.noaa.gov/data/indices). The SOI was smoothed with a six month moving average. Grey bars indicate the NW monsoon seasons 2001 and 2002 and the upwelling season 2001 and 2002.

carbonate/biogenic opal ratios measured off South Java is relatively low and falls with 0.7 even below those measured in the seasonal upwelling system off Arabia (>1.6 [*Haake et al.*, 1993; *Honjo et al.*, 1999]) and the river influenced Bay of Bengal (~1.6 [*Unger et al.*, 2003]).

[5] Stable nitrogen isotope ratios (δ^{15}N) determined in sinking matter off South Java slightly exceeds the mean δ^{15}N value of nitrate in the ocean (~5 [*Brandes and Devol*, 2002]) at the beginning of the NW monsoon (Figure 1). During NW monsoon the δ^{15}N values decrease which can be explained by a preferential uptake of the lighter isotope occurring at high nutrient levels [*Altabet and Francois*, 1994]. Since δ^{15}N values remain low even after the peak POC flux in March/April, it is assumed that inputs of ^{15}N-depleted, terrestrial nitrogen [*Amundson et al.*, 2003] contribute significantly to the low δ^{15}N values during the NW and the subsequent intermonsoon. During the upwelling season the δ^{15}N values increase and reach values > 5 due to inputs of heavier marine nitrogen from subsurface waters. The exceptionally high δ^{15}N value in April/May 2002 is most probably an artifact caused, e.g., by the decomposition of zooplankton in the sampling cup. Zooplankton reveal enhanced δ^{15}N values because of the isotopic fractionation during the trophic transfer of nitrogen [*Altabet*, 1996].

[6] Organic matter produced on land is nitrogen-poor [*Brodowskiy*, 1965], often depleted in ^{13}C and generally exhibits C/N ratios which exceed and δ^{13}Corg values which fall below those of tropical marine plankton (C/N ~6.6, δ^{13}Corg −18−−22‰, [*Fischer et al.*, 1997; *Redfield et al.*, 1963]. C/N ratios of sinking matter collected at water-depth > 1000 m are often > 6.6 due to a preferential decomposition of nitrogenous organic matter, inputs of terrestrial and/or resuspended sedimentary organic matter [*Lee and Cronin*, 1982]. The annual mean C/N ratio off South Java falls with 9.6 within the range of C/N ratio measured at other sites in the Indian Ocean (8.7–9.9 [*Haake et al.*, 1993; *Honjo et al.*, 1999; *Unger et al.*, 2003]) indicating no extraordinary, high contribution of nitrogen-poor organic matter to the POC export. This in addition to δ^{13}Corg values ranging between −20.4 and −21.96‰ and the low δ^{15}N values suggest a marine production that is predominantly fuelled by inputs of dissolved inorganic nitrogen (NO_3^-, NO_2^-, NH_4^+) from land especially during the NW monsoon and the subsequent intermonsoon.

[7] The annual mean POC/PIC ratio of 2.8 determined off South Java is the highest so far measured at water-depth > 1500 m in the tropical and subtropical ocean [*Klaas and Archer*, 2002] even though inputs of lithogenic and resuspended sedimentary carbonates could have reduced the ratio. For example, POC/PIC ratios obtained from the similar seasonal upwelling system off Arabia are (<1.3 [*Haake et al.*, 1993; *Honjo et al.*, 1999]). POC/PIC ratio such as those reported from the river-dominated northern Bay of Bengal (~1.7 [*Unger et al.*, 2003]) are already considered as high. In the Bay of Bengal, the efficient biological pump is related to nutrient, freshwater and inputs of lithogenic matter from rivers. Nutrient and freshwater inputs enhance the overall marine production but, by lowering surface salinity and supplying silica, also shift the biological community structure from carbonate producers to diatoms [*Ittekkot et al.*, 1991]. Lithogenic matter scavenged by sticky POC act like carbonate as ballast in marine aggregates and can increase the POC export by accelerating the sinking of particles in the water column [*Naqvi et al.*, 1996]. POC/lithogenic matter and carbonate/biogenic opal ratios (lower during the NW than during the SE monsoon) as well as POC/PIC ratios (higher during the NW than during the SE monsoon) off South Java testify to a similar process with a much more efficient biological pump responding to the monsoons caused seasonality (Table 1).

[8] During our experiment weak La Niña turned into weak El Niño conditions as indicated by the Southern Oscillation Index (SOI) falling from 2 to −1.5 (Figure 1). Due to La Niña-caused increased precipitation rates and associated river discharges organic carbon fluxes are higher during the NW monsoon 2001 than during the NW monsoon 2002 and the trap data exhibit lower values for δ^{15}N, C/N, carbonate/biogenic opal, and POC/lithogenic matter ratios (Table 1). The increased riverine nutrient and freshwater discharges raising the organic carbon export and reducing the carbonate export enhances POC/PIC ratio indicating furthermore much more efficient biological during La Niña conditions.

[9] In 2002, the SE monsoon period of upwelling is longer and fluxes are higher than in 2001 implying that El Niño strengthens upwelling and enhances the organic

Table 1. Sampling Year, Estimated Duration of the Upwelling and the NW Monsoon Seasons, Annual and Seasonal Averaged SOI, Flux Rates and Ratios Determined at the Sediment Trap Site[a]

	Upwelling		NW Monsoon		Annual	
	2001	2002	2001	2002	2001	2002
Duration, no. of day	90	130	150	150	365	365
SOI, hPa	−0.7	−1.4	0.3	−0.7	0.0	−1.0
POC flux, g m^{-2}	1.5	2.4	1.7	1.5	4.2	4.9
PIC flux, g m^{-2}	0.6	1.0	0.4	0.5	1.4	1.9
Biogenic opal flux, g m^{-2}	6.1	12.2	5.9	7.5	12.0	25.0
Lithogenic matter flux, g m^{-2}	20.6	30.2	33.6	29.5	69.8	72.2
POC/lithogenic matter, *100	7.28	7.95	5.06	5.08	6.02	6.79
Carbonate, g m^{-2}/biogenic opal, g m^{-2}	0.86	0.65	0.57	0.59	1.00	0.63
POC/PIC	2.33	2.49	4.16	2.83	2.92	2.57
$\delta^{15}N$	4.5	3.9	3.1	4.1	3.8	3.8
C/N	8.7	11.1	8.8	9.7	8.8	10.6

[a]The sample obtained in April 2002 revealing an $\delta^{15}N$ of 10.1 (Figure 1) was excluded by calculating the seasonal and annual averages because it seems to be biased by zooplankton (see text for further explanation).

carbon export to the deep sea (Figure 1). The evaluation of satellite-derived data sets covering approximately the last ~20 years, shows that a more intense upwelling and extended upwelling periods during El Niño events are caused by a reduced Indonesian Through Flow and by abnormal winds [*Sprintall et al.*, 1999; *Susanto et al.*, 2001].

[10] An additional factor linking ENSO and carbon fluxes is the low salinity upper layer that develops during the NW monsoon and reaches a thickness of up to ~100 m in May as shown by hydrographic profiles (Figure 2). In order to allow colder subsurface water to well up, this layer has to be eroded during the SE monsoon. Reduced precipitation rates during El Niño periods hinder the build-up of this low salinity layer (capping-effect) and could facilitate and enforce the entrainment of subsurface water during the upwelling season. Because upwelled subsurface water is enriched in CO_2, upwelling especially form the equatorial Pacific Ocean is an important source of atmospheric CO_2 [*Feely et al.*, 1999].

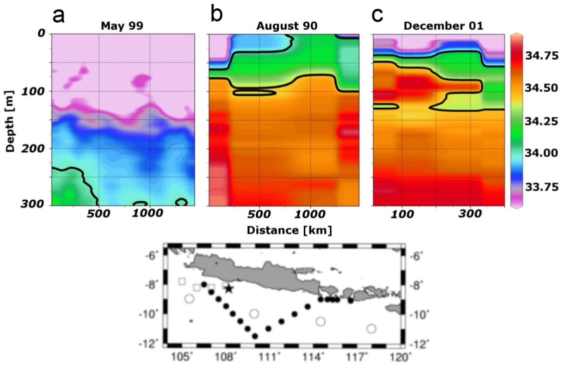

Figure 2. Salinity transects along the Indonesian continental margin (a) at the end of the rainy season 1999 (May), (b) during the upwelling season 1990 (August) and (c) after the upwelling periods 2001 (November). Thick black line indicate the 34 and 34.4 isolines. Sampling sites used to calculate the transects are shown on the map. The black circles, open circle and squares show the May 1999, August 1990 and the November 2001 data. The star reveals the sediment trap site.

[11] The CO_2 emission from the upwelling system off South Java which expands north-westward along the coast off Sumatra were studied using a biogeochemical carbon cycle model (HAMOCC5) online linked to a global Ocean Circulation Model (MPI-OM) [*Wetzel et al.*, 2005]. The model is forced by daily NCEP/NCAR reanalysis data from 1948 to 2003 and shows enhanced CO_2 emission from the upwelling system off Java and Sumatra during El Niño conditions (Figure 3). This link is caused by the capping-effect that as mentioned before suppresses upwelling of CO_2-enriched subsurface water and even leads to a net uptake of atmospheric CO_2 in La Niña years. The resulting ENSO-influenced CO_2 flux anomalies of the freshwater influenced region around Indonesia, including large parts of the Bay of Bengal (±20 Tg C yr^{-1}) represents ~5–8 % of the inversely related CO_2 flux anomalies derived from the equatorial Pacific [*Feely et al.*, 1999; *Wetzel et al.*, 2005]. These are probably underestimates since for example, the low pCO_2 levels observed in a buoyant low salinity layer in the Bay of Bengal formed by river discharges from the Indian subcontinent can only be explained by considering an enhanced CO_2 uptake via biological processes [*Kumar et al.,* 1996] which is also in agreement with our results.

4. Conclusions

[12] Our results show that enhanced freshwater fluxes and associated inputs of ballast material and nutrients from land promote the CO_2-uptake of the biological pump by enhancing the POC export and reducing the relative carbonate transport into the deep sea. Accordingly the biological pump responds to monsoonal and ENSO driven changes in the precipitation rates. Freshwater inputs reduce furthermore the upwelling of CO_2-enriched subsurface

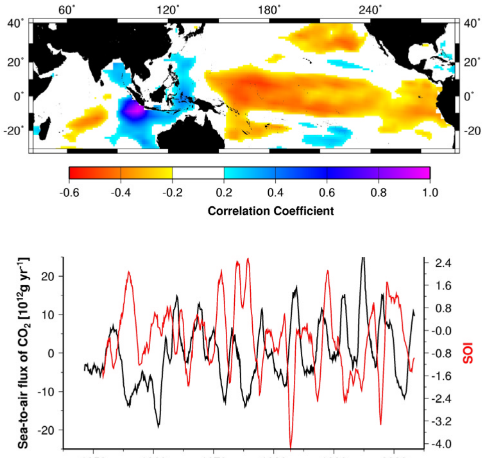

Figure 3. (top) Correlation between sea to air fluxes of CO_2 off South Java and Sumatra and those obtained at other regions averaged on a 1° × 1° grid. (bottom) Annual sea to air flux anomalies of CO_2 off Java and Sumatra and the Southern Oscillation Index (SOI) smoothed with a 12 month moving average.

water during the following NW monsoon by forming a buoyant low salinity surface layer. Via this capping-effect ENSO-induced changes in the precipitation rates and subsequently river discharges exert a significant impact on the CO_2 emission from the tropical ocean in SE Asia as indicated by our model results. The influence of precipitation rates and associated river discharges on the efficiency of the biological pump needs to be included into future studies in order to quantify the role of freshwater influenced continental margins on the air to sea CO_2 exchange.

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