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Comparative study of potential transfer of natural and anthropogenic cadmium to plankton communities in the North-West African upwelling

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HIGHLIGHTS

- We model the physical–biogeochemical dynamics in the North-West African upwelling.
- We model the transport of cadmium from natural and anthropogenic sources.
- We derive proxies of potential cadmium absorption and bioaccumulation in the plankton food chain.
- The anthropogenic signal off Morocco at least equals the natural upwelling signal off Mauritania.
- We compare our results with observed cadmium levels in mollusks and fishes.

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ABSTRACT

A Lagrangian approach based on a physical–biogeochemical modeling was used to compare the potential transfer of cadmium (Cd) from natural and anthropogenic sources to plankton communities (Cd-uptake) in the North-West African upwelling. In this region, coastal upwelling was estimated to be the main natural source of Cd while the most significant anthropogenic source for marine ecosystem is provided by phosphate industry. In our model experiment, Cd-uptake (natural or anthropogenic) in the North-West African upwelling is the result of an interplay between the Cd dispersion (by advection processes) and the simulated biological productivity. In the Moroccan waters, advection processes limit the residence time of water masses resulting in a low natural Cd-uptake by plankton communities while anthropogenic Cd-uptake is high. As expected, the situation is reversed in the Senegalo-Mauritanian upwelling where natural Cd-uptake is higher than anthropogenic Cd-uptake. Based upon an estimate of Cd sources, our modeling study shows, unexpectedly, that the anthropogenic signal of potential Cd-bioaccumulation in the Moroccan upwelling is of the same order of magnitude as the natural signal mainly present in the Senegalo-Mauritanian upwelling region. A comparison with observed Cd levels in mollusk and fishes, which shows overall agreement with our simulations, is confirming our estimates.

1. Introduction

As much as 40% of the world's population now lives within 100 km of the shoreline (Martínez et al., 2007) and this population continues to grow, increasing our reliance and impact on the coastal ocean. Although eastern boundary upwelling systems (EBUS) represent less than 1% of the global area of the ocean, they represent the most productive regions around the world contributing to about 11% of the global oceanic new primary production (Carr, 2001; Carr and Kearns, 2003) and 20% of the global fish catch (Fréon, 2009). At the same time, urbanization and industrial development have a negative effect on the quality of coastal waters (Shahidul Islam and Tanaka, 2004) with a threat of amplification by global warming (Parry et al., 2007), thereby posing potential health hazards on humans (Fleming et al., 2006).

Morocco is the second phosphate producer in the world. 27 million tons of phosphate ores is extracted and processed annually (Annual Report, Office Chérifien des Phosphates, Maroc, 2012) to produce phosphoric acid and phosphorus-based fertilizers. The production of phosphoric acid basically results from the chemical reaction between sulfuric acid and phosphate ores. During the reaction, calcium sulfate called phosphogypsum, is produced and spread out into the ocean. Phosphogypsum are particles containing significant abundance of crustal elements as heavy metals (the most toxic being mercury and cadmium; see list in Gaudry et al. (2007)). Thus, the Moroccan phosphate industry releases large amounts of heavy metals, particularly

Abbreviations: NW, North-West; Cd, cadmium; EBUS, Eastern Boundary Upwelling Systems; CCS, Canary Current System; CanC, Canary Current; CanUC, Canary Upwelling Current; 3D, three-dimensional; ROMS, Regional Oceanic Modeling System; GEBCO, General Bathymetric Chart of the Oceans; CFSR, Climate Forecast System Reanalysis.

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cadmium (Cd), in the North-West (NW) African upwelling around Safi and Jorf-Lasfar (33°N). Locally, these are responsible for a significant contamination of mollusk communities (Banaoui et al., 2004; Benbrahim et al., 2006; Chafik et al., 2001; Cheggour et al., 1999; Gaudry et al., 2007; Maanan, 2007, 2008). As a consequence, mussels for instance are considered unfit for human consumption in this region (Moustaid et al., 2005). Phosphate industry is also present though less developed in Mauritania and Senegal.

Nutrient-like profiles of Cd observed in the ocean indicate its uptake by phytoplankton at the surface (Boyle et al., 1976; Morel and Price, 2003; Ripperger et al., 2007; Yeats et al., 1995). Cd is then transferred to zooplankton grazers and upper trophic levels through dietary pathways, and finally ends up in the pool of sinking organic detritus from which Cd is remineralized by heterotrophic bacteria. Some heavy metals are also recognized to bioaccumulate in the marine food chain (Bryan, 1984; Kennish, 1997; Wang, 2002) which could also be the case for Cd although not yet proven. This effect could magnify fish contamination. Moreover such cycle, apart from a potential bioaccumulation in fishes, may also include an accumulation of Cd at the sediment interface through sedimentation of organic detritus and a potential release to the water column through oxic mineralization processes (Gobeil et al., 1987). The mechanisms driving phytoplankton Cd absorption are yet poorly known (Finkel et al., 2007; Horner et al., 2013; Morel and Price, 2003; Twining and Baines, 2013). Hence, the explicit representation of the Cd cycle in biogeochemical models would be rather arbitrary. Only one biological function has been clearly identified for Cd: the potential use of Cd (along with zinc) in carbonic anhydrase which enters the photosynthetic machinery in marine diatoms (Lane et al., 2005; Park et al., 2007; Xu et al., 2008). However, despite the lack of known uptake processes, laboratory experiments have shown that the Cd-uptake by phytoplankton occurs in direct proportion to dissolved Cd concentrations (Sunda, 2012; Twining and Baines, 2013). Moreover, Wang and Dei (2001) report exponentially increasing rate of metal uptake with phytoplankton growth rate. As an explanation, they mention luxury uptake and storage of several trace metals as observed in regions of high concentrations like upwelling regions (see review in Horner et al. (2013). A fair statement would be that despite high uncertainty about the driving processes, Cd does enter the trophic chain depending on its concentration in seawater and local primary production.

Wind-driven upwelling takes place all along the NW African coast at the eastern boundary of the North Atlantic subtropical gyre following the meridional migration of the atmospheric pressure systems. It occurs mainly in summer in northern Morocco, all year round (though more intense in summer) in southern Morocco, and in winter and spring south of Cape Blanc in the Senegalo-Mauritanian region (see Fig. 1; Mittelstaedt, 1991; Wooster et al., 1976). Coastal upwelling induces an equatorward baroclinic coastal jet arising from the geostrophic adjustment of the surface density gradient between cold upwelled coastal waters and warmer open ocean waters (Allen, 1973). Upwelling-induced vertical motions generally occur within the 0–100 km coastal band as estimated from the Rossby radius of deformation in the NW African region (Chelton et al., 1998), so the coastal jet is confined nearshore. Offshore, the background circulation is mainly driven by the eastern branch of the North Atlantic subtropical gyre. The Canary Current, seen as a natural extension of the zonal Azores Current (Mason et al., 2012; Sala et al., 2013; Stramma, 1984), flows southward along the NW African coast before feeding the North Equatorial Current. North of Cape Blanc (21°N), the Canary Current System (CCS) is thus composed of the Canary Current (CanC) and the Canary Upwelling Current (CanUC) (Mason et al., 2011). South of Cape Blanc, a cyclonic recirculation drives a poleward circulation opposed to the coastal upwelling jet (Mittelstaedt, 1991). The convergence of the water masses transported by the subtropical gyre and the recirculation gyre finally takes place in the Cape Verde Frontal Zone (Zenk et al., 1991) off Cape Blanc as attested by in situ and satellite observations (e.g. Lathuilière et al., 2008; Van Camp et al., 1991).

In this study, we aim at providing information on the fate of natural and anthropogenic Cd in plankton communities off NW Africa using a comparative modeling approach. We first detail our methodology which uses Lagrangian trajectories for drawing spatio-temporal maps of Cd-dispersion from the major Cd sources (i.e. Cd-rich waters naturally upwelled and phosphate industry). The potential uptake and bioaccumulation of natural and anthropogenic Cd in the plankton food chain

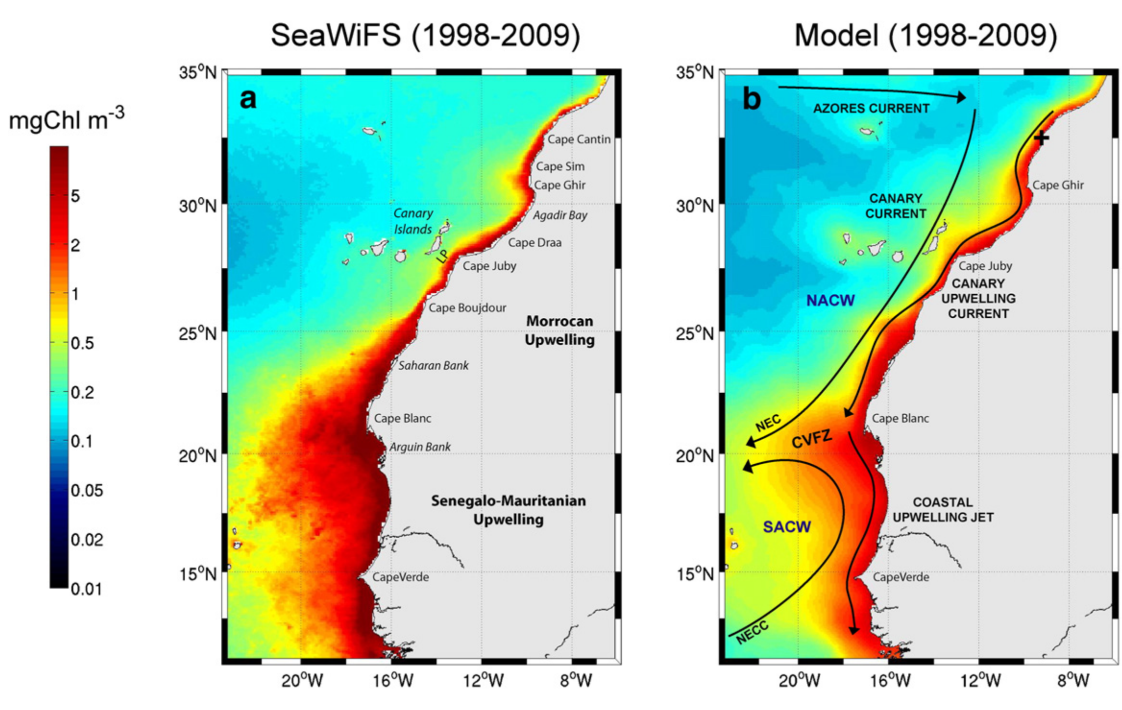

Fig. 1. Map of surface chlorophyll concentrations from (a) SeaWiFS and (b) ROMS-PISCES averaged over the period 1998–2009. We indicate major capes, main surface currents and deep water masses over the study area. LP: Lanzarote Passage; NEC: North Equatorial Current; NECC: North Equatorial Countercurrent; CVFZ: Cape Verde Frontal Zone; NACW: North Atlantic Central Water; SACW: South Atlantic Central Water. The black cross indicates the location of the anthropogenic Cd loads.