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Future export of particulate and dissolved organic carbon from land to coastal zones of the Baltic Sea

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ABSTRACT

The Baltic Sea is a semi-enclosed brackish sea in Northern Europe with a drainage basin four times larger than the sea itself. Riverine organic carbon (Particulate Organic Carbon, POC and Dissolved Organic Carbon, DOC) dominates carbon input to the Baltic Sea and influences both land-to-sea transport of nutrients and contaminants, and hence the functioning of the coastal ecosystem. The potential impact of future climate change on loads of POC and DOC in the Baltic Sea drainage basin (BSDB) was assessed using a hydrological-biogeochemical model (CSIM). The changes in annual and seasonal concentrations and loads of both POC and DOC by the end of this century were predicted using three climate change scenarios and compared to the current state. In all scenarios, overall increasing DOC loads, but unchanged POC loads, were projected in the north. In the southern part of the BSDB, predicted DOC loads were not significantly changing over time, although POC loads decreased in all scenarios. The magnitude and significance of the trends varied with scenario but the sign (+ or −) of the projected trends for the entire simulation period never conflicted. Results were discussed in detail for the "middle" CO_2 emission scenario (business as usual, a1b). On an annual and entire drainage basin scale, the total POC load was projected to decrease by ca 7% under this scenario, mainly due to reduced riverine primary production in the southern parts of the BSDB. The average total DOC load was not predicted to change significantly between years 2010 and 2100 due to counteracting decreasing and increasing trends of DOC loads to the six major sub-basins in the Baltic Sea. However, predicted seasonal total loads of POC and DOC increased significantly by ca 46% and 30% in winter and decreased by 8% and 21% in summer over time, respectively. For POC the change in winter loads was a consequence of increasing soil erosion and a shift in duration of snowfall and onset of the spring flood impacting the input of terrestrial litter, while reduced primary production mainly explained the differences predicted in summer. The simulations also showed that future changes in POC and DOC export can vary significantly across the different sub-basins of the Baltic Sea. These changes in organic carbon input may impact future coastal food web structures e.g. by influencing bacterial and phytoplankton production in coastal zones, which in turn may have consequences at higher trophic levels.

1. Introduction

The Baltic sea waterbody is a semi-enclosed brackish sea in Northern Europe that has a water renewal time of about 50 years (Leppäranta and Myrberg, 2009) with a drainage basin four times larger than the sea itself (Mörth et al., 2007). In the Baltic Sea drainage basin area (BSDB) riverine discharge is the largest input source of organic carbon (in dissolved and particulate form) (Kuliński and Pempkowiak, 2011), which makes the input of allochthonous organic matter (OM) from rivers important compared to autochthonous OM. Dissolved organic matter (DOM) is a complex and undefined mixture of various organic compounds, separated from particulate organic matter (POM) by filtering (often with a nominal pore size of 0.45 um, although filter cutoff and type varies between studies) (Zsolnay, 2003), and includes various constituents e.g. amino acids, peptides, carbohydrates, lipids, lignin and, humic and fulvic substances (Kuliński et al., 2016). Dissolved organic matter influences primary production as it is a source of energy and nutrients for bacteria, and by impacting light penetration in the water column (Hoikkala et al., 2015). Additionally, DOM affects the acid-base balance in surface water (Hruška et al., 2003), and plays a role in the transport of metals and organic contaminants by adsorption to DOM (Hoikkala et al., 2015). The terrestrial DOM (tDOM) make up

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most of the total DOM pool in the Baltic Sea due to its relatively higher stability compared to marine DOM (mDOM) originating from autochthonous primary production (Alling et al., 2008). Marine DOM, however, dominates the total inputs, but is more rapidly consumed by bacteria (Gustafsson et al., 2014a; Kuliński et al., 2016). Mineralization of tDOM (by bacterial respiration or photo-oxidation) in shelf areas is nevertheless an important factor impacting air-water CO_2 exchange and seawater pH (Gustafsson et al., 2014a, Kuliński et al., 2016) but degradation seems to be most important close to river mouths (Deutsch et al., 2012). POM usually constitutes a smaller fraction of the total riverine OM (Mattson et al., 2005), but it is degraded in coastal zones much more rapidly than tDOM (i.e. approximately 70% of terrestrial POM and 40% of tDOC annual inputs are estimated to be mineralized (Gustafsson et al., 2014a)), hence contributing disproportionately to the total coastal OM mineralization (van Dongen et al., 2008). Terrestrial POM thus constitutes an energy source at the lowest trophic levels, resulting in a flow from POM into DOM (Nagata, 2000). In addition, POM is a vector for contaminant transport in rivers (Josefsson et al., 2016). Riverine input of DOM and POM hence impact both the coastal ecosystems and the overall carbon budget in the Baltic Sea, making projections of inputs of both carbon species important for environmental management.

On a global scale, total organic carbon (TOC) export is related to rainfall, runoff, population density and land use, with the variability in DOC and POC flux being higher in cold temperate areas compared to other climate zones (Alvarez-Cobelas et al., 2012). Increased OC concentrations in many freshwater systems in Europe and North America during the past decades have been reported (e.g. Freeman et al., 2001, Monteith et al., 2007, Kokorite et al., 2012, Mattsson et al., 2015, de Wit et al., 2016). The numerous studies on this issue are, however, mainly conducted in temperate and boreal OC rich waters in the Northern hemisphere and suffer from several weaknesses/difficulties, i.e. use of censored data in trend analysis, underreporting of methods and statistical significance of observed trends, changing analytical techniques over time and uncertainty in correlations between surrogate parameters (e.g. light absorbance, COD) and DOC (Filella and Rodríguez-Murillo, 2014). This makes understanding the full global extent of this phenomenon challenging. The increasing DOC concentrations have been linked to several factors or combinations of these, including climate warming resulting in enhanced decomposition of peat soils, decreases in atmospherically deposited sulfur (i.e. recovery from acid rain), changes in hydrology and the balance between biological productivity and decomposition (see reviews e.g. Porcal et al., 2009, Pagano et al., 2014, Ritson et al., 2014). It has also been suggested that stronger primary production due to elevated CO_2 levels is a possible driver (Freeman et al., 2004). Other factors such as soil moisture and temperature that impact soil production and degradation of DOC (Futter et al., 2007) may also be important. Hence, several drivers for the observed changes are suggested and debated (Eimers et al., 2008; Lepisto et al., 2014). In the Baltic Sea region, however, analysis of long term monitoring data for TOC in boreal watersheds indicates that TOC export is mainly controlled by hydrometeorological factors such as changes in soil frost, seasonal precipitation patterns, drought and runoff (Lepisto et al., 2014; Sarkkola et al., 2009; Erlandsson et al., 2008; Ritson et al., 2014; Mattsson et al., 2015; Räike et al., 2016). Whereas TOC concentrations (as opposed to fluxes) in the far northern sub-watersheds have not changed during the past decades, the concentrations in the south show increasing trends. The latter coincides with the earlier ice break up in lakes already observed as a consequence of global warming and may hence be the result of various climate change related factors or the abovementioned stronger leakage of DOC from soils rich in organic carbon recovering from previous acidification (Humborg et al., 2007).

Projected air temperatures based on output from a range of general circulation models (GCMs) indicate that increases of 3–6 °C are likely in the BSDB, with most pronounced changes in the northern parts of the catchment and in the winter season (Helcom, 2013). Precipitation may increase on average by ca 12–18%, again with largest increases in the northern parts (Meier et al., 2012). In the BSDB these changes can cause the onset of an earlier spring flood, shorten cold seasons, elongate growing seasons and increase risk of extreme weather events such as drought and floods (Helcom, 2013), which in turn may influence the land-to-sea organic carbon transport. Humborg et al. (2007) discussed possible future trends in TOC export and argued that changes in hydrological patterns in the north, i.e. increased precipitation and temperature, causing increased runoff could either increase weathering by deeper percolation into soils or increase the release of OM by flushing out more topsoil (Smedberg et al., 2006). They also noted that half of the runoff in the boreal and sub-arctic watersheds is currently generated within a few weeks in May and June. Changes in timing and elongated duration of the spring flood, as previously predicted by Graham (2004), may therefore have a large impact on TOC flow patterns in the north. Few studies have, however, attempted to quantify the anticipated changes in OC delivery. Omstedt et al. (2012) used a model system including a hydrological and nutrient catchment model (CSIM) and the terrestrial vegetation-ecosystem model LPJ-GUESS to project climate change induced changes in carbon and oxygen cycles in the Baltic Sea and its drainage basin. Over 100 years, average yearly concentrations of TOC in river water changed < 5% in all sub-basins, while fluxes increased by 20–50% due to increased runoff in the northern and eastern parts of the drainage basin. The authors, however, did not separate between POC and DOC, and did not consider seasonal differences in carbon export. This distinction is important since the POC and DOC export response is different to climate change and input changes can have consequences for the coastal ecosystems. In addition, a shift in *timing* of input to coastal zones can be crucial (Reader et al., 2014).

The aim of this study is to quantify the possible impact of future climate change on the generation and transport of both particulate (POC) and dissolved organic carbon (DOC) in all rivers that discharge into the Baltic Sea and to make an assessment of seasonal differences. In the study, the hydrological and nutrient catchment model (CSIM) (Mörth et al., 2007; Lyon et al., 2014) was used to simulate loads to the Baltic Sea. Forcing was taken from three climate scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) (Nakićenović et al., 2000) that have been downscaled for the Baltic Sea drainage basin (Omstedt et al., 2012). The water discharge is in CSIM modelled from time series of precipitation and temperature which drive the land-to-sea transport of nutrients (N, P) and DOC. In a recent development of CSIM POC loads were included by implementing algorithms describing soil erosion, litter fall and primary production (Strååt et al., 2016). This enables CSIM to model future climate change effects of both POC and DOC loads and make source apportionment of POC. In the study predicted future changes in POC and DOC are discussed as the export may impact the coastal ecosystems and land-to-sea contaminant transport.

2. Method

2.1. POC and DOC model

Annual and seasonal riverine loads of POC and DOC from the BSDB were modelled in this study using a hydrological model, CSIM (Catchment Simulation Model) (Mörth et al., 2007; Lyon et al., 2014; Strååt et al., 2016). CSIM is based on the Generalized Watershed Loading Function model, a model originally developed to simulate stream flow, sediment and nutrient fluxes from watersheds in the United States (Haith and Shoemaker, 1987). CSIM uses daily information on precipitation and air temperatures to model water discharge from all the rivers draining into the Baltic Sea. The water fluxes drive the generation through the water flow path and land-to-sea transport of nutrients (N, P), DOC and POC. In the model, the BSDB is divided into 82 major catchments and 35 coastal areas and minor catchments