## Baltic Marine Environment Protection Commission

Third meeting of Joint HELCOM/ Baltic Earth Expert Network on Climate Change — EN CLIME 3-2019

Stockholm, Sweden, 19 August 2019

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| **Document title** | Draft key messages prepared by the EN CLIME Carbon and Nutrient Cycles Team |
| **Code** | 3-3 rev.1 |
| **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)**
Anna Rutgersson
Ari Laine
Georg Martin
Gregor Rehder
Harri Kuosa
Jesper Philip Aagaard Christensen
Jukka Käyhkö
Markku Viitasalo
Markus Meier
Matthias Gröger
Bo Gustaffson
Peter Thor
Urmas Lips
Jan-Hinrich Reißmann
Jacob Carstensen
Janika Laht
Mikhail Sofiev
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)<br><br>*Affiliation of expert*<br><br>Karol Kulinski – Institute of Oceanology Polish Academy of Sciences | Give a brief description of the parameter<br><br>Show links to other parameters.<br><br>Carbonate system ($CO_2$ system) is a major component of the acid/base balance in seawater and thus shapes the seawater pH.<br>It is characterized by the thermodynamic equilibria between hydrogen ions (pH) and the different $CO_2$ species ($CO_2$, $H_2CO_3$, $HCO_3^-$, $CO_3^{2-}$).<br>Both ions $HCO_3^-$ and $CO_3^2$ are bases and are part of the | What is expected to happen in the future? Present expected changes quantitatively e.g. through ranges whenever possible.<br><br>The atmospheric $CO_2$ concentration will increase in the future and influence the marine $CO_2$ system. It is thus likely that the net annual uptake will increase with increasing CO2 concentrations in the atmosphere Omstedt et al 2014). | 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<br><br>What are the direct consequences? Examples of effects can we already see, if available.<br><br>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.<br><br>In winter the surface Baltic Sea is 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. | What is happening? Provide information on already identified effects<br><br>What are the direct consequences? Examples of effects can we already see, if available. | 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 $CO_2$. Most previous research results concerning the carbon budget cover shorter periods, indicating a range between –1.16 and 2.9 mol m−2 y−1) (e.g.Wesslander et al.,2010;Kulinski and Pempkowiak,2012). Some studies indicate a sink (Kulinski and Pempkowiak (2012)) others a source (Norman et al., 2013, Parard et al., 2017).<br><br>It is unclear what is the source of total | Policy relevance:<br><br>What can be done about it (possible responses)?<br><br>Especially focusing on avoidance, alleviation, adjustment and adaptation.<br><br>What is already being done about it? Existing agreements/policies:<br><br>How does it affect measures taken to reduce pressures on the Baltic Sea?<br><br>Policy gaps |

**Commented [A1]:** Clarify what is special in the Baltic Sea regarding the carbonate cycle and how will it change with climate change? Is acidification different for the Baltic then for the oceans? It is important to explaine alkalinity in a very simple way.

**Commented [A2]:** Why is this important? We e.g. have no corals… resercah on responses of biota

**Commented [A3]:** I suggest to combine both variables, air-sea exchange and acidification to avoid repetition

**Commented [A4R3]:** Agreed

**Commented [A5]:** Uptake? Are we sure?

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| | total alkalinity ($A_T$) of 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.<br><br>Changes in the carbonate chemistry control the acidification mechanism.<br><br>The exchange of CO2 between the water and the atmosphere is controlled by the air–sea difference in partial pressure of CO2 (in practice the water-side concentration) at the surface and of the efficiency of the transfer processes. The partial pressure at the water surface is controlled by | | | 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.<br>During spring bloom it changed from about 50 µatm (Buch, 1945) to ca. 250 µatm (BACC II), while during summer from about<br>40 µatm (Buch, 1945) to 300 µatm (BACC II).<br><br>The $pCO_2$ seasonal cycle in the surface water together with the transfer velocity (mainly wind driven) controls the annual $CO_2$ exchange through the air/sea interface. The Baltic Sea is a sink or a source of CO2 to the atmosphere depending on the season, net annual mean is relatively small.<br><br>$A_T$ is increasing in the Baltic Sea in the last 20 years. The highest $A_T$ trend 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 et al., 2016). | | alkalinity increase in the Baltic Sea, and whether it will continue in the future with the same magnitude.<br><br>Ecosystem productivity and thus $pCO_2$ decrease in the period after the spring bloom (from mid-April until mid-June) is not explained quantitatively due to the missing N source. | |

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**Commented [A6]:** Please add the period and significance level

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| | biological, chemical and physical processes in the ocean. The efficiency of the transfer processes is determined by the resistance to the transfer in the atmosphere as well as in the water (can be simplified by using the wind speed). | | | | | | |

## 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<br>*Level of confidence:* ?? | Extremes<br>*Level of confidence:* | Mean change<br>*Level of confidence:* ?? | Extremes<br>*Level of confidence:* | | |
| Riverine nutrient loads and atmospheric deposition (incl. dissolved organic matter and nutrients)<br><br>*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.<br><br>Waterborne nutrient loads are strongly impacted by patterns of precipitation and run-off.<br><br>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).<br><br>Models suggest land-based nutrient management will have greater effect on loads than uncertainties caused by greenhouse gas emission scenarios (Saraiva et al. 2019)<br><br>DOC inputs will increase in areas affected by permafrost thaw (BACC II)<br><br>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)<br><br>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.<br><br>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. |

**Commented [A8]:**

**Commented [A9R8]:** Account for overflows of waste water treatment plants

**Commented [A11]:** Reformulate to account for that the greenhouse gasesand nutrient management which are the important aspects(not the model itself)

**Commented [A12]:** Limit to say that DOC inputs will increase (remove permafrost link), check with Michelle and rephrase.

**Commented [A10]:** Account for lag effects of the ecosystem

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| | | 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).<br><br>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). | | | |

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| | | plants (Zandersen et al., 2019). | | | | | |

## Atmospheric deposition of 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: 1). High, 2) medium* | *Level of confidence: medium* | *Level of confidence: high* | *Level of confidence: high* | | |
| Atmospheric deposition of nutrients<br><br>*Draft text by Mikhail Sofiev Finnish Meteorological Institute, Finland* | The timing and magnitude of nitrogen input from the atmosphere to the sea.<br><br>Airborne nutrient deposition is controlled by (i) atmospheric emission of nutrients and its seasonality, but also by (ii) regional wind patterns, (iii) the precipitation features.<br><br>Albeit small compare to the riverine input, airborne nutrient loads can impact the eutrophication of the open sea, where the riverine input does not easily reach. | 1) Modelling studies consensus is that the climate change per-se has very limited impact on AQ and related depositions. Much bigger impact comes from emission changes, which partly can be prompted by the climate change, i.e. the indirect impact is the main (Colette et al., 2015; Langner et al., 2012; Simpson et al., 2014; Soares et al., 2016) and references therein<br><br>2) Among the sources of concern is the NH3 evaporation from manure fields & storages: 40-100% more NH3 emission | Stronger and longer dry spells and heat waves prompt the vegetation fires, sources of NOy, NH3 and organic aerosols. Such events will cause strong episodic nutrient deposition onto the sea. | No trends in nutrient deposition can be reliably associated with the climate change. Emission reduction efforts keep reducing both NOy and NHx concentrations and depositions. However, NHx emission and model-predicted deposition reduction both stalled since mid-2000s (Gauss et al., 2019). | Major heat waves are occurring more frequently and are accompanied with stronger fires, especially to the east of the Baltic Sea. The fire-related emissions are also updating the records almost every other year (http://is4fires.fmi.fi). | Ammonia emission and its dynamics are among the worst-known processes controlling the nutrient deposition. | Reduction of NH3 emission, unlike NOx, requires large efforts and political and public consensus. Since the poorly controlled processes such as NH3 evaporation are likely to increase the semi-natural emission fluxes, need for additional efforts seems to be growing. |

**Commented [A13]:** Include also monitoring data (HELCOM and peer reviewed sources)

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| | | per each 5C temperature rise. (Sutton et al., 2013) (Skjøth and Geels, 2013) | | | | | |

Colette, A., Andersson, C., Baklanov, A., Bessagnet, B., Brandt, J., Christensen, J. H., Doherty, R., Engardt, M., Geels, C., Giannakopoulos, C., Hedegaard, G. B., Katragkou, E., Langner, J., Lei, H., Manders, A., Melas, D., Meleux, F., Rouïl, L., Sofiev, M., Soares, J., Stevenson, D. S., Tombrou-Tzella, M., Varotsos, K. V and Young, P.: Is the ozone climate penalty robust in Europe?, Environ. Res. Lett., 10(8), 084015, doi:10.1088/1748-9326/10/8/084015, 2015.

Gauss, M., Bartnicki, J. and Klein, H.: Atmospheric nitrogen deposition to the Baltic Sea, Oslo. [online] Available from: https://emep.int/publ/helcom/2018/index.html, 2019.

Langner, J., Engardt, M., Baklanov, A., Christensen, J. H., Gauss, M., Geels, C., Hedegaard, G. B., Nuterman, R., Simpson, D., Soares, J., Sofiev, M., Wind, P. and Zakey, A.: A multi-model study of impacts of climate change on surface ozone in Europe, Atmos. Chem. Phys., 12(21), doi:10.5194/acp-12-10423-2012, 2012.

Simpson, D., Andersson, C., Christensen, J. H., Engardt, M., Geels, C., Nyiri,  a., Posch, M., Soares, J., Sofiev, M., Wind, P. and Langner, J.: Impacts of climate and emission changes on nitrogen deposition in Europe: a multi-model study, Atmos. Chem. Phys., 14(13), 6995–7017, doi:10.5194/acp-14-6995-2014, 2014.

Skjøth, C. A. and Geels, C.: The effect of climate and climate change on ammonia emissions in Europe, Atmos. Chem. Phys., 13, 117–128, doi:10.5194/acp-13-117-2013, 2013.

Soares, J., Sofiev, M., Geels, C., Christensen, J. H., Andersson, C., Tsyro, S. and Langner, J.: Impact of climate change on the production and transport of sea salt aerosol on European seas, Atmos. Chem. Phys. Discuss., (February), 1–52, doi:10.5194/acp-2015-1056, 2016.

Sutton, M. A., Reis, S., Riddick, S. N., Dragosits, U., Nemitz, E., Theobald, M. R., Tang, Y. S., Braban, C. F., Vieno, M., Dore, A. J., Mitchell, R. F., Wanless, S., Daunt, F., Fowler, D., Blackall, T. D., Milford, C., Flechard, C. R., Loubet, B., Massad, R., Cellier, P., Personne, E., Coheur, P. F., Clarisse, L., Damme, M. Van, Ngadi, Y., Clerbaux, C., Skjøth, C. A., Geels, C., Hertel, O., Kruit, R. J. W., Pinder, R. W., Misselbrook, T. H., Bleeker, A., Dentener, F. and Vries, W. De: Towards a climate-dependent paradigm of ammonia emission and deposition, Philos. Trans. R. Soc. B Biol. Sci., 368(1621), doi:http://dx.doi.org/10.1098/rstb.2013.0166, 2013.

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

### Secondary parameters:

| Topic | Description | What is expected to happen?<br>*Level of confidence:* | Where is the change seen first? Is it already happening?<br>*Level of confidence:* | Other drivers<br>*Level of confidence:* | Knowledge gaps | Policy relevance |
|---|---|---|---|---|---|---|
| | 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* | *Give a brief description of the parameter* | *What is expected to happen in the future? Present expected changes* | *What is happening? Provide information on already identified effects* | *Quite a number of ecosystem parameters have other more* | | *Policy relevance:* |

**Commented [A14]:** Formulate the sentences as "if" statements.

**Commented [A15]:** Would be good to have some more details

**Commented [A16]:** This will depend on the future nutrient loads. Scenario simulations project a reduction under the BSAP

**Commented [A17]:** Wasmund (2017), Wasmund et al. (2017)

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

**Commented [A18]:** Increasing zooplankton biomass

[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<br>*Affiliation of expert*<br><br>Karol Kulinski – Institute of Oceanology Polish Academy of Sciences | Give a brief description of the parameter<br><br>Show links to other parameters.<br><br>Ocean Acidification – mechanism of seawater pH decrease mostly due to the rising $CO_2$ concentrations in the atmosphere and thus also in the surface seawater.<br>Since $CO_2$ dissolved in seawater forms the diprotic | What is expected to happen in the future? Present expected changes quantitatively e.g. through ranges whenever possible.<br><br>The atmospheric $CO_2$ concentration will increase and influence the marine $CO_2$ system; the mean pH decrease by 0.2±0.1 throughout the Baltic Sea is expected until 2100 (Omstedt et al., 2012)<br>pH decrease of 0.25 – 0.27 is expected until 2100 in the Baltic Proper and 0.33 in the Gulf of Bothnia (Kuznetsov nad Neumann (2013)<br>Eutrophication (increased nutrients loads) will not inhibit acidification , but the seasonal pH cycle will become amplified due to the increased biological production | What is happening? Provide information on already identified effects<br>What are the direct consequences? Examples of effects can we already see, if available.<br>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).<br>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 decade if the total alkalinity would be constant.<br>However, the pH trend expected based on the $pCO_2$ increase could not be definitively identified in the Baltic Sea. | Quite a number of ecosystem parameters have other more powerful drivers behind the present change.<br><br>This column presents other drivers for the reader to understand that mitigation/adaptation can be done also by regulating these drivers.<br><br>Enhanced organic matter production (euthrophication) and remineralization causes high amplitude of the seasonal pH changes in the Baltic Sea | 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.<br>The study by Kuznetsov and Neumann (2013) projects $A_T$ decrease in the Baltic Sea by 150 µmol $L^{-1}$ until 2100 even though the terrestrial $A_T$ loads will increase. This is due to the expected salinity decrease | Policy relevance: What can be done about it (possible responses)? Especially focusing on avoidance, alleviation, adjustment and adaptation.<br><br>What is already being done about it?<br><br>Existing agreements/policies:<br><br>How does it affect measures taken to reduce pressures on the Baltic Sea?<br><br>Policy gaps |

**Commented [A19]:** Is it possible to add results of scenario simulations, e.g. Kuznetsov et al. (2013) or Omstedt et al. (2012)?

**Commented [A20]:** Add information on scenario

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| | 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.<br><br>Ocean Acidification mechanism directly depends on "Changes in carbonate chemistry (incl. air-sea exchange of CO2)" | and mineralization (Omstedt et al., 2012)<br>Although loads of $A_T$ will increase the $A_T$ in the Baltic Proper it is expected to decrease by 150 µmol $L^{-1}$ until 2100 due to the salinity decrease in the Baltic. In consequence $A_T$ to S ratio is expected to increase (Kuznetsov and Neumann, 2013) | Ocean acidification (pH decrease) is to large extent mitigated in the Baltic Sea by the total alkalinity ($A_T$) increase (Müller et al., 2016).<br>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.<br><br>Müller J.D., Schneider B., Rehder G., 2016, Long-term alkalinity trends in the Baltic Sea and their implications for $CO_2$-induced acidification. Limnology and Oceanography 61, 1984-2002. | | | |

**Commented [A22]:** ?

**Commented [A23]:** Clarify the link to salinity? In general, for low confidence informaiton limit the presentation of numbers and figures.

**Commented [A24]:** See above

Parard, G. A. Rutgersson, S. R. Parampil, and A. A. Charantonis (2017) Earth Syst. Dynam., 8, 1093–1106, 2017, https://doi.org/10.5194/esd-8-1093-2017

Norman, M., Rutgersson A. and Sahlee, E. Impact of improved air–sea gas transfer velocity on fluxes and water chemistry in a Baltic Sea model, J. Mar. Syst. (2013), http://dx.doi.org/10.1016/j.jmarsys.2012.10.013

Omstedt, A, Humborg, C, Pempkowiak, J, Perttila, M, Rutgersson, A., Schneider, B., Smith, B. (2014). Biogeochemical Control of the Coupled CO2-O-2 System of the Baltic Sea: A Review of the Results of Baltic-C. Ambio43, 1, 49-59

Müller, J.D., Schneider, B. and Rehder, G.: Long-term alkalinity trends in the Baltic Sea and their implications for $CO_2$-induced acidification, Limnol. Oceanogr., 61, 1984-2002, 2016.

Kuznetsov, I. and Neumann T.: Simulation of carbon dynamics in the Baltic Sea with a 3D model, . J. Marine Syst., 111–112, 167–174, 2013.

Omstedt, A., Edman, M., Claremar, B., Frodin, P., Gustafsson, E., Humborg, C., Hagg, H., Morth, M., Rutgersson, A., Schurgers, G., Smith, B.,Wallstedt T. and Yurova, A.: Future changes in the Baltic Sea acid–base (pH) and oxygen balances, Tellus B 64, 19586, 2012.

## Oxygen concentrations and hypoxia

| Topic | Description | What is expected to happen? | | What is already happening? | | Knowledge gaps | Policy relevance |
|---|---|---|---|---|---|---|---|
| | | Mean change<br>*Level of confidence: Medium confidence* | Extremes<br>*Level of confidence: Medium confidence* | Mean change<br>*Level of confidence: High confidence* | Extremes<br>*Level of confidence: High confidence* | | |
| Oxygen concentrations and hypoxia<br><br>*Markus Meier, IOW and SMHI*<br><br>*Jacob Carstensen, Arhus University*<br><br>*Oleg Savchuk, Stockholm University* | Give a brief description of the parameter<br><br>Show links to other parameters.<br><br>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.<br><br>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.<br><br>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<br><br>What are the direct consequences? Examples of effects can we already see, if available.<br><br>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<br><br>What are the direct consequences? Examples of effects can we already see, if available.<br><br>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:<br><br>High relevance for the next update of the BSAP.<br><br>What can be done about it (possible responses)?<br><br>Mitigation by fully implementation of the BSAP nutrient load abatement strategy.<br><br>Especially focusing on avoidance, alleviation, adjustment and adaptation.<br><br>What is already being done about it? |

**Commented [A25]:** Include coastal hypoxia information (in the whole sheet)

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|---|---|---|---|---|---|---|---|
| | (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:<br><br>Reduction of nutrient loads since the 1980s<br><br>How does it affect measures taken to reduce pressures on the Baltic Sea?<br><br>Policy gaps |

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