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Biogeochemical processes and turnover rates in the Northern Benguela Upwelling System

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A R T I C L E   I N F O

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A B S T R A C T

Biogeochemical cycles of carbon, nutrients, and oxygen transmit mean states, trends and variations of the physical realm in coastal upwelling systems to their food webs and determine their role in regional budgets of greenhouse gases. This contribution focuses on biogeochemical processes in the northern Benguela Upwelling System (NBUS), where low oxygen levels in upwelling source water are a major influence on carbon and nutrient cycles. Based on measurements during numerous expeditions and results of 3-D regional ecosystem modeling (project GENUS; Geochemistry and Ecology of the Namibian Upwelling System) we here examine source water character, effects of low oxygen conditions on nutrient masses and ratios, and of diazotrophic N_2-fixation on productivity of the system and its transition to the adjacent eastern South Atlantic. In available observations, the effects of denitrification in water and sediment and phosphate release from sediments are minor influences on nitrate:phosphate ratios of the system, and excess phosphate in aged upwelling water is inherited from upwelling source water. Contrary to expectation and model results, the low N:P ratios do not trigger diazotrophic N_2-fixation in the fringes of the upwelling system, possibly due to a lack of seeding populations of *Trichodesmium*. We also examine the flux of carbon from the sea surface to either sediment, the adjacent sub-thermocline ocean, or to regenerated nutrients and CO_2. Observed fluxes out of the surface mixed layer are significantly below modeled fluxes, and suggest that regeneration of nutrients and CO_2 is unusually intense in the mixed layer. This contributes to very high fluxes of CO_2 from the ocean to the regional atmosphere, which is not compensated for by N_2-fixation. Based on observations, the NBUS thus is a significant net CO_2 source (estimated at 14.8 Tg C a^{-1}), whereas the CO_2 balance is closed by N_2-fixation in the model. Methane concentrations were low in surface waters in on-line measurements during 1 expedition, and based on these our estimate for the emission of methane for the entire Benguela system is below 0.2 Tg CH_4 a^{-1}.

1. Introduction

Upwelling systems (zones of coastal and open-ocean divergence in wind-driven surface water flow) are areas where cold sub-thermocline waters are injected into the sea surface and exhale CO_2. At the same time, they bring nutrients to light and foster high primary productivity. In these systems, very high phytoplankton productivity is channelled into a substantial portion of economically exploited fish stocks (Pauly and Christensen, 1995). Exhaled CO_2 is eventually recaptured by photosynthesis that depletes nutrients in upwelled surface waters, and exports carbon and nutrients back to deeper waters or to sediment as sinking organic matter. In theory, the CO_2 budget between degassing and assimilation/particle export is closed when aged and modified upwelled water masses with a surplus of phosphate (P*), characteristic of many upwelling waters, reach the adjacent ocean. Here N_2-fixation makes up any deficit in reactive N relative to P to restore Redfield conditions (C:N:P = 106:16:1) (Deutsch et al., 2007).

Coastal upwelling systems may differ from the rest of the subtropical ocean in their reaction to global warming. Whereas enhanced thermal stratification impedes the nutrient recharge of surface waters

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and causes lower average primary productivity in large parts of subtropical gyres (Behrenfeld et al., 2006), some eastern boundary upwelling systems show an increase in wind intensification (Sydeman et al., 2014) and primary productivity (Demarcq, 2009), and thus appear to substantiate the hypothesis of upwelling intensification as a reaction to global warming and enhanced land-sea atmospheric pressure gradients (Bakun, 1990; Bakun et al., 2010). Global warming is expected to cause a weakening, but also a widening of the Hadley circulation, and most coastal upwelling systems have been postulated to broaden in time and space due to enhanced land-sea pressure gradients (Wang et al., 2015). Increased nutrient delivery via upwelling may thus enhance productivity at the upwelling rims of subtropical gyres that become more oligotrophic, or may infuse nutrients to these nutrient deserts to counteract decreased cross-pycnocline mixing.

The fate of upwelled nutrients, and that of their twins CO_2 and O_2, depend on the efficiency of productivity and mineralisation, on nutrient losses and gains via processes acting in low oxygen environments (phosphate efflux from sediments and denitrification) that are associated with all eastern boundary upwelling systems, and on the export of particulate carbon and nutrients to sub-thermocline ocean waters (via the biological pump) and to sediments. In the project GENUS (http://genus.zmaw.de), we investigated these relationships in the NBUS during ship expeditions and with a regional numerical model system.

The NBUS is a distinct region of the larger Benguela Upwelling System in terms of seasonality of wind forcing and properties of upwelling water, productivity, and oxygen status (Hutchings et al., 2009). The northern boundary of the NBUS is the Angola Benguela frontal zone (ABFZ) at approximately 15°S to 17°S (Shannon et al., 1987). The southern boundary of the NBUS is the Lüderitz Upwelling Cell at 27°S, which separates the northern and southern sector of the BUS (Fig. 1a). According to Monteiro (2010) and other authors, the outer boundary of the coastal upwelling system coincides with the 500 m water depth contour, and the area is 179,000 km^2. In the NBUS the wind forcing has a strong seasonal cycle determined by the changing position of the subtropical atmospheric high-pressure zone over the South Atlantic (e.g., Tim et al., 2016). Winds in the NBUS are strongest during July, August, and September (austral winter months). The interaction between coastal trends and structure of the wind field causes Ekman transport and curl-driven upwelling along the entire Namibian coast (Fennel et al., 2012; Lass and Mohrholz, 2008; Mohrholz et al., 2014). During December to March the trade winds are weak, and upwelling subsides in austral summer.

The amount of nutrients upwelling into the surface layer is determined by upwelling intensity and nutrient concentrations in upwelling feed water. In the NBUS these are the South Atlantic Central Water (SACW), which is older, richer in nutrients and CO_2, and depleted in oxygen compared to the Eastern South Atlantic Central Water (ESACW), although both originate in the Cape Basin (Duncombe Rae, 2005; Mohrholz et al., 2014). Whereas ESACW has taken a direct route to the southern sector of the Benguela upwelling system and is the dominant source there, SACW has taken a longer route through South Atlantic and the equatorial current system to the subtropical Angola Dome. It is transported to the NBUS by a poleward undercurrent when wind-driven upwelling is weak in summer and spreads southward above the sediment to the Lüderitz cell and there is advected offshore (Fig. 1b). ESACW is the dominant water mass in the southern Benguela. The different character of the two water masses sets conditions at the sea surface with respect to nutrient masses, their stoichiometric ratios, and their carbon balance. It also determines the level of oxygen prevailing below the mixed layer in the upwelling system, and thus the presence or absence of processes that modulate conditions in the mixed layer.

Fig. 2 illustrates postulated first-order interdependencies between climate forcing and upwelling change in the upwelling system offshore Namibia and in the adjacent subtropical ocean, and outlines the storyline of this contribution. Assuming that upwelling velocity will

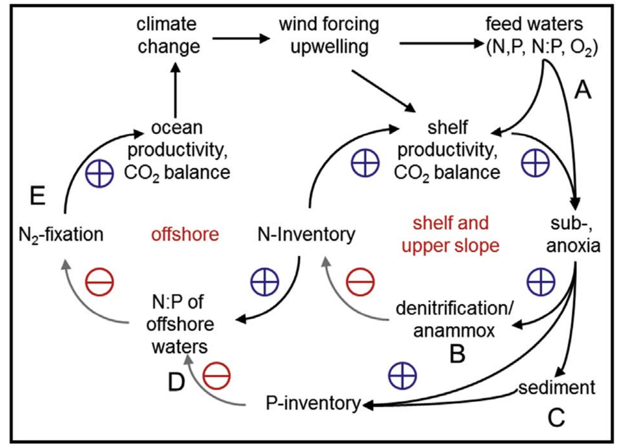

Fig. 2. Conceptual diagram of influences on shelf productivity in the northern Benguela Upwelling System, and their effects on and communication with ocean productivity in the adjacent South Atlantic Ocean.
Modified from (Deutsch et al., 2007).

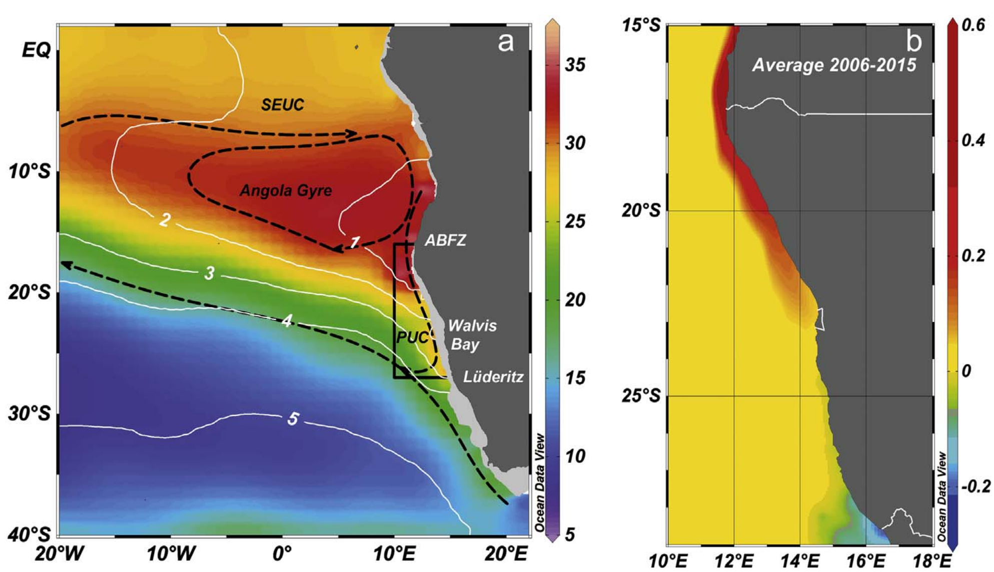

Fig. 1. a) Overview map of nitrate (μmol L^{-1}; colors) and oxygen (mL L^{-1}; white contours) concentrations at 300 m water depth in the SE Atlantic. Arrows sketch flow paths of intermediate water masses in the thermocline (SEUC: South Equatorial Undercurrent; PUC: Poleward Undercurrent). The black rectangle marks the working area in the northern Benguela. b) model-based annual average (model years 2006 to 2016) fraction of SACW in waters from the seafloor to 20 m above the seafloor. Blue colors mark the extent of waters originating in the Cape Basin (ESACW). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)