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Future climate change in the Baltic Sea region and environmental impacts

3

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6

Summary and keywords

8 The warming of the global climate is expected to continue in this century although
9 the magnitude of change depends on future anthropogenic greenhouse gas
10 emissions and the sensitivity of climate to them. The regional characteristics and
11 impacts of future climate change in the Baltic Sea countries have been explored
12 since at least the 1990s. Later research has supported many findings from these
13 early studies, but advances in understanding and improved modelling tools have
14 made the picture gradually more comprehensive and more detailed. Nevertheless,
15 many uncertainties still remain.

16

17 In the Baltic Sea region, warming is likely to exceed its global average,
18 particularly in winter and in the northern parts of the area. The warming is
19 accompanied by a general increase in winter precipitation, but in summer
20 precipitation may either increase or decrease, with a larger chance of drying in the
21 southern than in the northern parts of the region. Despite the increase in winter
22 precipitation, the amount of snow is generally expected to decrease, because a
23 smaller fraction of the precipitation falls as snow and mid-winter snow melt
24 episodes become more common. Changes in windiness are very uncertain,

25 although most projections suggest a slight increase in average wind speed over the
26 Baltic Sea. Climatic extremes are also projected to change, but some of their
27 changes will differ from the corresponding change in mean climate. For example,
28 the lowest winter temperatures are expected to warm even more than the winter
29 mean temperature, and short-term summer precipitation extremes are likely to
30 become more severe even in those areas where the mean summer precipitation
31 does not increase.

32

33 The projected atmospheric changes are accompanied by an increase in Baltic Sea
34 water temperature, reduced ice cover, and, according to most studies, reduced
35 salinity due to increased precipitation and river runoff. The seasonal cycle of
36 runoff is modified by changes in precipitation and earlier snowmelt. Global-scale
37 sea level rise also affects the Baltic Sea, but is counteracted by glacial isostatic
38 adjustment. In the northern parts of the Baltic Sea, the latter will still dominate
39 according to most projections, leading to a continued although decelerated
40 decrease in relative sea level. These changes in the physical environment and
41 climate will have a number of environmental impacts; for example, related to
42 atmospheric chemistry, freshwater and marine biogeochemistry, ecosystems, and
43 coastal erosion. However, future environmental change in the region will be
44 affected by several interrelated factors. Climate change is only one of them, and in
45 many cases its effects may be exceeded by other anthropogenic changes.

46

47 **KEYWORDS:** Climate change, Climate change projection, Baltic Sea, Baltic Sea
48 basin, Northern Europe, Climate change impacts

49

50

51 **Introduction**

52 During the last few decades, it has become increasingly clear that humans are
53 affecting the global climate. The global mean temperature has increased by nearly
54 1°C since the late 19th century, and anthropogenic emissions of carbon dioxide
55 (CO₂) and other greenhouse gases have been identified as the main culprit
56 (Bindoff et al., 2013). Much larger climate changes might occur during this
57 century and beyond, particularly if ongoing political efforts to reduce greenhouse
58 gas emissions are not succesful.

59

60 Since climate widely affects the natural environment and human activities,
61 adaptation to changing climate will be needed. To help the adaptation,
62 information on the possible characteristics of the future climate change and on the
63 sensitivity of natural and human systems to this change is required. This article
64 outlines the current knowledge on future climate change for the Baltic Sea and its
65 drainage basin in northern Europe. The potential environmental impacts of
66 climate change in the area also discussed, although in less depth than climate
67 change itself.

68

69 The Baltic Sea is a large semi-enclosed brackish water estuary adjoining the
70 northeastern Atlantic Ocean, with an area of 415000 km² with Kattegat included.
71 Its drainage basin covers 1.7 million square kilometres and hosts 85 million
72 people in 14 countries (HELCOM, 2015). Given this large population, it is
73 unsurprising that climate change is not the only environmental issue in the area. In
74 particular, the ecological state of the Baltic Sea has been severely degraded by
75 water- and airborne nutrient loads and other pollution from the surrounding land

76 areas. This far, the environmental effects of climate change have been in many
77 cases secondary to these direct anthropogenic impacts. Similarly, the question on
78 how the environment in the Baltic Sea region will change in the future is much
79 wider than how it will be affected by climate change alone. Nevertheless, climate
80 change already represents an additional stress factor for many natural systems
81 which is likely to become more important in the future.

82

83 This article first discusses the historical background of climate change research
84 for the Baltic Sea area, outlines the modelling tools and scenarios used for
85 constructing projections of future climate change, and puts the climate changes
86 projected for the Baltic Sea region in a global perspective. After this, climate
87 change in the Baltic Sea basin is discussed in more detail, covering various
88 aspects of the atmospheric climate, snow conditions, hydrology, and the ocean
89 climate in the Baltic Sea itself. Third, the potential environmental impacts of
90 climate change are explored. For the environmental impacts, in particular, this text
91 only scratches the surface of a very wide and complicated topic. Many of the
92 issues introduced in this article have been discussed in more depth in the first
93 (BACC Author Team, 2008) and the second (BACC II Author Team, 2015)
94 climate change assessments for the Baltic Sea basin.

95

96 **Historical context**

97 The possibility that changes in atmospheric CO₂ concentration could affect the
98 global climate was already raised in the 19th century (Arrhenius, 1896).
99 Measurements started in 1958 by Charles Keeling at Mauna Loa in Hawaii showed
100 that the CO₂ concentration was actually increasing, which is now convincingly

101 ascribed to human activities, mainly fossil fuel burning (Watson, Rodhe,
102 Oeschger & Siegenthaler, 1990; Ciais et al., 2013). Finally, in 1995, comparison
103 between climate model simulations and observed temperature changes allowed
104 the Intergovernmental Panel on Climate Change (IPCC) to declare that „*The*
105 *balance of evidence suggests a discernible human influence on global climate*“
106 (IPCC 1996, p. 4) – a conclusion that has been substantially strengthened by later
107 research. These facts raise two important questions. First, how will climate change
108 in the future, and second, how will this change affect humans and the natural
109 environment?

110

111 Climate will not change in the same way in all parts of the world. Although more
112 or less all areas are expected to become warmer, the magnitude of the warming
113 will vary. For other variables such as precipitation, even the sign of the change
114 will differ between regions. Estimates on the regional distribution of future
115 climate changes have been available from three-dimensional global climate models
116 (CCMs) since the 1980s (e.g., Stouffer, Manabe & Bryan, 1989).

117

118 The first GCMs were still very coarse-grained and their results thus allowed only
119 broad and tentative conclusions about the regional distribution of climate changes.
120 Nevertheless, many of these conclusions have stood the challenge of time. For
121 example, the models available for the first IPCC assessment consistently indicated
122 a greater than global average warming at high northern latitudes in winter, and
123 increases in precipitation at high latitudes throughout the year and at midlatitudes
124 in winter (Mitchell, Manabe, Meleshko & Tokioka, 1990, p. 135). Since then,
125 climate models have become much more sophisticated, with many more processes
126 included and finer horizontal resolution. The number of models developed in

127 different research institutions around the world has also greatly increased.
128 Nonetheless, the models used in the IPCC fifth assessment still nearly
129 unanimously agreed on these large-scale features of temperature and precipitation
130 change (Collins et al., 2013, p. 1059 and 1078).

131

132 Regional studies that specifically explored potential future climate change in areas
133 close to the Baltic Sea region also began to appear in the 1990s. In the first multi-
134 GCM study for northern Europe, Räisänen (1994) used four GCMs forced with a
135 gradual doubling of atmospheric CO₂. He found the average simulated winter
136 warming in Finland to be 3-4°C, whereas the warming in summer was slightly
137 over 2°C. Because these simulations were based on a highly idealized forcing
138 scenario, their results are not directly applicable to the real world. However,
139 similar idealized GCM experiments conducted in the early 2010s still largely
140 reproduced these early results, although with a tendency towards slightly larger
141 summer warming (Räisänen & Ylhäisi, 2015).

142

143 The realization that climate was changing and might change much more during
144 the next hundred years soon stimulated a surge of research on the impacts of
145 climate change. An early national example was the *Finnish Research Programme*
146 *on Climate Change* (SILMU; Kämäri, 1997) which explored the potential effects
147 of climate change on Finnish forests, peatlands, agriculture, inland waters and the
148 Baltic Sea. Guided by the GCM results available at that time, three idealized
149 scenarios of climate change were formulated for the impact assessment (Carter,
150 Posch & Tuomenvirta, 1996). These scenarios assumed a linear 0.1 to 0.6°C per
151 decade increase in the annual mean temperature and a 0.25 to 1.5 % per decade
152 increase in annual precipitation throughout the 21st century, with larger changes

153 in winter than in summer in both of these variables. Another early example of
154 impact research was the *Climate Change and Energy Production* project
155 (Sælthun, 1992; Sælthun et al. 1998), which assessed the hydrological effects of
156 climate change in the Nordic countries with a special emphasis on hydropower
157 projection, using temperature and precipitation change scenarios formulated by
158 Jóhannesson, Jónsson, Källén & Kaas (1995).

159

160 Nevertheless, the coarse resolution of GCMs (of the order of 500 km in the 1990s)
161 was perceived as a serious limitation for regional climate change studies. At such
162 a resolution, geographical features such as the Scandinavian mountains and the
163 Baltic Sea were at best marginally present in the GCMs. This motivated the
164 development of higher-resolution regional climate models (RCMs). By the end of
165 the 1990s, four countries in the Baltic Sea region – Sweden (Rummukainen et al.,
166 2000), Norway (Bjørge & Haugen, 1998), Denmark (Christensen, Christensen,
167 Machenhauer & Botzet, 1998) and Germany (Jacob and Podzun, 1997) – had
168 established their own regional climate modelling programs. Christensen et al.
169 (2001) provided the first multi-RCM intercomparison of climate change
170 simulations for the Scandinavian region. In the next decade, RCM simulations for
171 the European area were conducted in a coordinated manner within the
172 PRUDENCE (Christensen, Carter & Rummukainen, 2007) and ENSEMBLES
173 (van der Linden & Mitchell, 2009) projects. In the 2010's, an ensemble of very
174 high-resolution (12.5 km) RCM simulations for Europe has been produced under
175 the EURO-CORDEX initiative (Jacob et al., 2014).

176

177 Research on climate change and its impacts has been done in all Baltic Sea
178 countries. To collect the pieces together, an international team of authors

179 compiled in 2008 the first *Assessment of Climate Change for the Baltic Sea Basin*
180 (BACC Author Team, 2008). Seven years later, an update was published (BACC
181 II Author Team, 2015) to take advantage of the new knowledge gathered since the
182 first assessment. The two BACC assessments are comprehensive in scope,
183 covering both past and potential future climate changes in the Baltic Sea region
184 and the environmental impacts of these changes. In the second assessment, some
185 of the potential socio-economical impacts of climate change are also discussed.

186

187 **Models and scenarios**

188 It might seem tempting to predict future climate change simply by extrapolating
189 observed trends. However, such extrapolation would only make sense if past and
190 future climate changes had exactly the same causes. In reality, anthropogenic
191 climate change is the net effect of several factors – for example, changes in the
192 concentrations of CO₂ and other greenhouse gases, atmospheric aerosols and land
193 use – and the balance between them might differ between the past and the future.
194 Moreover, climate exhibits substantial natural variability – temperature,
195 precipitation and other climate variables vary from year to year and from decade
196 to decade, regardless of what humans are doing. Thus, climate changes, for
197 example, during the past half-century represent a combination of anthropogenic
198 change and natural variability, but it is often difficult to separate these
199 contributions from each other. Similarly, future climate changes will result from a
200 combination of anthropogenic change and natural variability, but it is not known
201 whether the natural variations will oppose or reinforce the anthropogenic
202 changes.

203

204 The main tool for constructing projections of future global and continental scale
205 climate change are *global climate models* (GCMs). These models are built on
206 basic physical principles such as conservation of mass, momentum and energy
207 that govern the behaviour of the atmosphere and the oceans. As input, a GCM
208 needs information on such “external” factors that it cannot predict itself. This
209 includes, for example, either the anthropogenic emissions or concentrations of
210 CO₂ and other greenhouse gases. In addition, the initial conditions of the
211 simulation (that is, the state of the atmosphere, oceans, sea ice and land surface in
212 the beginning of the model experiment) are needed. However, after the external
213 factors and the initial conditions have been specified, the model simulation is self-
214 contained. Thus, no information on observed climate changes is used when
215 simulating future climate change with GCMs.

216

217 GCMs simulate the evolution of atmospheric weather in a global three-
218 dimensional network of grid points, with a time step of tens of minutes. Their
219 output thus includes time series of temperature, winds and and other weather
220 parameters all around the world, not only near the surface but also higher up in the
221 atmosphere. Obviously, however, the detailed daily or even year-to-year evolution
222 of weather cannot be predicted decades in advance. What the models attempt to
223 predict is climate, that is, the long-term mean values and other statistical
224 properties of weather. In such long-term statistics, the effects of unpredictable
225 shorter-term variability are greatly reduced, although they still remain non-
226 negligible even in multi-decadal averages (Eriksson, Omstedt, Overland, Percival
227 & Mofjeld, 2007; Deser, Phillips, Bourdette & Teng, 2012).

228

229 A major limitation in GCMs is their relatively coarse resolution that is necessary
230 to keep the need of computing resources manageable. The CMIP5 generation of
231 models used in the 2010s (Taylor et al. 2012) typically had horizontal grid
232 spacings of 100-250 km, whereas the earlier models were even coarser. This is a
233 limitation in simulating regional climate and climate change, particularly as the
234 skilful scale of GCMs is several times larger than their nominal grid scale (Grotch
235 & MacCracken, 1991).

236

237 *Regional climate models* (RCMs) have higher spatial resolution than GCMs
238 (typically 10-50 km) but cover a limited geographic area, a few thousands of
239 kilometres across. They therefore need boundary conditions that specify the time-
240 evolving atmospheric state at their horizontal boundaries. In climate change
241 projection, the boundary conditions are derived from GCM simulations. Thus,
242 climate changes in a RCM simulation depend on the driving GCM as well as the
243 RCM itself (Déqué et al, 2012). Nevertheless, the higher resolution of RCMs
244 compared with GCMs allows a better description of geographic features such as
245 mountain ranges and the land-sea distribution that affect the regional climate. Due
246 to their higher resolution, the RCMs also better resolve the details of atmospheric
247 weather systems, which enhances the simulation of extremes such as storms and
248 heavy precipitation.

249 Another technique for constructing scenarios of future climate on small scales is
250 *statistical downscaling*. In this case, observed statistical relationships between the
251 large-scale atmospheric state and the local conditions are combined with either
252 GCM or RCM simulations of larger-scale climate, to infer what these large-scale
253 conditions would imply on the local scale. With statistical downscaling, scenarios
254 can be constructed for truly local conditions, below the scale resolved by RCMs.

255 On the other hand, statistical downscaling relies strongly on the assumption that
256 the relationship between the large-scale and local conditions remains unchanged
257 despite climate change (Wibig et al., 2015; Benestad, 2016).

258

259 A complication in both GCM- and RCM-based studies of future climate are model
260 biases, that is, differences between the simulated and observed present-day
261 climate. Even in state-of-the-art RCM simulations, the biases in temperature may
262 reach several °C, and precipitation biases of several tens of per cent are common
263 (Wibig et al., 2015). In the ideal case that these biases remain similar in the
264 simulation of future climate, they have no large effect on the simulated
265 temperature and precipitation changes. Nevertheless, such biases generally
266 preclude the direct use of RCM output in, for example, hydrological models,
267 without some form of statistical adjustments (Graham, Andréasson & Carlsson,
268 2007; Rätty, Virta, Bosshard, & Connelly 2017). Because there is no unique
269 “correct” method for doing these adjustments, this intermediate step introduces
270 additional uncertainties to the projection of (e.g.) river runoff and consequently
271 Baltic Sea salinity.

272

273 In general, the word *projection* is preferred over *prediction* when referring to
274 model simulations of future climate change. This is because these projections are
275 conditional on the evolution of greenhouse gas emissions and other anthropogenic
276 forcing. This evolution becomes naturally increasingly uncertain with increasing
277 time horizon. To cope with this uncertainty, emission or forcing scenarios are
278 constructed using different but internally consistent assumptions. During the 21st
279 century, two sets of scenarios have been widely used for climate projection: the
280 SRES (Special Report on Emissions Scenarios; Nakićenović and Swart, 2000) and

281 the RCP (Representative Concentration Pathways; van Vuuren et al., 2011)
282 scenarios. These scenarios cover a wide range of CO₂ emissions and
283 concentrations (Fig. 1), but nearly all of them indicate a monotonic increase in
284 CO₂ concentration at least until the end of this century. The only exception is
285 RCP2.6, in which a deep decline of CO₂ emissions leads to a slow decrease of the
286 CO₂ concentration in the second half of the century. In addition to CO₂, other
287 greenhouse gases, anthropogenic aerosols and land use change are also included
288 in the SRES and RCP scenarios.

289 **Global perspective on future climate change**

290 The warming of the global climate is projected to continue in this century, but the
291 magnitude of the change is uncertain (Fig. 2). The choice between different RCP
292 (or SRES) scenarios has only a moderate effect in the next few decades, but
293 becomes the dominating source of uncertainty by the end of the century (see also
294 Hawkins & Sutton, 2009). However, the projections from different GCMs also
295 differ from each other. For the ensemble of models in Fig. 2, the changes in global
296 mean temperature from the years 1986-2005 to 2081-2100 vary from 0 to 2°C
297 under the lowest (2.6) and from 2.5 to 5°C under the highest (8.5) RCP scenario.

298

299 Two factors contribute to the inter-GCM differences in climate change under the
300 same forcing scenario (Collins et al., 2013). First, there are genuine differences in
301 the response of the models to external forcing such as increases in greenhouse gas
302 concentrations, as well as subtle differences in the implementation of the
303 scenarios. Second, there is unforced natural variability in the simulated climate.
304 This stochastic variability is a very minor source of uncertainty in multi-decadal
305 to centennial projections of the global mean temperature. However, it is more

306 important for climate change on regional and local scales, particularly for
307 variables such as precipitation or wind speed (Hawkins & Sutton, 2011; Pryor &
308 Barthelmie, 2010). Such unforced variability also occurs in the real world and sets
309 an upper limit for the predictability of future climate. In some cases, this
310 variability may be strong enough to dominate over the effects of anthropogenic
311 climate change throughout the 21st century (Maraun, 2013).

312

313 The projected warming is generally larger over land than sea and over high than
314 low latitudes (Collins et al., 2013). It is thus unsurprising that most GCMs project
315 the annual mean warming in the Baltic Sea region to exceed the global average
316 (Fig. 3). The warming in the Baltic Sea region tends to increase with increasing
317 global mean warming, but the correlation is not one-to-one. In some models, the
318 regional warming is twice the global mean. However, there are also a few model
319 simulations in which the Baltic Sea region warms less than the world on the
320 average, or even becomes colder. When present in GCM simulations, cooling in
321 the Baltic Sea region adjoins larger cooling over the northern North Atlantic (e.g.,
322 model FIO-ESM in Fig. 12.9 of Collins et al., 2013). It is not clear whether such a
323 dramatic outcome is a real although unlikely possibility or results from a
324 deficiency in some specific GCMs. Although many GCMs simulate some local
325 cooling over parts of the northern North Atlantic, due to reduced northward heat
326 transport by the ocean circulation, this cooling only rarely extends over the
327 surrounding land areas (Collins et al., 2013, Fig. 12.9).

328

329 **Projected climate change in the Baltic Sea region**

330 ***Temperature***

331 Most GCMs project a very large warming over the Arctic Ocean in late fall and
332 winter, due to increased ocean-to-atmosphere heat flux through reduced ice cover
333 and other amplifying feedbacks (Collins et al., 2013). This strong warming
334 extends in a muted form to the Baltic Sea region, particularly its northern parts
335 (Fig. 4a). The warming in summer is weaker but nonetheless exceeds the global
336 average in most GCMs (Fig. 4c; Räisänen & Ylhäisi, 2015). Projections from
337 RCMs agree with this large-scale pattern (Christensen, Kjellström & Zorita,
338 2015). However, the intermodel variation of both the GCM and the RCM
339 projections is substantial even for the same emissions scenario (Fig. 4e; Fig. 11.3
340 in Christensen et al., 2015), although some warming occurs in nearly all of the
341 projections.

342
343 The warming in winter will likely be accompanied by a decrease in temperature
344 variability, both on daily and interannual time scales (Räisänen, 2002; Räisänen et
345 al., 2004; Kjellström et al., 2007; Nikulin et al., 2011; Ylhäisi & Räisänen, 2014).
346 This decrease is partly connected to the geographical distribution of the projected
347 temperature changes (Holmes, Woollings, Hawkins & de Vries, 2016). Larger
348 warming over the Arctic Ocean and northern Eurasia than over the northern North
349 Atlantic reduces the time mean temperature gradient, making temperatures less
350 sensitive to variations of the atmospheric circulation. As a result, the lowest
351 winter temperatures are projected to increase even more than the winter mean
352 temperature. In summer, the variability might either slightly increase or remain at
353 its current level. Both GCM and RCM simulations support increased temperature

354 variability in summer in central Europe (Räisänen et al., 2004; Kjellström et al.,
355 2007; Nikulin et al., 2011; Ylhäisi & Räisänen, 2014; Holmes et al., 2016), but the
356 signal is far less clear further north in the Baltic Sea region. Even if the variability
357 remains at its current level, periods of hot weather are expected to become more
358 severe and more common following the increase in the summer mean temperature
359 (Nikulin et al., 2011).

360 ***Precipitation***

361 On the large scale, precipitation is projected to increase in high northern latitudes.
362 This is both due to increased northward moisture transport in the atmosphere
363 (which is mainly caused by the larger moisture content of warmer air but is also
364 affected by changes in atmospheric circulation) and increased moisture supply
365 from local evaporation (Held & Soden, 2006; Collins et al., 2013). Conversely,
366 precipitation is projected to decrease in many subtropical and lower-midlatitude
367 areas, including the Mediterranean region. However, the transition between
368 increasing and decreasing precipitation occurs further north in summer than in
369 winter. For the Baltic Sea basin, this suggests a general increase in precipitation in
370 winter (Fig. 4b). In summer, precipitation may either increase or decrease, with a
371 larger chance of drying in the southern than in the northern parts of the region
372 (Fig. 4d).

373

374 Projections of precipitation change are less robust than those of temperature
375 change, varying widely between different GCMs and RCMs (Fig. 4f; Fig. 11.5 in
376 Christensen et al., 2015). This reflects, in part, the large natural variability of
377 precipitation – in comparison with this variability, the projected anthropogenic
378 precipitation changes are smaller than the changes in temperature (Räisänen &

379 Ruokolainen, 2006; Hawkins and Sutton, 2011). Moreover, changes in
380 atmospheric circulation may induce substantial variations in precipitation change
381 on local scales, but this variability is smoothed out when averaging the projections
382 of different models (Knutti, Furrer, Tebaldi, Cermak & Meehl, 2010). Thus, much
383 larger local increases or decreases in precipitation might occur than is suggested by
384 Fig. 4 (see Fig. 11.5 in Christensen et al., 2015).

385

386 Following the increase in saturation humidity with temperature, warming is
387 generally accompanied by an increase in atmospheric water vapor (Held and
388 Soden, 2006). Therefore, heavy short-term precipitation is likely to increase even
389 in many regions where the mean precipitation decreases. For the Baltic Sea
390 region, most RCMs suggests an increase in extreme daily precipitation both in
391 winter and in summer (Nikulin et al., 2011; Christensen et al., 2015, Fig. 11.6).
392 This also holds for the southern parts of the basin, where the same models
393 generally project a decrease in mean summer precipitation. On the other hand,
394 model simulations suggest a decrease in the number of precipitation days in the
395 southern and central parts of the Baltic Sea basin in summer (Lehtonen,
396 Ruosteenoja & Jylhä, 2014). This might increase the risk of long dry periods,
397 particularly in the southern parts of the region (Orlowsky and Seneviratne, 2012).

398 **Wind**

399 Future changes in wind speeds are more uncertain than the changes in temperature
400 and precipitation. This holds for both the long-term mean and extremes of wind
401 speed. The 13 RCMs used in the BACC II assessment show no clear preference
402 for either increasing or decreasing wind speeds over land areas of the Baltic Sea
403 basin during this century, although local increases and decreases of ± 5 -10% (or

404 even more for extremes of wind speed) occur in some of the individual models
405 (Christensen et al., 2015, Figs. 11.8-11.9). Ruosteenoja, Jylhä and Kämäräinen
406 (2016) analysed the changes in mean wind speed in Finland in a large number of
407 GCMs, obtaining largely similar results.

408

409 Changes in wind speed are highly dependent on changes in the large-scale
410 atmospheric circulation. The upper row in Fig. 5 shows an example of an RCM
411 simulation with a very strong circulation change. A pronounced decrease in sea
412 level pressure over the Arctic Ocean combined with an increase over central
413 Europe indicates both an increase in the climatological north-south pressure
414 gradient and a northward shift of cyclone activity. Both of these factors enhance
415 wind speeds in northern Europe. By contrast, the simulation in the bottom row
416 suggests only very small changes in the pressure distribution and wind speeds.
417 Future changes in the atmospheric circulation depend on a multitude of partly
418 compensating factors and are therefore difficult to predict (Shepherd, 2014).

419

420 In contrast with land areas, most RCM simulations suggest a slight increase in
421 mean wind speed over the Baltic Sea (Christensen et al., 2015, Fig. 11.8; see also
422 Fig. 5). This is associated with reduced winter sea ice, which favors stronger near-
423 surface wind speeds by weakening the stability of the atmospheric boundary layer.
424 In many RCMs, a local maximum in wind speed change also occurs over the
425 Baltic Sea in summer, due to a strong projected warming of the Baltic Sea surface.
426 However, such stability effects are most important when the winds are relatively
427 weak. The projected changes in the strongest winds do not differ much between
428 the Baltic Sea and the surrounding land areas (Christensen et al., 2015, Fig. 11.9).

429

430 **Snow**

431 Climate models project an increase in winter precipitation in the Baltic Sea basin,
432 but in a warmer climate a smaller fraction of precipitation falls as snow and
433 midwinter snowmelt episodes become more common. In general, a decrease in
434 snow cover duration and snow depth is to be expected, but the decrease will be
435 less dramatic in the colder (northern and eastern) than in the milder (southern and
436 western) parts of the region (Räisänen and Eklund, 2012; Christensen et al., 2015,
437 Fig. 11.10). This is because typical mid-winter temperatures in the coldest parts of
438 the region will remain well below zero even after a moderately large warming,
439 whereas warming in milder areas will lead to a much larger increase in the
440 frequency of above-zero winter temperatures.

441

442 Figure 6 illustrates this dynamics for three locations (Kiruna in Swedish Lapland,
443 Joensuu in eastern Finland, and Riga in Latvia) based on RCM simulations from
444 the ENSEMBLES project. The simulated temperatures increase at all three
445 locations and so does (in most or all models) total winter precipitation. However,
446 in Riga and Joensuu snowfall decreases throughout the winter, although less in
447 Joensuu than Riga. In Kiruna, midwinter snowfall actually increases, although the
448 snowfall in autumn and spring months is reduced. The amount of snow, as
449 indicated by the water equivalent of the snow pack, is reduced in both Riga and
450 Joensuu much more drastically than could be expected from the relatively
451 undramatic decreases in midwinter snowfall. This is partly due to a later start of
452 the snowfall season, partly because of stronger midwinter snowmelt (Räisänen
453 and Eklund, 2012). In Kiruna, the increase in midwinter snowfall nearly
454 compensates these two factors, leading to only a modest decrease in snow amount

455 at the height of the snow season in March. Even in Kiruna, however, snow comes
456 later in the fall and melts earlier in the spring.

457

458 Even in the future, snow conditions will vary substantially from year to year.
459 Individual snow-rich winters are still likely to occur, although they become
460 gradually less common (Räisänen and Eklund, 2012).

461

462 The heaviest individual snowfall events typically occur when the temperature is
463 close or just below zero (O' Gorman, 2014). At such temperatures, the air can
464 hold more moisture than in colder conditions but is still cold enough for the
465 precipitation to fall as snow. As such temperatures are expected to remain
466 common even in the future, only small changes in daily extremes of snowfall are
467 projected for the northern and eastern parts of the Baltic Sea basin (Räisänen,
468 2015). Further southwest, where snowfall as a whole becomes substantially less
469 frequent, a slight decrease in snowfall extremes is likely, but the extremes are
470 reduced much less in percentage terms than the total winter snowfall.

471 ***Hydrology***

472 Future changes in river flow are affected by changes in three main meteorological
473 factors: precipitation, evaporation, and snow conditions. The total annual runoff
474 that eventually enters the Baltic Sea is set by the difference between precipitation
475 and evapotranspiration, but the snow pack acts a major seasonal storage of water
476 that strongly regulates the seasonality of runoff generation. Snow naturally plays a
477 larger role in the colder northern than in the milder southern parts of the region
478 (Graham et al., 2008; Sonnenborg, 2015).

479

480 In general, evapotranspiration is projected to increase in a warmer climate if
481 sufficient water is available, although there is substantial uncertainty in the
482 magnitude of the change (Graham et al., 2008; Collins et al., 2013, Fig. 12.25).
483 However, in the northern parts of the Baltic Sea Basin, increases in precipitation
484 are expected to overcome the increase in evapotranspiration, resulting in larger
485 total annual river discharge. Further south, the projected precipitation increase is
486 smaller and more uncertain, and most model simulations suggest reduced annual
487 mean river flow (Graham et al., 2008; Collins et al., 2013, Fig. 12.24). Although it
488 appears more likely that the increases in north will outweigh the decreases in
489 south than vice versa, the change in the total annual river flow to the Baltic Sea is
490 quite uncertain (Graham et al. 2008, Fig. 3.34).

491

492 The seasonal cycle of river runoff is projected to change (Graham et al., 2008;
493 Sonnenborg, 2015). In areas that are currently characterized by snowmelt floods
494 in the spring, these floods are likely to occur earlier and decrease in magnitude
495 because less snow accumulates during the shorter winter. Conversely, increases in
496 precipitation together with reduced storage in snow act to increase the mean
497 runoff and risk of flooding in winter. The runoff in late spring and summer is
498 likely to decrease in most of the basin, due to the earlier snowmelt, increased
499 evapotranspiration and possibly, particularly in the southern parts, reduced
500 summer precipitation. However, in lake-rich river basins there is a considerable
501 time lag between the runoff in the upper parts of the basin and the river flow that
502 eventually reaches the Baltic Sea (Vehviläinen and Huttunen, 1997). Changes in
503 the seasonality of runoff generation will have their strongest and most immediate
504 effects in the upper sub-basins, proceeding downward the lake chain in the course
505 of weeks and months. In regulated watersheds, the seasonality is further

506 modulated by changes in regulation practices that may be undertaken, in part, as
507 adaption to climate change (Veijalainen, Dubrovin, Marttunen & Vehviläinen,
508 2010).

509

510 **Changes in Baltic Sea ocean climate**

511 The Baltic Sea has several characteristics that make the impacts of climate change
512 potentially different, and in some respects more difficult to anticipate, than is the
513 case with the wider world ocean. First, it is a semi-enclosed basin receiving
514 abundant river runoff from the surrounding land areas. Because of this, the water
515 is far less saline than in the world ocean and the salinity is sensitive to changes in
516 both the river runoff and saltwater intrusions through the Danish Straits. Second,
517 the exchange of energy, water and momentum between the atmosphere and the
518 Baltic Sea is modulated by seasonal ice cover, whose extent is highly sensitive to
519 winter climate. Third, ongoing land uplift counteracts the large-scale sea level rise
520 particularly in the northern parts of the Baltic Sea. Finally, the ecological impacts
521 of climate change in the Baltic Sea occur against a background of severe
522 eutrophication caused by nutrient input from the surrounding land areas.

523

524 In the following, five aspects of Baltic Sea ocean climate change are discussed:
525 changes in ice cover, water temperature, salinity, sea level and storm surges. Ice
526 cover and water temperature affect the climate in the land areas surrounding the
527 Baltic Sea, particularly in the relatively densely populated coastal regions. Water
528 temperature and salinity together determine the density stratification of the Baltic
529 Sea water mass, and thereby modulate the circulation of water and nutrients.
530 Salinity is also biologically important for a wide range of organisms dwelling in

531 the Baltic Sea. Changes in mean sea level and the height of storm surges affect
532 coastal erosion and need to be considered when assessing the needs and options
533 for coastal management.

534

535 The Baltic Sea is affected by the atmospheric climate change that occurs over the
536 Baltic Sea itself. It is also affected by changes in river discharge from the
537 surrounding land areas and by the sea level rise in the world ocean. A range of
538 time scales are involved in the response of the Baltic Sea to climate change, with
539 water temperature and ice cover reacting much faster to atmospheric temperature
540 change than salinity responds to changes in freshwater input (Omstedt & Hansson,
541 2006). A key tool for assessing the changes within the Baltic Sea are three-
542 dimensional regional ocean model simulations, which have been available since
543 the turn of the 21st century (Graham et al., 2008, Section 3.8; Meier, 2015).
544 Projections for the changes in ice cover and sea level have also been derived by
545 many other methods.

546

547 ***Ice cover***

548 Ice conditions in the Baltic sea are primarily determined by the mean winter
549 temperature (Tinz, 1996; Meier, Döscher & Halkka, 2004; Omstedt & Hansson,
550 2006; Jylhä, Fronzek, Tuomenvirta, Carter & Ruosteenoja, 2008; Luomaranta et
551 al. 2014). In a warmer climate, the ice cover will therefore become thinner, less
552 extensive, and less long-lived.

553

554 The most commonly used measure of the Baltic Sea ice winter severity is the
555 annual maximum ice extent (MIB). Several studies have derived empirical

relationships between MIB and winter temperature using observations (Tinz, 1996; Omstedt & Hansson, 2006; Jylhä et al. 2008; Luomaranta et al. 2014). For example, Luomaranta et al. (2014) found the exponential relation

$$MIB = Ae^{-BT} \quad (1)$$

where T is the mean temperature of the November-March season averaged over the Baltic Sea coast, $A = (90.2 \pm 4.2) \times 10^3 \text{ km}^2$ and $B = (0.253 \pm 0.015) (\text{°C})^{-1}$. This implies a 22% decrease in ice extent for each 1°C of winter warming. On the other hand, totally ice-free winters are hard to reach, since some ice tends to form in the north of Gulf of Bothnia and in the eastern extreme of Gulf of Finland even during relatively short cold periods. Regional ocean model simulations for the Baltic Sea suggest that such ice-free winters would remain very rare even under the strong greenhouse gas forcing that characterises the SRES A2 scenario in the late 21st century (Meier, 2006). Nevertheless, the projected warming indicates a large increase in the frequency of mild ice winters already in the first half of this century, together with a virtual elimination of ice winters that would have been classified as severe in the 20th century (Luomaranta et al., 2014).

Water temperature

Following the warming of the atmosphere, the water in the Baltic Sea will become warmer. However, the magnitude of this change is modulated by changes in ice conditions and vertical mixing. Vertical mixing itself is affected by changes in temperature and salinity, which together determine the density of sea water. However, in contrast with more saline ocean water, the brackish water in the Baltic Sea reaches its maximum density when the temperature is a few degrees above the freezing point. These interlinked and nonlinear processes allow the

580 warming of the surface water to differ from the warming of the air above, both in
581 its annual mean and its seasonal cycle. The vertical gradient of water temperature
582 is also projected to change, with larger warming near the surface than at greater
583 depth (Meier, 2015).

584

585 As a specific example, regional Baltic Sea model simulations suggest a
586 pronounced maximum of sea surface warming in the Bothnian Bay and Bothnian
587 Sea during summer (Meier et al., 2012). This results from the nonlinear
588 relationship between temperature and water density (Hordoir & Meier, 2011).
589 After the ice melt in spring, seasonal warming first increases the density of the
590 surface water. This triggers thermal convection, which mixes the heat down in the
591 water column. Therefore, the surface water only warms up slowly. However, once
592 the temperature in the surface layer exceeds the point of maximum density,
593 further warming suppresses vertical mixing. After this, the warming at the surface
594 accelerates, because the heat input from the atmosphere is distributed in a much
595 thinner water layer. In a warmer climate, the point of maximum density is reached
596 earlier in spring. Consequently, a larger fraction of the spring- and summertime
597 heat input stays near the surface. The net result is a larger summertime
598 temperature increase in the surface water than either in the air above or in the
599 water at greater depth.

600 ***Salinity***

601 Most climate change projections suggest an increase in total river runoff to the
602 Baltic Sea. The local freshwater input given by the difference of precipitation and
603 evaporation over the Baltic Sea might also increase to some extent (Rutgesson,
604 Omstedt & Räisänen, 2002). This increased freshwater supply would reduce the

605 salinity of the Baltic Sea water. The decrease might be substantial, although its
606 magnitude is rather uncertain. For example, in the ensemble of ocean model
607 simulations of Meier et al. (2012) the volume-averaged Baltic Sea mean salinity
608 decreases from 8 to nearly 6 g kg⁻¹ during the 21st century. The pattern of the
609 projected change roughly mirrors the current salinity distribution. Thus, the
610 largest decrease occurs in the Danish straits region, where the present-day salinity
611 is largest, and the smallest decrease in the eastern and northern parts of the Baltic
612 Sea, particularly the Bothnian Bay, where the water is less saline.

613 ***Sea level change***

614 The sea level in the world ocean is projected to rise due to loss of land-based ice
615 masses and thermal expansion of ocean water (Church et al., 2013). On the other
616 hand, the loss of the Fennoscandian ice sheet in the end of the latest glaciation is
617 still causing ongoing land uplift due to glacial isostatic adjustment (GIA). The
618 land uplift rate varies from near zero at the Schleswig-Holstein coast in the
619 southwest to 10 mm yr⁻¹ in the Bothnian Bay (Hill, Davis, Tamisiea & Lidberg,
620 2010; Johansson, Pellikka, Kahma & Ruosteenoja, 2014). Therefore, the relative
621 sea level rise will be largest along the southwestern and southern coasts of the
622 Baltic Sea. Around the Gulf of Bothnia, the relative sea level is still projected to
623 decrease during this century, except for the most extreme scenarios. However, the
624 decrease will be slower than this far.

625

626 The rate of future global sea level rise is not well known. In the IPCC 5th
627 Assessment Report, the projections for the change from the 20-year period 1986-
628 2005 to the year 2100 range from 28-61 cm for the RCP2.6 scenario to 52-98 cm
629 for RCP8.5 (Church et al., 2013). However, some semiempirical models, built on

630 the connection between observed sea level and temperature changes, have given
631 higher estimates of global sea level rise, in extreme cases up to 200 cm by the
632 year 2100 (Table 4 of Johansson et al., 2014). The largest uncertainty concerns the
633 marine-based sectors of the Antarctic ice sheet, whose response to climate change
634 is very difficult to model and might turn out to be larger than was expected in the
635 IPCC 5th Assessment. A study by DeConto & Pollard (2016) suggests that, under
636 the high-end RCP8.5 scenario, the loss of Antarctic ice alone could raise the
637 global sea level by up to one meter by the year 2100, and up to 15 meters by the
638 year 2500.

639

640 Sea level rise will not be uniformly distributed around the world, even when local
641 land uplift or subsidence is disregarded (Church et al., 2013). The change in the
642 Baltic sea region is likely to be smaller than the global average (Johansson et al.,
643 2014; Grinsted, 2015). In particular, ice melt from the Greenland ice sheet and
644 smaller northern hemisphere high-latitude glaciers would only weakly affect the
645 sea level in the Baltic Sea. Due to changes in the Earth's gravity field and other
646 geophysical effects, the sea level rise associated with the loss of land ice is small
647 (or even locally negative) in nearby regions, but slightly larger than the global
648 average in the opposite hemisphere (Bamber & Riva, 2010; Slangen, Katsman,
649 van de Wal, Vermeersen & Riva, 2012).

650

651 As the best estimate, the absolute sea level rise in the Baltic Sea (before
652 accounting for land movement) would be about 80% of the global mean. Grinsted
653 (2015) combines a scenario with a mid-range 70 cm global sea level change
654 during this century with the simultaneous land uplift, arriving at a relative sea-
655 level rise of 60 cm near Hamburg, but a sea level fall of 35 cm in the Bothnian

656 Bay. Excluded from this estimate are local effects from changes in winds and sea
657 ice. These local effects might act to increase the sea level in the northern parts of
658 the Baltic Sea, by up to 20 cm in the northernmost Bothnian Bay in spring (Meier,
659 2015, Fig. 13.7). However, the large uncertainty in the future rate of global sea
660 level rise also makes the estimates of local sea level change quite uncertain.

661 ***Storm surges***

662 The impacts of sea level change depend on both the mean change and changes in
663 variability. Of particular importance are the high extremes caused by wind storms,
664 known as storm surges. Future changes in both mean and extreme wind speeds are
665 still rather uncertain, and the same applies to storm surges. Some model
666 simulations suggest an increase in extreme storm surges whereas others do not
667 (Meier, 2006). However, a recent study, in which a high-resolution hydrodynamic
668 model was driven by output from eight GCMs, supports an increase in storm
669 surges as a consensus projection for the whole Baltic Sea in all seasons
670 (Vousdoukas, Voukouvalas, Annunziato, Giardino & Feyen, 2016). On the other
671 hand, the magnitude of the projected increase (of the order of 5%, or 10 cm for
672 long-term extremes) is relatively modest. Therefore, the absolute change in sea
673 level extremes in the future will probably be mainly determined by the change in
674 the mean sea level, particularly in the southern Baltic Sea where the largest
675 increase in mean sea level is projected (Gräwe & Burchard, 2012).

676

677 The distribution of storm surge heights has a heavy tail. This means that, even in
678 the absence of climate change, surges might in rare cases reach much higher than
679 even 100-year long observational records would suggest. For example, in
680 Travemünde at the German Baltic Sea coast, a surge in 1872 exceeded the normal

681 water level by 3.2 m (Jensen & Müller-Navarra, 2008). This is about 1.0 m higher
682 than any other surge in the time series that goes back to the 1820s.

683

684 **Environmental impacts of climate change**

685 Changes in climate affect the environment in several ways. Some of the effects
686 are direct (for example, the effects of temperature and precipitation on vegetation
687 survival and productivity), others indirect (for example, changes in marine
688 ecosystems that follow when changes in nutrient input due to changed river runoff
689 alter the relative competitiveness of different species). In addition to climate
690 change, however, the environment in the Baltic Sea region is subject to nutrient
691 pollution and many other anthropogenic pressures. Moreover, some changes
692 would occur even in the absence of the human impact and climate change, for
693 example due to the continuing land uplift. Due to this complexity, it has been in
694 most cases difficult to pinpoint the climate change contribution to the
695 environmental changes observed this far (BACC II Author Team, 2015).
696 Similarly, the environmental changes that will occur in the future will result from
697 several interrelated factors of which climate change is but one.

698

699 This article gives a very brief overview of the potential environmental impacts of
700 climate change in the Baltic Sea region. The topics considered are atmospheric
701 chemistry, terrestrial and freshwater ecosystems, terrestrial carbon storage, Baltic
702 Sea biogeochemistry, ecosystems in the Baltic Sea, and finally, coastal erosion and
703 coastline changes. All of these are discussed in more depth in the first (BACC
704 Author Team, 2008) and the second (BACC II Author Team, 2015) BACC
705 assessments.

706 ***Atmospheric chemistry***

707 Major air pollutants in the Baltic Sea region include acidifying components such
708 as sulphur and nitrogen oxides and ammonia (NH₃), together with ozone
709 (Simpson et al., 2015). Large changes in the severity of air pollution and thus its
710 impacts have taken place during the past century. The emissions increased
711 dramatically during the 20th century and particularly after the Second World War.
712 Beginning from the 1980s, however, control measures have reduced the emissions
713 of, in particular, sulphur compounds.

714

715 Future changes in the level of air pollution are also expected to be primarily
716 determined by policy- and technology-driven changes in emissions. Potential
717 climate change effects are secondary, but some of them have been identified. For
718 example, climate change may slightly increase nitrogen deposition within the
719 Baltic Sea drainage basin (Langner, Andersson & Engardt, 2009). Furthermore,
720 higher temperatures may increase ammonia emissions from land sources owing to
721 increased evaporation (Skjøth & Geels 2013; Sutton et al., 2013). Finally, reduced
722 ice cover might lead to increased shipping and thus increased shipping emissions
723 of many pollutants over the Arctic Ocean, which would primarily affect the
724 northern parts of the Baltic Sea basin (Tuovinen, Hakola, Karlsson & Simpson,
725 2013).

726 ***Terrestrial and freshwater ecosystems***

727 Ecosystems both on land, in inland lakes and rivers, and in the Baltic Sea are
728 sensitive to climate (Smith et al., 2008; Dippner et al., 2008; Niemelä et al., 2015;
729 Viitasalo et al., 2015). However, they are also affected by anthropogenic pressures
730 such as loss of natural habitat, increases in carbon dioxide and ozone

731 concentrations, toxic chemicals, and increased nutrient input via the atmosphere
732 and from agriculture and wastewater. Furthermore, the direct physical effects of
733 climate change are compounded by food web interactions and competition
734 between species. Therefore, the effects of climate change on ecosystems are in
735 many cases difficult to predict and to separate from other factors.

736

737 Although not the only facet of climate change, the greenhouse gas induced
738 warming of climate is the “largest” of the expected changes – that is, more clearly
739 discernible from natural variability than, for example, changes in precipitation
740 (Hawkins & Sutton, 2011). It is therefore useful to highlight the effects of
741 temperature change with a few examples. Higher temperatures are projected to
742 lengthen the growing season for terrestrial plants, and promote northward and
743 upward shifts in the boundaries of species occurrence (Smith et al., 2008). The
744 latter will mean the advance of species in colder areas where they have not thrived
745 before, sometimes at the cost of the original species in that area, but in some cases
746 also retraction near the warm limit of the range. Examples of the potential
747 consequences are displacement of tundra plants by grasses and trees, and
748 increased share of broadleaved trees in boreal forests. Changes such as increases
749 in treeline altitude and increased plant species diversity at mountain tops are
750 already observable in nature (e.g., Kullman, 2004, 2010).

751

752 Continuing with forests, increased temperatures are expected to increase the
753 growth of coniferous trees in the northern parts of the Baltic Sea basin, but may
754 reduce it in the south where the growth tends to be limited by water availability
755 (Lindner et al., 2010). However, the earlier dehardening associated with milder
756 winters might make the trees more vulnerable to temperature backlashes in the

757 spring in some areas (Jönsson, Linderson, Stjernquist, Schlyter & Barring, 2004).
758 Another risk associated with the warming is a northward expansion of pests and
759 pathogens (Lindner et al., 2010). Finally, the increase in temperatures may make
760 trees more prone to windthrow by delaying the freezing of the soil in the autumn
761 (Peltola, Kellomäki & Väisänen, 1999). On the other hand, the increase in carbon
762 dioxide concentration is thought to enhance the positive and reduce the negative
763 effects of climate change on forests and plants in general (Lindner et al., 2010).
764
765 The projected atmospheric warming acts to increase the water temperature in
766 inland lakes and shorten the ice season. Due to the earlier ice break-up, the
767 seasonal warming in spring will start earlier and the stratified summer period
768 (when the warm surface water is less dense than the colder water below) will
769 become longer. The earlier ice melt will also increase the amount of sunlight
770 available for phytoplankton in early spring. The hydrological regime in lakes will
771 also change (section “Hydrology”), with potentially major changes in the
772 seasonality of water and nutrient input into lakes.
773
774 The warming of water will favor warm-water species at the expense of cold-water
775 species. Together with the increased stratification, it could also enhance
776 eutrophication. On the other hand, a shortening of the ice season reduces the risk
777 of anoxia during winter and spring. On the whole, the effects of climate change on
778 lake ecosystems are complex and will depend on the individual characteristics of
779 lakes (Smith et al, 2008).
780

781 ***Terrestrial carbon storage***

782 Most studies point towards increased terrestrial carbon storage in the Baltic Sea
783 basin in the future. However, the actual outcome is uncertain due to a number of
784 compensating processes (Smith et al., 2008; Niemelä et al., 2015). Warming and
785 increased CO₂ concentration both favour higher primary production, particularly
786 in the northern parts of the area where water availability is mostly not a limiting
787 factor. However, higher temperatures also increase respiration and accelerate the
788 decomposition of organic matter in the soil. Another question mark is the
789 interaction between the carbon and the nitrogen cycles (Churkina et al., 2010; de
790 Vries & Posch, 2011). Anthropogenic nitrogen deposition has probably played a
791 major role in enhancing ecosystem carbon sequestration in Europe. Anticipated
792 decreases in nitrogen deposition due to more stringent emission control may thus
793 act to reduce the carbon sequestration in the future. Besides these factors, changes
794 in land use and forest management may also have a large impact on the ecosystem
795 carbon storage (Zachle et al., 2007).

796

797 ***Baltic Sea biogeochemistry***

798 The main limiting nutrients for the primary production in the Baltic Sea are
799 nitrogen and phosphorus (Smith et al., 2008). A fraction of their input to the
800 Baltic Sea occurs as deposition from the atmosphere, but over three quarters of the
801 nitrogen input and more than 90% of the phosphorus input is waterborne, entering
802 the Baltic Sea via rivers or directly from point sources at the coastline (HELCOM,
803 2015). This input of nutrients is largely dependent on human activities,
804 particularly agriculture but also forestry and releases from municipal wastewater
805 plants. After increasing dramatically for most of the 20th century, the nutrient

806 input has started to decrease. Nevertheless, socioeconomic factors such as
807 increasing meat consumption might make it harder to achieve further decreases in
808 the future (Hägg, Humborg, Morth, Medina & Wulff, 2010).

809

810 Nutrient input to the Baltic Sea is also modulated by variations in meteorological
811 and hydrological conditions (HELCOM, 2011; Humborg et al., 2015). Both
812 temperature and precipitation affect the fraction of released nutrients that reaches
813 the Baltic Sea. Increases in precipitation, as projected at least for the northern
814 parts of the Baltic Sea basin, tend to increase the nutrient transport by increasing
815 river runoff. On the other hand, retention processes that remove nutrients from
816 water before it reaches the Baltic Sea may become more efficient with increasing
817 temperature (Veraart, de Klein, & Scheffer, 2011; Hong et al., 2012). The
818 seasonality of the nutrient input is also likely to change, because the projected
819 changes in precipitation and snow conditions imply increased river runoff in
820 winter but reduced runoff during late spring and summer (Section “Hydrology”).

821

822 The increase in nitrogen and phosphorus input has increased the biological
823 production in the Baltic Sea by a factor of 2-4 (Schneider, Eilola, Lukkari, Muller-
824 Karulis & Neumann, 2015). This eutrophication has dire ecological consequences
825 (HELCOM, 2009; Schneider et al., 2015). It promotes toxic algal blooms and the
826 development of near-dead deep-water areas due to oxygen depletion and
827 production of hydrogen sulfide (H₂S). Another potentially important
828 environmental issue in the Baltic Sea is the acidification of sea water induced by
829 increasing atmospheric CO₂ concentration (Omstedt et al., 2012).

830

831 How will the eutrophication-related problems and particularly the oxygen
832 depletion change in the future? If anthropogenic nutrient input is reduced
833 following the current Baltic Sea Action Plan (HELCOM, 2007), the situation is
834 projected to improve, although quite slowly. However, with constant or increasing
835 nutrient input, even larger areas with oxygen depletion would develop (Meier et
836 al., 2011; Schneider et al., 2015). This is partly due to the internal cycling of the
837 nutrients that have accumulated in the Baltic Sea and its sediments during the past
838 century, but projected climate changes also play a role. First, the solubility of
839 oxygen in the Baltic Sea water decreases with increasing temperature. Second, the
840 projected warming accelerates the recycling of organic matter in the Baltic Sea.
841 Third, increases in river runoff may increase the transport of nutrients from land
842 to the Baltic Sea. However, the net effect of runoff changes is uncertain because
843 many projections suggest a decrease in runoff from the southern parts of the
844 Baltic Sea basin (Graham et al., 2008; Collins et al., 2013, Fig. 12.24).

845

846 Climate change might also modify the biogeochemical conditions in the Baltic
847 Sea by altering the frequency and magnitude of saltwater inflows from the North
848 Sea. Some studies have suggested an increase in such inflows in the future, but the
849 evidence is inconclusive (Schimanke, Dieterich & Meier, 2014; Meier, Höglund,
850 Eilola & Almroth-Rosell, 2016). The consequences of the inflows are also
851 complicated. Contrary to intuition, stronger and more frequent saltwater inflows
852 might lead to an expansion of dead bottom areas and increased risk for toxic
853 cyanobacteria blooms, at least in some parts of the Baltic Sea (Meier et al., 2016).

854

855 Oceans currently absorb a quarter of the anthropogenic CO₂ emissions (Ciais et
856 al., 2013, Table 6.3). The resulting acidification alters the sea water chemistry and

857 may have serious ecological consequences. During the past 1-2 centuries, the pH
858 of the Baltic Sea surface water is estimated to have decreased by about 0.15. A
859 further decrease in pH in this century is expected. The magnitude of this decrease
860 depends primarily on the magnitude of anthropogenic CO₂ emissions, with a
861 decrease of 0.4 pH units possible under a high-end emission scenario (Omstedt et
862 al., 2012).

863

864 ***Marine ecosystems***

865 Marine ecosystems in the Baltic Sea are strongly affected by eutrophication, toxic
866 chemicals and other anthropogenic pressures such as overfishing. However, the
867 ecosystems are also sensitive to climate. Climate change directly affects the
868 metabolism, growth, survival and productivity of individual organisms, but it also
869 indirectly influences the structure of communities, for example by shaping the
870 temporal and spatial match or mismatch of interacting species (Viitasalo et al.,
871 2015). These indirect effects are particularly difficult to predict, especially as
872 climate change is compounded by many other anthropogenic pressures.

873

874 Climate change is expected to affect the Baltic Sea ecosystems at least via
875 increases in water temperature, reduced sea ice and changes in salinity.
876 Furthermore, changes in temperature and salinity together regulate the density of
877 sea water, thus affecting its vertical mixing (Viitasalo et al., 2015). Some of the
878 effects are relatively straightforward. For example, a decrease in sea ice extent
879 and duration is a serious threat for ice-dwelling species such as the Baltic Ringed
880 Seal, which may lose much of its current winter habitat (Meier, Döscher &
881 Halkka, 2004). Other effects are more complicated but no less important. In

882 particular, increases in water temperature together with reduced ice cover may
883 lead to major changes in the seasonal succession and species composition of the
884 phytoplankton community (Viitasalo et al., 2015; Sommer & Lengfellner, 2008).
885 One consequence of this is an increased risk of cyanobacteria blooms. On the
886 other hand, a decrease in salinity might reduce phytoplankton productivity, at
887 least in the Gulf of Bothnia. The decrease in salinity together with poor oxygen
888 conditions in the deep basins would also disfavor the main Baltic Sea piscivore
889 cod, with many cascading effects to lower levels in the food web (Viitasalo et al.,
890 2015).

891

892 It is still poorly known how the projected CO₂-induced acidification will affect the
893 Baltic Sea ecosystems. Although many key species in the Baltic Sea food web
894 appear to be physiologically tolerant to the pH decreases expected in the coming
895 century, the acidification may nevertheless change the relative competitiveness of
896 different species and in this way restructure the ecosystems (Havenhand, 2012).

897

898 ***Coastal erosion and coastline changes***

899 The Baltic Sea coastlines are affected by a wide range of geological processes,
900 human activities, and climatic factors. The main climatic factors are wind, waves,
901 storm surges, ice jams and flooding (Łabuz, 2015). The response of the coastline
902 to climate change depends on both the nature of the climate change and the
903 characteristics of the coastline. In general, the submergent and soft coast relief of
904 the southern Baltic Sea area is under most threat of retreat, particularly as the
905 projected sea level rise accentuates its vulnerability to storm surges and wave
906 erosion. The bedrock-dominated coasts of Finland and northern Sweden are less

907 vulnerable, particularly as the local land uplift counteracts the absolute sea level
908 rise.

909

910 Apart from the effects of sea level rise, shortening of the ice season in a warmer
911 climate will also increase the exposure of shorelines to wave and wind erosion.
912 On the other hand, the erosion caused by the ice pack itself will be reduced.
913 Another potentially important but uncertain factor is changes in the frequency and
914 strength of wind storms. The direction of the wind during the storms is also
915 important, because the height of the waves and the storm surge depend on the
916 fetch of the wind over the open Baltic Sea.

917 **Conclusion**

918 The main drivers and interactions that are expected to shape climate change and
919 environmental change in the Baltic Sea region in this century are summarized in
920 Fig. 7. The ultimate drivers of climate change are divided into three categories –
921 increase in atmospheric greenhouse gases, other anthropogenic forcing and natural
922 variability. Similarly, three aspects of large-scale climate change are identified
923 that will affect the climate change in the Baltic Sea region – global warming,
924 changes in atmospheric circulation and changes in ocean circulation.

925

926 When considering what can and what cannot be confidently said about future
927 climate change in the Baltic Sea region, it is essential to understand that

928

- 929 1. Of the three drivers in the top row of the diagram, only the increase in
930 greenhouse gas concentrations is both reasonably well understood and
931 predictable. Other types of anthropogenic forcing, such as changes in

932 aerosol emissions or land use, may either amplify or counteract the
933 greenhouse-gas-induced changes., but their net effect is difficult to predict.
934 This is partly due to limitations in current scientific understanding, partly
935 due to the short atmospheric lifetime of aerosols that allows for potentially
936 fast changes in aerosol concentrations. Both forced (solar variability and
937 volcanic eruptions) and unforced (internal dynamics of the climate system)
938 natural climate variability is generally considered to have only limited
939 predictability.

940 2. The best understood effect from increasing greenhouse concentrations is a
941 thermodynamically governed widespread increase in atmospheric
942 temperatures and moisture content, nicknamed as “global warming”.
943 Projections for changes in atmospheric and oceanic circulation are more
944 uncertain, both because of the complicated dynamics involved and because
945 anthropogenic circulation changes are superimposed with strong natural
946 variability.

947 3. The anthropogenic greenhouse gas forcing and the resulting global
948 warming are expected to increase gradually with time.

949

950 Consequently, the most certain (or least uncertain) aspects of regional climate
951 change in the Baltic Sea basin are those that are most strongly affected by the
952 large-scale global warming. These include increases in atmospheric temperature
953 and Baltic Sea water temperature, decreases in ice cover in the Baltic Sea, lakes
954 and rivers, and increasing sea level at the southern coasts of the Baltic Sea where
955 the large-scale sea level rise is not counteracted by glacial isostatic adjustment.
956 These changes can be considered nearly certain, at least after the first few decades
957 when they might still be masked by natural variability. They might only be

958 reversed in the unexpected case that the large-scale warming would be regionally
959 cancelled by a dramatic decrease in the North Atlantic thermohaline circulation.

960

961 Shortening of the snow season and decrease in snow amount are both driven by
962 increased temperature but are likely to be counteracted by increased winter
963 precipitation. Consequently, changes in snow conditions are subject to somewhat
964 larger uncertainty than the warming *per se*. The increase in winter precipitation is
965 also at least partly driven by the large-scale warming which tends to increase the
966 atmospheric moisture content and hence enables larger moisture transport from
967 south and west. Similarly, the increase in atmospheric humidity favors stronger
968 precipitation extremes. However, precipitation is highly sensitive to atmospheric
969 circulation and its changes are therefore not as strongly governed by atmospheric
970 thermodynamics as the temperature change. It is mainly for this reason that
971 climate change projections are more uncertain for precipitation than temperature.
972 Finally, changes in wind climate are to a large extent dictated by the atmospheric
973 circulation and are therefore among the most uncertain aspects of climate change.

974

975 These considerations have a clear implication on the environmental impacts of
976 climate change. The impacts that are most strongly related to warming are more
977 predictable than those related to precipitation and, in particular wind changes.
978 Nevertheless, for the environmental changes climate change is only one part of
979 the story. In some cases, climate change may become a dominant driver of
980 environmental change; in others, its effects might remain small compared with the
981 direct human influence. Some drivers of climate change, such as changes in land
982 use and in CO₂, ozone and aerosol concentrations, also have direct environmental
983 effects.

984

985 How to reduce the uncertainty in the climate change projections for the Baltic Sea
986 region? More detailed modeling and deeper understanding of the regional
987 atmospheric, oceanic and hydrological processes will undoubtedly be helpful.
988 However, a large part of the uncertainty originates from outside the Baltic Sea
989 region. This uncertainty can only be reduced by an improved understanding and
990 modelling of the processes that control the magnitude of the global-scale
991 warming, changes in atmospheric circulation and the North Atlantic ocean
992 circulation. A lot of hard work is still needed with all of these issues. Finally, part
993 of the uncertainty is essentially irreducible. The current understanding suggests
994 that natural climate variability is largely unpredictable in the long run, although
995 the ocean circulation might give it some predictability for the first decade or so
996 (Koenigk, König Beatty, Caian, Döscher & Wyser, 2012). Similarly, future
997 greenhouse gas emissions will depend on political and economical decisions that
998 are extremely difficult to predict decades in advance.

999

1000 **Further reading**

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1415 **Figures**

1416
1417 **Figure 1.** Total anthropogenic CO₂ emissions (left) and CO₂ concentrations for the SRES
1418 (top) and RCP (bottom) scenarios. The figure is based on the best-estimate values given
1419 in Appendix II of IPCC (2001) and Appendix II of IPCC (2013).

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1423 **Figure 2.** Global mean temperature change under the four RCP scenarios, as simulated
1424 by the models used by Collins et al. (2013). **Left:** multi-model mean change relative to the
1425 mean temperature in 1986-2005. The observed temperature time series up to the year
1426 2015 is given as the mean of the HadCRUT4 (Morice, Kennedy, Rayner & Jones, 2012),
1427 GISS (Hansen, Ruedy, Sato & Lo, 2010) and NCDC (Smith, Reynolds, Peterson &
1428 Lawrimore, 2008) estimates. **Right:** Temperature changes in the individual models from
1429 1986-2005 to 2031-2050 and 2081-2100. Unit is °C.

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Figure 3. Comparison between global (horizontal axis) and Baltic Sea drainage basin (vertical axis) area and annual mean temperature changes from 1986-2005 to 2081-2100. The same GCM simulations are included as in Fig. 2 (33 for RCP2.6, 42 for RCP4.5, 26 for RCP6.0 and 42 for RCP8.5).

Figure 4. Temperature change (ΔT) and precipitation change (ΔP) from 1986-2005 to 2081-2100 under the RCP4.5 scenario in the 42 GCMs used by Collins et al. (2013). (a)-(d): maps of multi-model mean change. (e)-(f) Seasonal cycles of Baltic Sea drainage basin mean temperature change and precipitation change. The black lines show the multi-model mean and the grey bars the mean ± 1 standard deviation (thus, this range covers approximately two thirds of the model projections). The Baltic Sea drainage basin is delineated by the thick purple line in (a)-(d). For reference, the multi-model global mean warming for these simulations is 1.8°C .

Figure 5. Changes in annual mean sea level pressure (left) and wind speed (right) from the years 1961-1990 to 2071-2100. The results are based on the SRES A2 emissions scenario and were produced using the same RCM (Rossby Centre regional Atmosphere-Ocean model; RCAO) using boundary data from two GCMs: ECHAM4/OPYC3 (top) and HadAM3H (bottom). Redrawn from Räisänen et al. (2004).

Figure 6. Simulated 30-year mean seasonal cycles (August to June) of temperature (T), precipitation (PR), snowfall ($PRSN$), and water equivalent of the snow pack (SWE) at three locations in the Baltic Sea basin: Kiruna in Swedish Lapland, Joensuu in eastern Finland, and Riga in Latvia. Black = 1980-2010, blue = 2025-2055, red = 2069-2099. The figure is based on 12 RCM simulations from the ENSEMBLES project under the SRES A1B emissions scenario (Räisänen, 2015). Closed (open) circles indicate months in which all 12 (10 or 11) models agree on the sign of the change relative to 1980-2010.

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1465 **Figure 7.** A schematic overview of the main drivers and interactions that are expected to
 1466 affect the climate and the environment in the Baltic Sea region in the 21st century. The
 1467 arrow from “Drivers of climate change” to “Regional climate change” refers to local
 1468 climate forcings such as land use change. The arrows from “Large-scale climate
 1469 change” and “Glacial isostatic adjustment” to “Physical changes in the Baltic Sea”
 1470 refer to sea level change.