Document title	Draft key messages prepared by the EN CLIME Carbon and Nutrient Cycles Team
Code	3-3
Category	DEC
Agenda Item	Agenda Item 3 – Key messages for the primary parameters
Submission date	13.8.2019
Submitted by	Secretariat
Reference	

Background

The following document contains the draft key messages prepared by the Carbon and Nutrient Cycles Team under the joint HELCOM/Baltic Earth Expert Network on Climate Change (EN CLIME).

The Carbon and Nutrient Cycles Team experts are as follows:

Karol Kulinski (confirmed team lead)
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Oleg Savchuck (outside expert)
Joakim Lagner

Key messages for the following parameters are included in this document (available experts in the team presented on the right):

Parameters	Experts
Changes in carbonate chemistry (incl. air-sea exchange of CO2)	Anna Rutgersson; Gregor Rehder; Janika Laht; Jesper Philip Aagaard Christensen; Karol Kulinski; Marcin Kawka; Matthias Gröger; Peter Thor
Riverine nutrient loads and atmospheric deposition (incl. dissolved organic matter and nutrients)	Bo Gustafsson; Janika Laht; Joakim Langner; Jukka Käyhkö; Marcin Kawka; Markus Meier; Mikhail Sofiev
Pelagic habitats (incl. phytoplankton and zooplankton community structure, spring blooms, functional traits etc.)	Harri Kuosa; Markku Viitasalo; Peter Thor
Acidification	Anna Rutgersson; Georg Martin; Gregor Rehder; Jacob Carstensen; Jesper Philip Aagaard Christensen; Karol Kulinski; Peter Thor
Oxygen concentration and hypoxia	Ari Laine; Gregor Rehder; Harri Kuosa; Jacob Carstensen; Jan-Hinrich Reißmann; Jesper Philip Aagaard Christensen; Markku Viitasalo; Oleg Savchuck; Urmas Lipps

Guidance for preparing key messages and the fact sheet:

The following guidance has been compiled from discussions and outcomes of previous EN CLIME and Team meetings and from the background documents, e.g. Terms of Reference.

The fact sheet should present a consensus view by the regions climate experts on the climate change driven changes in the outlined parameters, as well as related issues identified as of relevance to the policy process. The intention is for the fact sheet to be a science driven exercise, relying exclusively on, and synthesizing, already existing detailed, peer reviewed information from leading marine and climate scientists. The information is to be condensed to key messages, including information on trends where possible. In the final fact sheet the information is to be present visually, in an accessible and stable way across years. To make the information as accessible as possible the parameters can at later stage of the process be combined under wider topics in order to make the fact sheet more usable for policy makers. Information to support the statements in the factsheet will be available as separate publications (BACC II, BACC III, BEAR reports etc.), clearly referenced and the fact sheet itself fully-citable. While already existing BACC reports should be used as supporting material for the EN CLIME work, that subsequent results coming out of BACC III can be used to amend the key messages where needed prior to publication.

The fact sheet will strive to be a concise and easily accessible resource from science to regulators and policymakers and will contain information, using agreed language, on what has happened and what can be expected to happen in the future. As discussed in EN CLIME 2-2019 wherever possible the information should be presented in approximate ranges (near term, medium term and long term) and that changes in extremes as well as in means should be taken into account for each of the primary parameters.
While the fact sheet should be made as approachable as possible, the overall complexity of the issue also needs to be communicated. In this respect the EN CLIME has highlighted the interlinkages between different parameters and supported the possibility to include some sort of info-graphic to visualize the interlinkages.

The titel 'Description' should be included to the fact sheet in a very concise manner, describing the underlaying factors, and linkages to other parameters.

EN CLIME has in previous meeting discussed the importance of describing the uncertainty of predictions and noted that uncertainty varies depending on the temporal ranges used and between parameters, which needs to be taken into account in the description. Hence different uncertainties can be given for different parameters and time intervals.

Action requested

The Meeting is invited to review and revise the draft key messages and agree on them, keeping in mind that the intention is to streamline he presentation of all messages to the extent possible.

Changes in carbonate chemistry (incl. air-sea exchange of CO2)

Topic	Description	What is expected to happen?		What is already happening?		Knowledge gaps	Policy relevance
		Mean change	Extremes	Mean change	Extremes		
		Level of confidence:	*Level of confidence:*	*Level of confidence:*	*Level of confidence:*		
Changes in carbonate chemistry (incl. air-sea exchange of CO2) *Affiliation of expert* Karol Kulinski – Institute of Oceanology Polish Academy of Sciences	Give a brief description of the parameter Show links to other parameters. Carbonate system (CO_2 system) is a major component of the acid/base balance in seawater and thus shapes the seawater pH. It is characterized by the thermodynamic equilibria between hydrogen ions (pH) and the different CO_2 species (CO_2, H_2CO_3, HCO_3^-, CO_3^{2-}). Both ions HCO_3^- and CO_3^{2} are bases and are part of the total alkalinity (A_T) of	What is expected to happen in the future? Present expected changes quantitatively e.g. through ranges whenever possible. The atmospheric CO_2 concentration will increase in the future and influence the marine CO_2 system.	What is expected to happen in the future? Present expected changes quantitatively e.g. through ranges whenever possible.	What is happening? Provide information on already identified effects What are the direct consequences? Examples of effects can we already see, if available. There is clear seasonal pattern in the partial pressure of CO_2 (pCO_2) in the surface Baltic Sea. It is controlled by the biologically driven processes (organic matter production and remineralization) as well as changes in the mixed layer depth. In winter the surface Baltic Sea is	What is happening? Provide information on already identified effects What are the direct consequences? Examples of effects can we already see, if available. Extremely low pCO_2 levels (Gregor please give the number here) in the surface layer of the central Baltic Sea have been detected in summer 2018 – likely as a consequence of extremely shallow mixed layer depth and intense cyanobacteria bloom Gregor please correct that if I am wrong	Due to the high spatial and temporal variability of the seawater pCO_2 it is not known whether the Baltic Sea as a whole is a net sink or net source of CO_2. It is unclear what is the source of total alkalinity increase in the Baltic Sea, and whether it will continue in the future with the same magnitude.	Policy relevance: What can be done about it (possible responses)? Especially focusing on avoidance, alleviation, adjustment and adaptation. What is already being done about it? Existing agreements/policies: How does it affect measures taken to reduce pressures on the Baltic Sea? Policy gaps

Commented [A1]: I suggest to combine both variables, air-sea exchange and acidification to avoid repetition

Commented [A4]: There are more knowledge gaps such as the causes of drop in pCO2 after the spring bloom.

Commented [A3]: You should add an explanation. As there are no publications yet available, I suggest to skip this text.

	seawater. A_T is defined as an excess of proton acceptors over proton donors (or bases over acids). Thus A_T controls change in seawater pH upon the addition of CO_2 or other acids and is regarded as the buffer capacity of seawater. Changes in the carbonate chemistry control the acidification mechanism.			oversaturated with CO_2, while in the productive periods pCO_2 goes down below the atmospheric level with 2 clear minima: during spring bloom and N_2-fixing cyanobacteria bloom. The difference between seawater pCO_2 and atmospheric pCO_2 during the productive periods has increased due to the eutrophication and development of cyanobacteria blooms. During spring bloom it changed from about 50 µatm (Buch, 1945) to ca. 250 µatm (BACC II), while during summer from about 40 µatm (Buch, 1945) to 300 µatm (BACC II). The pCO_2 seasonal cycle in the surface water controls the annual CO_2 exchange	and give some reference		

				through the air/sea interface. A_T is increasing in the Baltic Sea. The highest A_T trend was found in the Gulf of Bothnia (7.0 $\mu mol\ kg^{-1}\ yr^{-1}$), followed by 3.4 $\mu mol\ kg^{-1}\ yr^{-1}$ in the central Baltic whereas no trend could be detected in the Kattegat (Müller et al., 2016).			

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Riverine nutrient loads and atmospheric deposition (incl. dissolved organic matter and nutrients)

Topic	Description	What is expected to happen?		What is already happening?		Knowledge gaps	Policy relevance
		Mean change	Extremes	Mean change	Extremes		
		Level of confidence: ??	*Level of confidence:*	*Level of confidence:* ??	*Level of confidence:*		
Riverine nutrient loads and atmospheric deposition (incl. dissolved organic matter and nutrients) *Draft text by Michelle McCrackin Baltic Sea Centre, SU*	The timing and magnitude of nitrogen and phosphorus inputs from land to the sea via waterborne and atmospheric transport. Waterborne nutrient loads are strongly impacted by patterns of precipitation and run-off. External nutrient loads strongly impact the eutrophication status of the sea.	GCMs suggest the north be wetter and the south will be drier (BACC II). Models suggest land-based nutrient management will have greater effect on loads than uncertainties caused by greenhouse gas emission scenarios (Saraiva et al. 2019) DOC inputs will increase in areas affected by permafrost thaw (BACC II) Existing scenario simulations of the Baltic Sea were carried out with nutrient load		No statistically significant linear trends in annual river discharge to the sea has been detected. Winter flows have increased due to temperature while spring flows have decreased (BACC II) PLC reports statistically significant reductions in riverine nutrient loads to the sea relative to the 1997 to 2003 reference period (PLC6). These reductions are not attributed to climate. DOC inputs to the sea have increased over the past century		How fertilization practices, crops grown, and land use will change in response to climate change.	The coastal countries have agreed to reduce nitrogen and phosphorus loads from land to the sea in the Baltic Sea Action Plan (BSAP). The effects of climate change, both on the eutrophication and the delivery of nutrients from land to sea have not been incorporated into the BSAP. The Water Framework Directives requires EU member states to develop programmes of measure to reduce nutrient inputs in their River Basin Management Plans.

		scenarios that span the range of plausible future socio-economic conditions from the most optimistic (BSAP) to the worst scenario (Saraiva et al., 2019; Meier et al., 2019). In the reference scenario, nutrient loads represent the average loads of the period 2010-2012. The high or worst case scenario assumes changes caused by a 'fossil-fuelled development' scenario coupled to increasing river runoff. Changes in nitrogen and phosphorus loads were calculated from regional assumptions, e.g., on population growth, changes in agricultural practices such as land and fertilizer use and expansion of sewage water treatment		but the cause is not known (BACC II).			

		plants (Zandersen et al., 2019).					

Pelagic habitats (incl. phytoplankton and zooplankton community structure, spring blooms, functional traits etc.)

Topic	Description	What is expected to happen?	Where is the change seen first? Is it already happening?	Other drivers	Knowledge gaps	Policy relevance
		Level of confidence:	*Level of confidence:*	*Level of confidence:*		
	Spring bloom phenology (timing and length)[1)]	Spring blooms start earlier and are longer	Observed for a time series 2000-2014 from the Baltic Proper and the Gulf of Finland; consequence is potential mismatch with timing of zooplankton	Warming and prevalent high pressures	Long-term development, effect on species composition and carbon transfer (including settling)	
	Changes in plankton communities[2)]	Both phyto- and zooplankton communities are composed of smaller species	Observed on the northern Baltic Sea between 1979 and 2011	A complex set of drivers including warming, eutrophication and trophic cascades	Evaluation on the importance of the climate change component	
	Summer biomass of cyanobacteria[2)]	Increasing blooms	Observed on the northern Baltic Sea between 1979 and 2011	Warming, decreasing salinity and changes in nutrient ratios	Evaluation on the importance of the climate change component	
	Spring bloom dinoflagellate biomass increase[3)4)]	Shifting diatom/dinoflagellate ratios	Observed in some basins	Ice free winters favor dinoflagellates	The connection still not clear, the effect may depend on other factors	
Pelagic habitats (incl. phytoplankton and zooplankton	*Give a brief description of the parameter*	*What is expected to happen in the future? Present expected changes quantitatively e.g. through ranges whenever possible.*	*What is happening? Provide information on already identified effects*	*Quite a number of ecosystem parameters have other more*		*Policy relevance: What can be done about it (possible responses)?*

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Commented [A6]: This will depend on the future nutrient loads. Scenario simulations project a reduction under the BSAP

Commented [A7]: Wasmund (2017), Wasmund et al. (2017)

Commented [A8]: Increasing zooplankton biomass

community structure, spring blooms, functional traits etc.) *Harri Kuosa, Markku Viitasalo (FEI)* *Affiliation of expert*	*Show links to other parameters.*		*What are the direct consequences? Examples of effects can we already see, if available.*	*powerful drivers behind the present change.* *This column presents other drivers for the reader to understand that mitigation/adaptation can be done also by regulating these drivers.*		*Especially focusing on avoidance, alleviation, adjustment and adaptation.* *What is already being done about it?* *Existing agreements/policies:* *How does it affect measures taken to reduce pressures on the Baltic Sea?* *Policy gaps*

1) Groetsch PMM, Simis SGH, Eleveld MA and Peters SWM (2016). Spring blooms in the Baltic Sea have weakened but lengthened from 2000 to 2014. Biogeosciences 13: 4959–4973

2) Suikkanen S, Pulina S, Engström-Öst J, Lehtiniemi M, Lehtinen S, Brutemark A (2013). Climate Change and Eutrophication Induced Shifts in Northern Summer. PLoS ONE 8(6): e66475.doi:10.1371/journal.pone.0066475

3) Klais R, Tamminen T, Kremp A, Spilling K, Woong An B, Hajdu S, Olli K (2013). Spring phytoplankton communities shaped by interannual weather variability and dispersal limitation: Mechanisms of climate change effects on key coastal primary producers. Limnol Oceanogr 58: 753-762

4) BACC2

Acidification

Topic	Description	What is expected to happen?	Where is the change seen first? Is it already happening?	Other drivers	Knowledge gaps	Policy relevance
		Level of confidence:	*Level of confidence:*	*Level of confidence:*		
Acidification *Affiliation of expert* Karol Kulinski – Institute of Oceanology Polish Academy of Sciences	Give a brief description of the parameter Show links to other parameters. Ocean Acidification – mechanism of seawater pH decrease mostly due to the rising CO_2 concentrations	What is expected to happen in the future? Present expected changes quantitatively e.g. through ranges whenever possible. The atmospheric CO_2 concentration will increase and influence the marine CO_2 system	What is happening? Provide information on already identified effects What are the direct consequences? Examples of effects can we already see, if available. The mean CO_2 concertation is increasing in the surface Baltic Sea due to the increase of CO_2 in the atmosphere. (Schneider et al., 2015, BACC II). According to the thermodynamics of the CO_2 system the increase of 2.0 ppm yr^{-1} in the atmospheric pCO_2 should result in the pH decrease of about 0.02 per	Quite a number of ecosystem parameters have other more powerful drivers behind the present change. This column presents other drivers for the reader to understand that mitigation/adaptation can be done also by regulating these drivers.	It is unclear what is the source of total alkalinity increase in the Baltic Sea, and whether it will continue in the future with the same magnitude.	Policy relevance: What can be done about it (possible responses)? Especially focusing on avoidance, alleviation, adjustment and adaptation. What is already being done about it? Existing agreements/policies:

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	in the atmosphere and thus also in the surface seawater. Since CO_2 dissolved in seawater forms the diprotic carbonic acid, hydrogen ions are released. Although the major fraction of the hydrogen ions are taken up by carbonate ions (buffer reaction), a significant fraction stays in the water column and thus causes a decrease of the pH. Ocean Acidification mechanism		decade if the total alkalinity would be constant. However, the pH trend expected based on the pCO_2 increase could not be definitively identified in the Baltic Sea. Ocean acidification (pH decrease) is to large extent mitigated in the Baltic Sea by the total alkalinity (A_T) increase (Müller et al., 2016). The highest A_T increase was found in the Gulf of Bothnia (7.0 µmol kg^{-1} yr^{-1}), followed by 3.4 µmol kg^{-1} yr^{-1} in the central Baltic whereas no trend could be detected in the Kattegat. Müller J.D., Schneider B., Rehder G., 2016, Long-term alkalinity trends in the Baltic Sea and their implications for CO_2-induced acidification.	Enhanced organic matter production (euthrophication) and remineralization causes high amplitude of the seasonal pH changes in the Baltic Sea		How does it affect measures taken to reduce pressures on the Baltic Sea? Policy gaps

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	directly depends on “Changes in carbonate chemistry (incl. air-sea exchange of CO_2)”		Limnology and Oceanography 61, 1984-2002.			

Oxygen concentrations and hypoxia

Topic	Description	What is expected to happen?		What is already happening?		Knowledge gaps	Policy relevance
		Mean change	Extremes	Mean change	Extremes		
		Level of confidence: Medium confidence	*Level of confidence: Medium confidence*	*Level of confidence: High confidence*	*Level of confidence: High confidence*		
Oxygen concentrations and hypoxia *Markus Meier, IOW and SMHI* *Jacob Carstensen, Arhus University* *Oleg Savchuk, Stockholm University*	Give a brief description of the parameter Show links to other parameters. Dissolved oxygen concentration in the water column is controlled by physical transport supply (advection and diffusion) and biological oxygen demand for oxidation of organic matter. Due to limited ventilation largely incapable to meet the oxygen demand by elevated concentrations of organic matter in the water column and sediments	What is expected to happen in the future? Present expected changes quantitatively e.g. through ranges whenever possible. Projected warming and global mean sea level rise may reinforce eutrophication and oxygen depletion in the Baltic Sea by reducing air-sea and vertical transports of oxygen -, intensifying internal nutrient cycling, and increasing river-borne nutrient loads. However, the response of deep-water oxygen conditions to	What is expected to happen in the future? Present expected changes quantitatively e.g. through ranges whenever possible. For the end of the century (2069-2098), hypoxic area is projected to change only slightly in the ensemble mean under reference/present-day (-14 … -5%) and high (-2 … +5%) nutrient load scenarios (see EN-CLIME Nutrient loads) compared to the period 1976-2005.	What is happening? Provide information on already identified effects What are the direct consequences? Examples of effects can we already see, if available. Despite the decrease of nutrient loads from land after the 1980s, recently observed oxygen consumption rates are higher than ever observed, limiting the impact of natural ventilation by oxygen-enriched saltwater intrusions in the open Baltic Sea. Improving oxygen conditions	What is happening? Provide information on already identified effects What are the direct consequences? Examples of effects can we already see, if available. In the Baltic Sea hypoxia has expanded considerably since the first oxygen measurements became available in 1898. In 2016 the annual maximum extent of hypoxia covered an area of about 70,000 km^2, comparable with the size of Ireland, whereas 150 years	A recent assessment suggests that the biggest uncertainties in projections of biogeochemical cycles are caused by (1) poorly known current and future bioavailable nutrient loads from land and atmosphere, (2) the setup of numerical scenario experiments (including the spin up strategy), (3) differences between the projections of global and regional climate models, in particular, with respect to the global mean sea level rise and regional water cycle, (4) differing model-specific responses of the simulated biogeochemical cycles to long-term changes in external nutrient loads	Policy relevance: High relevance for the next update of the BSAP. What can be done about it (possible responses)? Mitigation by fully implementation of the BSAP nutrient load abatement strategy. Especially focusing on avoidance, alleviation, adjustment and adaptation. What is already being done about it?

	(eutrophication), the Baltic Sea deeps suffer from deoxygenation and hypoxia. Hypoxic area is defined as the extent of bottom water with oxygen concentrations below a threshold such as 2 mL O2 L^{-1}. Hypoxia is characterized by the lack of higher forms of live.	changing climate will mainly depend on the nutrient load scenario. In the case of high (low) nutrient loads, the impact of the changing climate would be considerable (negligible). Scenario simulations suggest that the complete implementation of the Baltic Sea Action Plan (BSAP) resulting in required load reductions will lead to a significantly improved ecosystem state of the Baltic Sea irrespective of the driving global climate model. The latter was shown for the ecosystem indicators water clarity and summer mean oxygen deficit due to biogeochemical oxygen consumption compared to saturated oxygen conditions.	Under the BSAP scenario, hypoxic area will be reduced by 50 to 60% in the ensemble mean at the end of the century compared to 1976-2005.	have been observed in some coastal systems, where inputs of nutrients and organic matter have been abated. However, hypoxia remains a large problem for many coastal systems, displaying unaltered or even worsening conditions.	ago hypoxia was presumably not existent or at least very small. Hypoxia was mainly caused by accumulation of increasing riverborne nutrient loads and atmospheric deposition. The impacts of other drivers like observed warming and eustatic sea level rise were comparatively smaller but still important.	and climate of the Baltic Sea region, and (5) unknown future greenhouse gas emissions.	Existing agreements/policies: Reduction of nutrient loads since the 1980s How does it affect measures taken to reduce pressures on the Baltic Sea? Policy gaps

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Meier, H. E. M., K. Eilola, E. Almroth-Rosell, S. Schimanke, M. Kniebusch, A. Höglund, P. Pemberton, Y. Liu, G. Väli, and S. Saraiva, 2019b: Correction to: Disentangling the impact of nutrient load and climate changes on Baltic Sea hypoxia and eutrophication since 1850. Climate Dynamics, 53:1167-1169, https://doi.org/10.1007/s00382-018-4483-x

Meier, H. E. M., M. Edman, K. Eilola, M. Placke, T. Neumann, H. Andersson, S.-E. Brunnabend, C. Dieterich, C. Frauen, R. Friedland, M. Gröger, B. G. Gustafsson, E. Gustafsson, A. Isaev, M. Kniebusch, I. Kuznetsov, B. Müller-Karulis, A. Omstedt, V. Ryabchenko, S. Saraiva, and O. P. Savchuk, 2018b: Assessment of eutrophication abatement scenarios for the Baltic Sea by multi-model ensemble simulations. Frontiers in Marine Science, 5:440, https://doi.org/10.3389/fmars.2018.00440

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