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Modelling climate change effects on nutrient discharges from the Baltic Sea catchment: processes and results

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Abstract The effects of climate changes on nutrient discharges within the Baltic Sea catchment were modelled, indicating increases in concentrations of phosphorus, but decreases in nitrogen for the southern Baltic Sea catchment. The process-based hydrological and nutrient flux model, HYPE, was set up for the entire Baltic Sea catchment area. The model was then used to examine how water and nutrient fluxes may change during four different climate scenarios. Changes to discharge varied regionally, with increases seen in the northeastern Baltic Sea catchment and decreases in the south and southwest. Changes to total nutrient loads did not necessarily follow the changes in discharge, indicating significant changes in nutrient concentrations. This indicates the importance of a process-based hydrological and nutrient model for analyses: it is the net result of several different nutrient sink and source processes that determine the predicted status of nutrients as a result of climate change.

Key words water quality modelling; nutrient modelling; climate change; discharge modelling; Baltic Sea

INTRODUCTION

Eutrophication, caused by excess nutrient inflows, is one of the most serious and hardest to mitigate challenges facing the Baltic Sea. Anthropogenic nutrient inflows from land to sea are a result of emissions from industry and urban wastewater treatment plants, rural households, atmospheric deposition, and diffuse land sources, especially agriculture. The amounts of these nutrients that make their way to the sea depends on processes such as plant uptake, denitrification, mineralisation, erosion, subsurface leaching from soil, re-suspension from river and lake sediments and biochemical processes in the freshwater system. These processes are temperature and precipitation dependent and are therefore affected by changes in climate.

Previous studies have evaluated how freshwater inflows to the Baltic Sea might change in a future climate (Graham, 2004). Using the delta change method to adapt regional climate model (RCM) outputs of precipitation and temperature for hydrological modelling, Graham (2004) compared four climate scenarios. Scenario results varied from a small decrease in total mean annual freshwater inflow to the Baltic Sea, to an increase of 15%. A consistent trend showing an increase in discharge from the north of the basin and a decrease in the south could also be observed. Although the HBV-BALTIC model used in the aforementioned study is useful for determining freshwater influxes to the Baltic, the low resolution of the sub-basins and the conceptual approach means that the model is less suitable for predicting flow in the ungauged basins of the Baltic Sea, at points upstream in the catchment, and cannot be used to determine flow pathways for nutrient fluxes. Similarly, the limitations to the modelling approach of Mörth *et al.* (2007) for pan-Baltic nutrient loads are similar to those for HBV-BALTIC, i.e. a low sub-basin resolution and a conceptual description of hydrological and nutrient flux processes.

A number of studies have investigated the effect of future climate change on water quality assuming similar future anthropogenic nutrient inputs. Such studies show large variations in results and show even contradictory conclusions between catchments; for example, Bouraoui *et al.* (2002) and Varanou *et al.* (2002). Rosberg & Arheimer (2007) also concluded that such climate studies depend on a number of interacting assumptions and uncertainties as well as the climate change scenario modelled. These varied results indicate the need for process-based nutrient modelling. Examination of the effect of both future climate and future management change on freshwater and nutrient fluxes to the Baltic Sea requires an approach in which all climate dependent hydrological and nutrient processes are explicitly accounted for.

DATA AND METHODS

A pan-Baltic application of the high-resolution, process-based hydrological and nutrient flux model, HYPE (Lindström *et al*., 2010), was set up using readily available regional and global databases (Table 1), for 5128 sub-basins with a median area of 325 km^2. The data input, modelling and calibration were kept homogenous over the model domain in order to ensure a consistent treatment of the model domain. When using a modelling tool to assess water resources and their quality for a basin entailing several political entities, it is an advantage that the methods and data used are homogenous. The calibrated and validated model application, called Balt-HYPE, was then used to simulate the effects of a number of future climate change scenarios on both freshwater and nutrient influxes to the Baltic Sea.

Table 1 Summary of data inputs to the Balt-Hype model.

Data type	Details (source)
Topography/routing	Hydro1K (USGS, 2000)
Precipitation and temperature	ERAMESAN 1980–2004, Jansson *et al.* (2007), (grid resolution = 11 km)
Land cover	Global Landcover 2000 (GLC, 2009)
Soil types	European Soils Database (JRC, 2006)
Point sources (URBAN/RUral)	HYDE population database, EEA treatment level, method by Bouwman *et al.* (2005).
Point sources (industrial)	EEA Industrial Emissions database
Agriculture data	EUROSTAT and CAPRI (Britz *et al*., 2007) for Nuts regions
Atmospheric deposition	MATCH model (Andersson, 2007)
Discharge measurements	GRDC (GRDC 2009), BALTEX (BHDC 2009)
Nutrient concentration measurements	European Environmental Agency Waterbase (EEA, 2009)

The Balt-HYPE application was calibrated against 35 daily river discharge stations and 20 water quality stations, and verified against 121 daily discharge stations. Due to the low availability of pan-Baltic water quality data, no validation of water quality was carried out. Nevertheless, initial values for water quality parameters were taken from the literature where appropriate, and from a calibrated and validated pan-Sweden application of the HYPE model (Strömqvist *et al*., 2011). For calibration and verification, the model was forced with precipitation and temperature data from the ERAMESAN reanalysis database (Jansson *et al*., 2007). The calibration methodology used is described in Strömqvist *et al.* (2011) and can be described as a simultaneous, uniform calibration of a multi-basin model. Although step-wise in process, the calibration is homogenous in space, i.e. a single set of land-use and soil-type linked parameters is optimised to all the available flow data in the model domain. The advantage of this approach is that parameters can then be used in all ungauged basins within the model domain to better simulate flows in ungauged basins. A disadvantage is that because the model has not been individually tuned to every basin, simulated discharge and concentrations in some rivers will be worse than in other models. Nevertheless, it is believed that this approach more robustly links model processes to climate, land use and soil-type and provides better estimates in ungauged rivers and for ungauged periods.

Effects of future climate on discharges and nutrient fluxes were studied by forcing the model with four different regionally downscaled climate scenarios. The scenarios consisted of various combinations of global climate model (GCM) driven by various emission scenarios and starting states, downscaled with a regional climate model (RCM), the Rossby Centre Coupled Atmosphere Ocean model (RCAO) to 25-km resolution (Meier *et al*., 2011). The RCM results were bias-corrected for daily precipitation and temperature using the distribution based scaling (DBS) method (Yang *et al*., 2010) whereby the RCM results for a control period (1981–2005) were compared with the observed data used in model calibration (ERAMESAN) for the same period. Scaling factors were derived from this comparison and applied to the future climate time-series.

The scaling factors adjust the mean and variability of the RCM data without affecting the climate change signal. To evaluate the effects of the future climate scenarios on nutrients and discharge, the Balt-HYPE model was run for two time-slices, 1971–2000 and 2071–2100, and results for the two periods compared. A time-slice approach was chosen instead of a transient approach, as the effects of long-term trends in nutrient storage in the model could not be verified. Therefore, the future climate change results can be considered to show the effects of a future climate on present nutrient status, rather than a scenario for the end of the century. For discharge results, there are no differences between transient and time-slice runs of the HYPE model.

RESULTS

Figure 1 indicates that the model captures variability of discharge well across all basins, TN concentrations fairly well, and TP concentrations fairly. Further calibration and validation results from the Balt-HYPE model are discussed in Donnelly *et al.* (2010). When forcing the calibrated model with climate scenarios, it was found that the spatial variation of changes for each variable was relatively consistent between climate scenarios (Table 2); however, when aggregated to total discharge and nutrient load changes to the Baltic Sea, results are more variable (Fig. 2). The spatial distributions shown in Fig. 2 are generally similar for all scenarios.

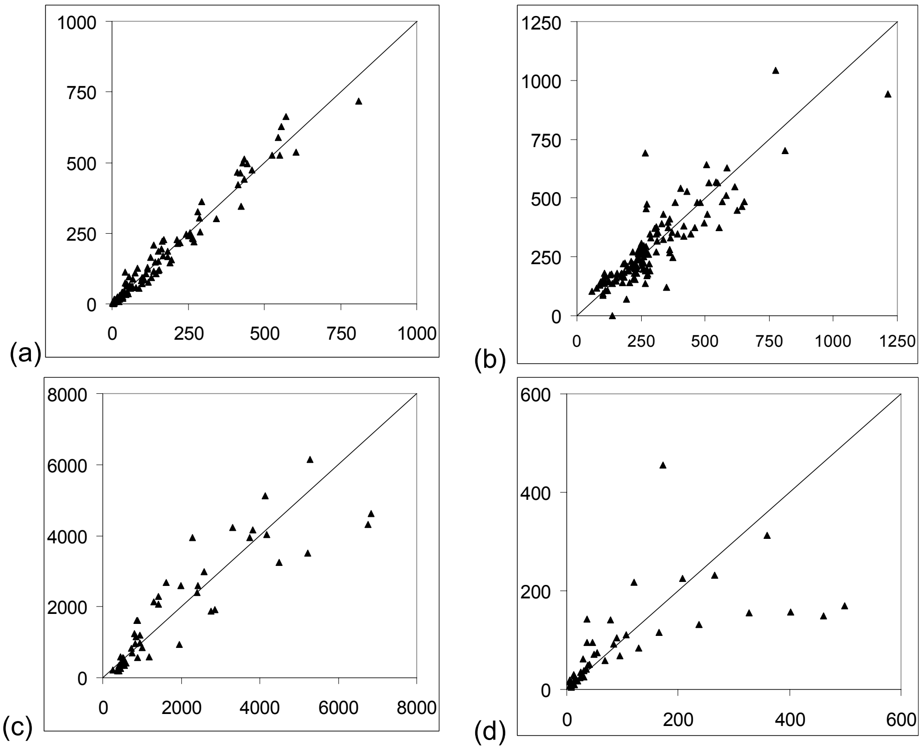

Fig. 1 Comparison of measured (x-axis) and modelled (y-axis) mean annual values of: (a) discharge (m^3 s^{-1}), (b) specific discharge (mm/year), (c) TN concentration (µg/L) and (d) TP concentration (µ/L).

Table 2 Percent changes in mean annual discharge and nutrients to the Baltic Sea: Period 2 (2071–2100) minus Period 1 (1971–2000).

Percent change in mean annual:	Q	TN load	TP load
E5_RCAO_A1B_3_25km	3	–3	14
E5_RCAO_A1B_1_25km	12	1	17
E5_RCAO_A2_25km	14	4	23
Had_RCAO_A1B_25km	12	4	17

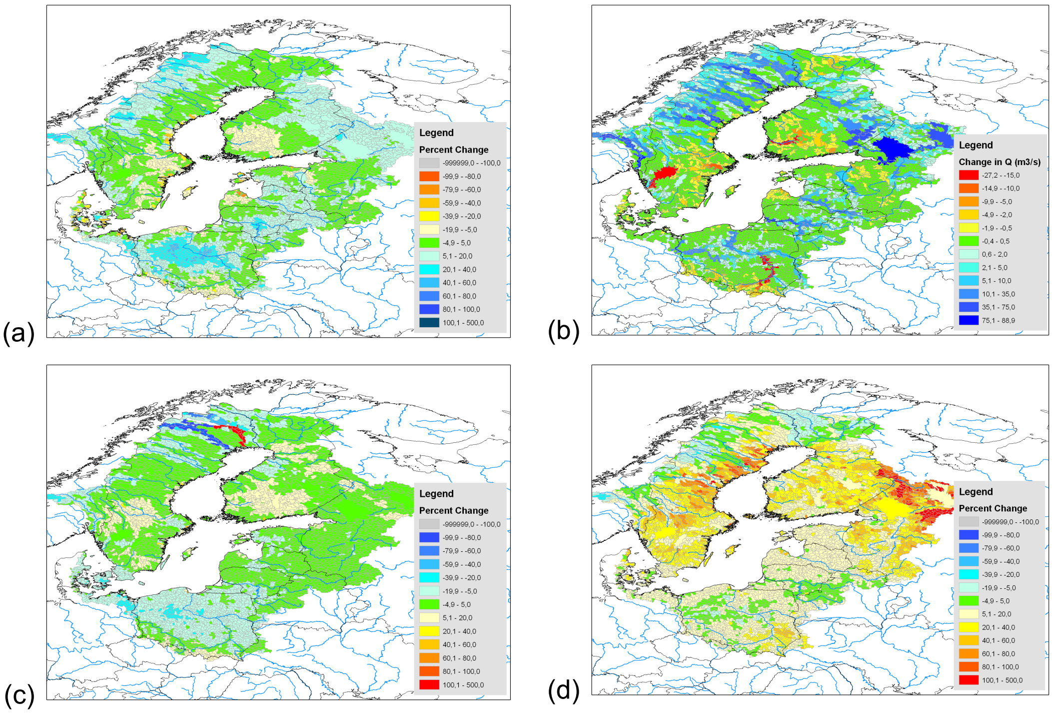

Fig. 2 Mean annual changes (percent) across the Baltic Sea catchment for the ECHAM5-RCAO-A1B-3-25km scenario: (a) specific discharge, (b) discharge, (c) TN concentration, (d) TP concentration. Percent change is defined as the difference between the mean annual value for period 2 (2071–2100) and period 1 (1971–2000), divided by period 1. (This figure can be viewed in colour at: http://www.smhi.se/polopoly_fs/1.16035!348-02%20186-Donnelly_etal_final%5B1%5D.pdf.)

DISCUSSION

Changes in total inflow to the Baltic Sea, as shown in Table 2, lie within the range reported by Meier *et al.* (2006) for a number of simulations of the HBV-Baltic model (Graham, 1999), driven by older downscaled climate scenarios from the PRUDENCE project. Simulated climate change impacts on TN and TP concentrations and loads to the Baltic Sea have not been presented before.

Results for nutrients show that it is impossible to generalise whether nutrient concentrations will increase or decrease in a future climate. Results varied in both space and time and for different nutrients, indicating the importance of a process-based hydrological and nutrient model to determine locally the effects of climate change on water quality. In order to understand why, for example, a decrease in TN concentrations is seen in northern Germany and Poland, it is necessary to examine the changes in nutrients due to each of the processes acting on nitrogen within the model. The model processes that lead to changes in TN concentrations at the sub-basin outlets include plant uptake, leaching, denitrification in the soil and in lakes and streams, primary production and mineralisation. Changes in precipitation and temperature magnitudes and variability can cause changes to the dominant flow pathways in the soil or in the seasonality of high groundwater levels. These changes to water levels and flow pathways are important because the availability of nutrients in the different soil layers from which runoff occurs varies in both time and space. Therefore, the amount of nutrients leaching from the soil is affected. Similarly, changes in timing of precipitation events affect the availability of particulate phosphorous for erosion from into lakes and streams.

In Denmark, northern Germany and Poland increases in both TON (total organic nitrogen) and TIN (total inorganic nitrogen) concentrations were seen. The southwest regions are the most densely populated and intensely farmed regions of the Baltic Sea catchment, hence nutrient load inputs here are largest. In other parts of the model domain, TON was also shown to decrease, but TIN was shown to increase in most of the northern parts of the model domain, for example in southern Sweden. Precipitation, temperature and evapotranspiration are all seen to increase over the entire model domain (for all scenarios), so it is not possible to directly correlate the annual mean changes in TIN with changes in the forcing, nor with the changes in discharge. Changes to denitrification and mineralisation act to either increase or decrease the availability of nutrients both for plant uptake and runoff to watercourses, whilst changes to the dominant flow paths of runoff or the seasonality of high groundwater levels determine the rate at which the available nutrients are transported in the runoff.

Table 3 Summary of processes contributing to changes in N loads in the Vistula River catchment.

10^3 ton [N]/year	1971–2000	2071–2100	Difference
Mineralisation in soil	330	381	51
Denitrification from soil	433	485	52*
Plant uptake from soil	850	866	16*
Load from soil	114	110	–4
Point Sources	18	18	0
Total load to streams/lakes (gross load)	132	128	–4
Denitrification streams/lakes	3	4	1*
Net load to sea	109	103	–6

* Increase in denitrification decreases N in gross load.

For example, the modelled budget of TN for the Vistula River (Table 3) shows small decreases of TN concentrations in discharge for most of the catchment. Denitrification in the soil and uptake of nutrients by plants, both sinks of N, are seen to increase with rising temperatures by about 12%, and 2%, respectively, i.e. a loss of 68 000 ton N/year. Nevertheless, the total decrease in N leaching from the soil (i.e. the gross load) is only 4000 ton N/year, about 6%, indicating other processes acting to balance out the increased losses due to denitrification. In this case, mineralisation, which is temperature and soil moisture dependent, increased by 51 000 ton N/year, increasing the availability of N in the soil. Other changes to the gross load are caused by changes to the dominant flow pathways and seasonality of groundwater level increases. In the southern Swedish rivers, no change or only a small increase in TN concentrations was observed. Here, the increases in denitrification and plant uptake balanced out the increases in mineralisation, netting little to no change in concentrations of leached TN. Finally, spurious results for changes to TN and TIN concentrations are seen for two rivers in the far north. Both of these rivers include areas of glacier which are modelled as endless sources of snowmelt in the current version of the HYPE model. For the climate scenarios, the strong increases to temperature for this region therefore contribute to large increases in cold runoff affecting N processes. No consideration is made in the model for changes in glacial area or these extreme changes in stream temperature; hence, climate scenario results for glacially-fed rivers should be disregarded and future model development should focus on “climate-proofing” such processes.

Values for changes to phosphorous loads were rather different to those for nitrogen. Figure 3 shows for Denmark, northern Germany and northern Poland, i.e. the more populated and agriculturally exploited parts of the catchment, little to no increase in TP (when viewed as a percent increase in TP). Nevertheless, when viewed as absolute increases in TP, these increases were larger than in the rest of the Baltic Sea basin. Particulate phosphorous was predicted to increase as a result of increased precipitation and discharge, which cause higher erosion of particle bound phosphorous. Soluble phosphorous was seen to decrease in the south due to increased primary production of plankton algae in surface water which consumes SP and produces PP, a process which is dependent on the stream temperature. The net effect was a slight increase in TP. Seemingly more significant increases of 20–60% are seen across southern Sweden, southern Finland and into Russia, where small increases in TP compared to small initial values may be significant. Here, both SP and PP concentrations increased; however, the absolute increases here, as compared to the southeast of the Baltic Sea basin were very small.

CONCLUSIONS

Four climate scenarios, dynamically downscaled using an atmosphere–ocean coupled regional climate model, were used to drive a high-resolution hydrological and nutrient process model of the Baltic Sea basin. The spatial distribution of changes to discharge and nutrient concentrations across the basin was similar between scenarios, but locally varied considerably for each scenario. Total discharge to the Baltic Sea was shown to increase by between 3 and 14%, TP loads between 14 and 23%, while TN loads were shown to decrease by 3% in one scenario, but increase by up to 4% in other scenarios. The high spatial variability of changes to TN and TP concentrations indicates the need for process-based modelling of nutrient transport, because the balance between the many climate dependent processes that act on the nitrogen and phosphorous cycles was shown to greatly affect the final result. As a consequence, it is of high importance that the climate dependence of each of these processes is adequately simulated. Future work should therefore focus on verifying the response of modelled processes to climate change, investigating the long-term development of nutrient storages in the soil, and re-calibrating and validating the water quality parameters in the model as more data become available. These projections present possible scenarios for how discharge and nutrient fluxes to the Baltic Sea may change in a future climate.

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