



Major potentially climate induced changes in the coastal ecosystem of the western Gulf of Finland – a review



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Preface

This report is a part of the VACCIA project (Vulnerability Assessment of ecosystem services for Climate Change Impacts and Adaptation). The VACCIA project is included in and funded by the LIFE+ program of the European Union. The general aim of the project is to investigate and evaluate the vulnerability of ecosystem services to climate change and to assess the possibilities for adaptation to those changes. This is to be achieved by: gathering knowledge of climate change impacts on ecosystems and their services; studying different possibilities for human society to adapt its activities to the changing conditions; conveying the acquired information to different stakeholders and to the public; and by supporting planning and decision-making both on local and regional levels. The VACCIA project started in 2009 and is running for three years until the end of 2011.

VACCIA is coordinated by the Finnish Environment Institute (SYKE) and the other key partners of the project are the Finnish Meteorological Institute (FMI) as well as the Universities of Helsinki, Jyväskylä and Oulu. Thirteen different Actions (sub-projects) have been established in order to reach the goals set for the project. Nine of these Actions are connected to specific LT(S)ER (Long-Term (Socio)-Ecological Research network) areas in Finland. These LT(S)ER areas are intensively studied sites or regions with a wealth of existing information, and are closely integrated into the local-scale economy and activities.

The report in question belongs to VACCIA Action 5. Action 5 will focus on the coastal ecosystems in the western Gulf of Finland and is connected to the Western Gulf of Finland LTER area (WelFin). The LTER-site WelFin is maintained and developed together by the research and monitoring bodies that use Tvärminne Zoological Station (University of Helsinki) in Hanko for their activities. The region comprises a number of natural resources with conservation, recreation, or economic values, which directly are influenced by climate induced pressures. The aim of Action 5 is to facilitate the identification of changes in management criteria of coastal ecosystems. The material used in the work of Action 5 is collected within the WelFin-area. The responsible actor in VACCIA Action 5 is Tvärminne Zoological Station (University of Helsinki), while Hanko Bird Observatory (HALIAS), the Association for Water and Environment of Western Uusimaa (LUVY) and Novia University of Applied Sciences together with the research- and development institute Aronia have been important collaborators.

Summary

Global climate change has recently drawn much attention, as convincing and extensive evidence of past and ongoing global temperature rise have been presented. Long-term measurements from the Baltic Sea area have shown an increasing trend in air temperature and precipitation. Furthermore, sea water temperature has increased and sea ice cover has declined due to the climate warming.

The aim of this report was to identify recent potentially climate induced major changes in the coastal ecosystems of the western Gulf of Finland. Both abiotic and biotic constituents were included. The study was a literature review of existing published information concerning the topic.

Climate induced changes in coastal marine ecosystems include both abiotic and biotic changes complexly interconnected with each other and with other ongoing processes descending from additional anthropogenic or natural forcing mechanisms. It is particularly difficult to distinguish between eutrophication effects and the climate induced effects. Major identified changes were: long-term decline in seawater salinity; increased water turbidity; advanced sea ice break-up; phytoplankton annual biomass-maximum shift from spring towards late summer; decreased charophyte vegetation in shallow areas; increased reed (*Phragmites australis*) cover and distribution; dominance shift in benthos from the amphipod *Monoporeia affinis* to the bivalve *Macoma balthica*; increase and a successful spreading by the invasive polychaete *Marenzelleria viridis*; recent decline in blue mussel (*Mytilus edulis*) populations; strong increase in roach (*Rutilus rutilus*) and other cyprinid fish; decrease in pike (*Esox lucius*) in the outer archipelago areas; rapid decline in common eider (*Somateria mollissima*) population; strong increase in the great cormorant (*Phalacrocorax carbo*) population; and advanced spring migration of bird species

Tiivistelmä

Ilmastonmuutos on viime aikoina saanut paljon huomiota osakseen. Laajaa ja vakuuttavaa näyttöä edeltävästä sekä meneillään olevasta globaalista ilmaston lämpenemisestä on esitetty. Itämeren alueen pitkän aikavälin muutoksissa on nähtävissä nouseva trendi ilman lämpötilan sekä sadannan suhteen. Lisäksi, meriveden lämpötila on noussut ja itämeren talvinen jääpeite pienentynyt.

Tämän raportin tarkoituksena on löytää ja tunnistaa viimeaikaisia, mahdollisesti ilmastonmuutoksesta johtuvia merkittäviä muutoksia läntisen Suomenlahden rannikkoekosysteemeissä. Sekä abioottiset että bioottiset osatekijät huomioitiin ja sisällytettiin raporttiin. Raportti on kirjallisuuskatsaus olemassa olevaan julkaistuun aiheeseen liittyvään aineistoon.

Ilmastonmuutoksen vaikutukset rannikonläheisessä meriekosysteemeissä koostuvat sekä abioottisista että bioottisista toisiinsa monitahoisesti yhdistyvistä muutoksista, jotka vuorovaikuttavat lisäksi muiden, ekosysteemiä ohjaavien processien kanssa. Erityisen vaikeaa on erottaa rehevöitymisestä johtuvat muutokset ilmastonmuutoksen vaikutuksista. Merkittävimmät muutokset olivat: suolaisuuden väheneminen pitkällä aikavälillä; lisääntynyt veden sameus; aikaistunut keväinen jäiden lähtö; kasviplanktonin kasvuhipun hivuttautuminen keväästä kohti loppukesää; vähentyneet charofyytit; lisääntynyt kaislan (*Phragmites australis*) levinneisyys ja kaislikoiden kattavuus; pohjaeläimistön dominanssivaihdos valkokatkasta (*Monoporeia affinis*) liejusimpukkaan (*Macoma balthica*); kasvanut monisukaismadon (*Marenzelleria viridis*) populaatio ja levinneisyys; äskettäinen sinisimpukkapopulaation (*Mytilus edulis*) heikkeneminen; särjen (*Rutilus rutilus*) ja muiden särkikaloiden vahva kannan lisääntyminen; hauen (*Esox lucius*) vähentyminen ulkosaaristossa; nopea haahkakannan (*Somateria mollissima*) vähentyminen; merimetsokannan (*Phalacrocorax carbo*) vahva kasvu; sekä aikaistunut lintujen kevätmuutto.

Sammandrag

Global klimatförändring har de senaste tiderna fångat mycket uppmärksamhet i grad med att övertygande och omfattande bevis för både tidigare och fortgående global uppvärmning har framförts. Långtidsdata från östersjöområdet har visat en ökande trend i både lufttemperatur och nederbörd. På grund av klimatuppvärmningen har också havsvattnets temperatur stigit medan det årliga istäcket på Östersjön har minskat.

Målsättningen med denna rapport var att identifiera nyligen inifrån betydande förändringar i västra Finska vikens kustekosystem, vilka potentiellt kan kopplas till klimatförändring. Studien var en litteraturundersökning över redan existerande publicerad information gällande ämnesområdet.

Klimatinducerade förändringar i marina kustekosystem består av både abiotiska och biotiska förändringar som på ett komplext sätt är sammanlänkade med varandra och med andra pågående processer härstammande från antingen ytterligare antropogena eller naturliga mekanismer. Det är särskilt svårt att skilja emellan effekter av eutrofiering och klimatförändring. De betydande identifierade förändringarna var: långtidsminskning i havsvattnets salinitet; ökad turbiditet; tidigarelagd smältning av havsis; förflyttning av fytoplanktontoppen från vårbloomingen mot sensommar; minskad kranalgsvegetation i grunda områden; ökad täckning och utbredning av vassen (*Phragmites australis*); dominansskifte i bottenfauna från vitmärla *Monoporeia affinis* till östersjömussla *Macoma balthica*; ökning och framgångsrik utbredning av den invasiva havsbortsmasken *Marenzelleria viridis*; minskad populationsstorlek hos blåmusslan (*Mytilus edulis*); kraftig ökning av mört (*Rutilus rutilus*) och andra cyprinider; minskade mängder gädda (*Esox lucius*) i ytterskärgården; snabb nedgång i eider (*Somateria mollissima*) stammen; kraftig ökning av storskarv (*Phalacrocorax carbo*); och fåglars tidigarelagd vårflyttning.

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1 Introduction

1.1 The Baltic Sea and Gulf of Finland

The Baltic Sea is a temperate brackish water sea with noticeable geographical and seasonal variations in its environmental conditions (Kullenberg 1981, Leppäkoski & Bonsdorff 1989, Matthäus 1996). Decreasing temperature and salinity gradients run from the southwest to north and northeast. Salinity ranges from near marine values (25 psu) in the Danish Straits to limnic conditions (< 1 psu) in river outflows and the most sheltered inlets of the Gulf of Bothnia and Gulf of Finland, with vertical gradients including a permanent halocline at the depth of 50–70 m in the central Baltic Sea (Voipio 1981, Kautsky & Kautsky 2000). The drainage area of the Baltic Sea is about four times larger than the total sea surface, and is inhabited by over 85 million people in 14 countries (9 coastal nations), executing strong anthropogenic influence on the marine ecosystem (HELCOM 2002). Anthropogenic factors that have affected the Baltic Sea are pollution (HELCOM 2004), eutrophication (HELCOM 2005), fisheries (ICES 2007) and the recent climate change (HELCOM 2007).

The Gulf of Finland (hereafter GoF) is a moderately deep (mean depth 37 m, max. 123 m) 400 km long elongated basin in the northeast part of the Baltic Sea (e.g. Laine et al. 2007, Soomere et al. 2009). It has a sharp declining west–east salinity gradient maintained by the influence of saltwater intrusions from the Baltic Proper to the western entrance of the gulf and freshwater runoff from the drainage area mainly at the east end of the gulf (e.g. Westerbohm 2006). Surface salinity ranges from 5–7 psu in the western GoF to almost that of freshwater in the easternmost part, where Baltic's largest river, the Neva, discharges to the sea (e.g. Laine et al. 2007). Fluctuations in salinity and temperature result in a high spatio-temporal variability in water stratification (Soomere et al. 2009). Major currents in the GoF generally follow an anti-clockwise pattern, with a large westward surface flow of freshwater along the northern coast (Alenius et al. 1998, Andrejev et al. 2004). Sea ice covers at least partly the GoF for 4–5 months during winter (Soomere et al. 2009). The GoF is one of the most severely eutrophied sub-basins in the Baltic Sea (Pitkänen et al. 2009) and an extensive and increasing ship traffic through the gulf heightens the risk of pollution and oil disasters (Leppäranta et al. 2009).

1.1.1 Baltic Sea ecosystems

The temperate brackish water character of the Baltic Sea sets the facilities and limitations for the existing ecosystem that consists of a mixture of both freshwater and marine organisms (e.g. Hällfors et al. 1981, Rheinheimer 1996). Relatively few species have been able to adapt to the harsh conditions of the Baltic Sea, and even those are limited by the close presence of their physiological and ecological tolerances (Hopkins et al. 2006). A species' tolerance for the environment and, on the other side, the environmental barriers, form the range of distribution within which the species can survive and exist (Holt et al. 2005). Many Baltic Sea species live as marginal populations near the edge of their range, which makes them susceptible to environmental change (e.g. Svensson et al. 2005, Westerbohm 2006). Baltic Sea

ecosystems are in general relatively poor of species, lack high functional diversity and are often maintained by only few functionally important key-species (HELCOM 2003, Hopkins et al. 2006). This makes these ecosystems especially prone to climate induced changes, while species rich and functionally diverse ecosystems generally have been assumed to better adapt to environmental change (Chapin et al. 2000, CBD 2003).

1.2 A changing climate

Global climate change has recently drawn much attention, as convincing and extensive evidence of past and ongoing global temperature rise have been presented (IPCC 2007). Different definitions of the term “climate change” occur and it is obviously of great importance to draw a distinction between them (Pielke 2004). This report uses the definition employed by the Intergovernmental Panel on Climate Change (IPCC), which is: “Climate change is any change in climate over time whether due to natural variability or as a result of human activity” (IPCC 2007). The accelerated global warming since the middle of the 20th century has been addressed to human activities due to growing emissions of greenhouse gases (carbon dioxide and methane) (IPCC 2007). This recent change has further altered regional atmospheric air pressure regimes, wind conditions, cloudiness and precipitation.

1.2.1 The Baltic Sea

The climate of the Baltic Sea area is characterized by large seasonal variations, originated from its northern location and topographical properties, and is influenced by a major air pressure system, the North Atlantic Oscillation (NAO) (HELCOM 2007). NAO affects the atmospheric circulation and thereby the temperature, wind conditions, precipitation and oceanographic characteristics in the Baltic Sea (Hänninen et al. 2000, Omstedt et al. 2004). In addition to the natural climate fluctuations, the global climate change has also influenced the Baltic Sea region. Long-term measurements from the Baltic Sea area have shown an increasing trend in average surface air temperature (Omstedt et al. 2004, FMI 2010, Tietäväinen et al. 2010) and precipitation (HELCOM 2007, IPCC 2007). Furthermore, sea water temperature has risen (Fonselius & Valderama 2003, MacKenzie & Schiedek 2007) and sea ice cover of the Baltic Sea has declined (Omstedt et al. 2004, HELCOM 2007) due to the climate warming. Sea water salinity in the Baltic Sea is also strongly connected to climate variability, via irregular Atlantic inflows and freshwater runoff (Hänninen et al. 2000, Zorita & Laine 2000). Still, no overall long-term tendency in salinity has been shown (Windsor et al. 2001, Fonselius & Valderama 2003) even if modelled predictions have expected a reduction of salinity due to an increase in precipitation and the consequent increase in fresh water runoff from the Baltic sea catchment area (Meier & Kauker 2003, Graham 2004). However, salinity will respond much slower than temperature to climate changes (Stigebrandt & Gustafsson 2003), which can explain the absence of an observable long-term trend. Additional alterations in the environment coupled to the changing climate are for instance differed wind conditions, diverged cloudiness, changing occurrence of extreme events (e.g. temperature extremes and storms) and fluctuations in the timing of seasonal and annual events (spring runoff, autumn low flow, ice and snow cover formation, water stratification etc.) (HELCOM 2007). A thorough examination of

potentially climate forced changes in the Baltic Sea area is given in BACC Author Team 2008.

1.2.2 The Gulf of Finland

In the GoF similar potentially climate induced changes have occurred, i.e. rising sea water temperature (HELCOM 2007), impaired sea ice conditions (Jevrejeva et al. 2004) and increased windiness (Soomere & Keevallik 2003). Contrary to the general development, salinity in the GoF has shown a decreasing trend, which has been in accordance with the contemporary increase in freshwater runoff to the Gulf (Rönkkönen et al. 2004, Westerbom 2006, Laine et al. 2007, Soomere et al. 2009). Near-bottom oxygen conditions have improved, apparently because of the salinity decline and the consequent loss of stratification (Laine et al. 2007). A clear long-term reduction of water transparency has also been observed in the GoF, which originates at least partly from the enlarged riverine input of turbid water in addition to eutrophication effects (i.e. amplified phytoplankton growth) (Fleming-Lehtinen & Kaartokallio 2009).

1.2.3 Effects on biota

Global climate change has already affected the biota world-wide (McCarty 2001, Walther et al. 2002, Parmesan 2006) and will continue to influence the distribution and abundance of species in the future (e.g. Thomas et al. 2004). Effects of climate changes in marine ecosystems comprise altered nutrient cycling and contaminant distribution and changes at all trophic levels from bacteria to seabirds and marine mammals (HELCOM 2007). Climate induced changes in water temperature, water balance, circulation and salinity are likely to have impacts on the biota and the biological processes in the Baltic Sea, affecting the species, their distribution and their interactions. Examples of potentially climate forced changes already happened in the Baltic Sea biota are; temperature related change in phytoplankton species composition and biomasses, temperature and salinity induced dominance shifts in the pelagic zooplankton community, distribution shifts in zoobenthos species owing to salinity decline and oxygen depletion, reduced abundance and spatial distribution of marine fish species due to lower salinity and advanced arrival of migrating waterbirds and altered winter distribution of wintering waterfowl as a response to temperature increase (Möllman et al. 2005, Ojaveer & Kalejs 2005, Jonzén et al. 2006, HELCOM 2007, Suikkanen et al. 2007). On a larger view, direct and indirect impacts of climate changes in the Baltic Sea have also been seen on the ecosystem level, affecting even large-scale ecosystem dominance shifts (e.g. that of cod to sprat dominance) (Österblom et al. 2007). Observed potential climate changes effects on the biota in the GoF are similar to the changes from the whole Baltic Sea area and consist, for instance, of deterioration of herring condition and alteration of zooplankton community structure in line with decreasing salinity (Rönkkönen et al. 2004) and changes in soft-bottom benthic fauna due to altered oxygen conditions (Laine et al. 2007).

2 Features of the study

2.1 The objective and methods

The aim of this report is to identify recent potentially climate induced major changes in the coastal ecosystems of the western Gulf of Finland. Both abiotic and biotic constituents are included. Different long-term monitoring data, both abiotic and biotic, produced by different parties (Tvärminne Zoological Station, FMI, LUVY and HALIAS) operating in the area, have been identified (Alsuhail 2009). Although much of the data remain to be analyzed, there exists a large body of publications, recently incorporated in the Action 5 GIS-database, which rely on these data, or on independently collected observations in the region. This study is a literature review of the existing published information concerning the topic.

Abiotic alterations were looked for in hydrographic factors, wind and wave action as well as in ice conditions. Biotic changes were searched for among all main organism groups from bacteria to birds. A list of 959 publications was searched through in order to find relevant literature. The list included the majority of all publications produced at or in connection to Tvärminne Zoological Station from year 1984 until 2009. After the search a subset of 91 potentially relevant publications was chosen. These publications were thoroughly examined and finally involved in the review if they appeared useful. Additionally, newer and other relevant scientific publications, monitoring reports and academic thesis concerning the coastal environment of the western GoF were searched for and included in the review.

2.2 Study area – coastal western Gulf of Finland

The study area comprises the northwest GoF along the Finnish southwest coast, from the area around Hanko peninsula in west to the whole archipelago area of Raasepori in east. The core of the study area is a ca 600 ha nature reserve area, in the archipelago outside Tvärminne Zoological Station (N 59°50' E 23°15') south of the Hanko peninsula between the towns Hanko and Tammisaari. The rest of the study region belongs mostly to a large marine Natura-2000 area, and it also encompasses the 52 km² Tammisaari Archipelago National Park. The area is typified by variable coastal morphology and characterized by a vast archipelago consisting of numerous islands, islets, skerries and reefs (e.g. Westerbom 2006). The archipelago transits from the most sheltered bays and inlets near the mainland towards the exposed areas before the open sea, forming a zonation consisting of the inner, middle and outer archipelago (Häyrén 1900). The study area is influenced by the proximity to the open sea through local currents and occasional upwelling, supplying it with salty nutrient-rich water (Haapala 1994, Alenius et al. 1998), and by substantial freshwater input from the rivers (Fiskarsin joki and Mustion joki) discharging to the Pohjanpitäjänlahti Bay (Munsterhjelm 1997, Raateoja et al. 2005). Thereby, a decreasing south-north salinity gradient runs through the area, with the surface salinity being 5–6 psu in the outer archipelago and 2–3 psu in the inner parts depending on the season (Munsterhjelm 1997, Westerbom 2006). The innermost bays in the area, especially in the spring, can be extremely low in saline (Munsterhjelm 1997). The summer sea surface water temperature varies from +14 to +18 °C in the outer zone,

from +16 to +20 °C in the central zone and often exceeds +20 °C in the sheltered inner areas (Munsterhjelm 2005). Southerly winds dominate through most of the year (Laakkonen 1981). The study area is influenced by eutrophication (Munsterhjelm 2005, Holmberg et al. 2008), and near-bottom hypoxia (oxygen depletion) occur with temporal and spatial variations (Holmberg et al. 2008). The area is locally affected by anthropogenic pollution from industries and municipal wastewater discharges (Holmberg & Jokinen 2004, Holmberg et al. 2008).

3 Abiotic changes in coastal western Gulf of Finland

3.1 Temperature

Seawater temperature dynamics are affected by atmospheric temperature changes through heat exchange between air and water surface (Siegel et al. 2006), but regionally also through water exchange from adjacent deep-bottom water and from freshwater runoff (Stipa 1999). Temperature is generally a crucial factor for several biological and ecological processes, such as metabolism, growth, activity, reproduction, migrations, species distribution and population size (CBD 2003).

Long-term (1939–2007) water surface temperature data from Tvärminne Storfjärden in the middle archipelago, measured as the mean of weekly values in the summers (June–August), showed a considerable inter-annual variation (min. 11.2 °C , max. 18.1 °C) but no significant trend (Lehtonen et al. 2009).

3.2 Salinity

Seawater salinity in the coastal region is determined by the influence of freshwater flow originating from runoff (and direct precipitation) and by saltwater intrusion from adjacent open sea areas (Stipa 1999). Salinity is one of the most important environmental factors in the Baltic Sea, determining the composition and distribution of species by affecting e.g. survival, reproduction and growth (Bernes 2005, Hopkins et al. 2006).

Long-term (1939–2007) salinity data from Tvärminne Storfjärden (5m depth), measured as the mean of weekly values throughout the years, fluctuated strongly over the 70-year period, but showed a slightly declining trend (Lehtonen et al. 2009). A somewhat decreasing salinity trend in the same area has also been noticed in Lappalainen et al. 2001 and Westerbohm 2006.

3.3 Oxygen

Oxygen concentrations in near-bottom waters is caused by the balance between biological oxygen consuming processes (i.e. the breaking-down of dead organic matter originating from biological production) and physical oxygen supplying processes (i.e. currents and water mixing events), thereby affected by eutrophication and stratification of the water column (Conley et al. 2009). Oxygen conditions in the coastal areas are usually determined by the stratification and mixing of the water column, following salinity, freshwater runoff and temperature development (Stipa 1999).

Hypoxia (i.e. oxygen depletion, $O_2 < 2 \text{ mL L}^{-1}$) can destroy benthic communities and fish habitats, but also alter the biogeochemical cycles of nutrients (Diaz & Rosenberg 2008). These phenomena, linked to eutrophication, have been reported to increase around the Baltic coasts in recent decades (Karlson et al. 2002).

Oxygen conditions have generally been good in the areas around the SW part of Hanko peninsula and no clear trend could be found in the near-bottom oxygen concentration during a period from 1989 to 2009 (Holmberg & Jokinen 2004, 2008, Suonpää et al. 2010). In the shallow Tammisaari archipelago waters, oxygen conditions have also been good with no observable trend (Holmberg et al. 2003). In Pohjanpitäjänlahti Bay, however, hypoxic conditions have occurred frequently and there seems to be a long-term (1972–2006) declining trend in autumn concentrations of near-bottom oxygen (Holmberg et al. 2008).

3.4 Nutrients

Nutrients (mainly nitrogen and phosphorous) are essential for the biological production of the seas, but an excess of them may develop a state of eutrophication (e.g. Karjalainen 1999). Nutrient input to the sea is mainly transported from the land by freshwater runoff and originates to a large extent from anthropogenic loading (Fleming-Lehtinen et al. 2008). The vertical distribution of nutrients is detrimental for pelagic production, and is affected by water mixing through convection and currents (Haapala 1994). Eutrophication affects coastal ecosystem in several ways, directly and indirectly, and causes for instance increasing primary production (e.g. cyanobacterial blooms and increased growth of annual filamentous algae) and changes in the benthic fauna and fish communities (Bonsdorff et al. 1997a).

In the outer archipelago south of Tvärminne the annual mean of total phosphorous concentration seems to have increased since the early 1970's according to monitoring data (Lappalainen et al. 2001). However, in the areas around the SW part of Hanko peninsula, no clear changes in the nutrient concentrations (1 m depth) occurred during a 20 year monitoring period from 1989 to 2009 (Holmberg & Jokinen 2004, 2008, Suonpää et al. 2010). There was no obvious change in the nutrient concentrations in neither the middle nor the inner archipelago waters of Ekenäs, during the period 1987–2006 (Holmberg et al. 2003, 2008). However, it is most likely that an upward nutrient trend throughout the study area would be visible from a longer time-series, while effects of increasing eutrophication, measured as elevating chl-a (chlorophyll-a) concentrations, have been shown since the early 1970's (Raateoja et al. 2005).

3.5 Transparency

Water transparency is determined by the transfer of sunlight into the water and is usually measured as Secchi depth, i.e. the depth of visibility from above the surface (e.g. Soomere et al. 2009). Water transparency is influenced by the amount of light absorbing matter in the water, such as humus, chlorophyll and suspended particles (measured as turbidity) and is thus impaired by eutrophication and turbid runoff (Schiewer 2008). The optical properties of sea water are essential for the light-demanding primary production (e.g. phytoplankton growth and macrophyte distribution) (Andersson et al. 1996, Bäck & Ruuskanen 2000) and also affects, for example, visual predatory fish (Sandström & Karås 2002).

Long-term (1939–2007) Secchi depth values, give an estimation of mean water clarity for the period at Tvärminne Storfjärden, showing a clear decline in transparency from ca 7 m at the beginning to about 3.5 m by 2007, with an accelerating decrease at mid 1980's (Lehtonen et al. 2009). Additionally, a trend of decreasing transparency (given as increased turbidity) has also been found in shallow bays and inlets from all over the study area during a period between 1978 and 2003 (Munsterhjelm 2005).

3.6 Wind and waves

Wind is induced by atmospheric air flow, whereas waves are caused by the wind in exposed sea areas (Tolvanen & Suominen 2005). Wind and wave action creates currents and surface turbulence that counteract the stabilisation of the water column (Viitasalo 1994, Alenius et al. 1998) and affect, for example, the distribution of plankton organisms (e.g. larval dispersal of blue mussels) (Westerbom 2006, Westerbom & Janttu 2006).

Earlier (1967–1985) wind data has shown a statistically significant increasing trend in windiness at Tvärminne (Viitasalo et al. 1995). Long-term wave data from the coastal western GoF could not be found.

3.7 Ice

Sea ice is formed commonly, during sufficiently cold winters usually between December and April, and is affected by air temperature, wind conditions and coastal morphology (Omstedt et al. 2004, Soomere et al. 2009). Changes in ice cover extent and duration may alter the stabilisation of the water column in spring, thereby affecting the timing of the vernal phytoplankton bloom, which can further disturb higher trophic levels through food web interactions (HELCOM 2007). Sea ice is also an important restricting factor for the sublittoral biota as a result of its mechanical abrasion (Kiirikki & Ruuskanen 1996, Westerbom 2006) and it furthermore serves as a context for a bacterial sea ice community (Kaartokallio 2005).

A time series from Jussarö in the western GoF showed advancement in the ice break-up date during the period 1979–2004 (Lehikoinen et al. 2006).

4 Biotic changes

4.1 Bacteria

Aquatic bacteria are a very heterogeneous group of organisms, essential for the recirculation of material and energy in the aquatic ecosystem (Uitto et al. 1997, Autio 2000). They are heterotrophic organisms but can utilize nutrients both in organic and inorganic forms (Cotner & Wetzel 1992). The bacteria are subjected to substantial seasonal and inter-annual variation, depending on fluctuating environmental conditions, resources and grazing (Kuparinen & Kuosa 1993, Tuomi 1998, Autio 2000). The highest bacterial production typically occurs after the peak of the phytoplankton spring bloom, which supplies the bacteria with organic substances (e.g. Tuomi et al. 1999).

In spite of the many surveys conducted in the western GoF coastal areas, concerning aquatic bacteria (Virtanen 1985, Lignell et al. 1992, 2008, Kuparinen & Heinänen 1993, Tuomi 1998, Tuomi et al. 1999, Autio 2000, Kaartokallio et al. 2005, Hoikkala et al. 2009), no long-term studies, inter-annual comparisons or information of possible changes in the bacterial community are available. A reason for this may be the fact that the full understanding of the role of bacteria in marine ecosystems developed quite late, not before the early 1980's (Sherr & Sherr 2000), which means that there was little or no interest in this field of research before that time. However, experimental and field study results from coastal areas in western GoF have indicated that temperature would act as the most important regulator for bacterial activity and growth (Tuomi et al. 1999, Autio 2000), thus suggesting the possibility of changes with a warming climate. Nevertheless, other experiments from the same area have revealed the importance of other factors, such as nutrient availability (Kuparinen & Heinänen 1993) and the amount of carbon substrate (Hoikkala et al. 2009). In coastal ecosystems material from river runoff may provide additional organic substrates for bacteria (Ducklow & Carlson 1992). Climate forced increase in runoff may thus benefit the bacteria, especially in early spring before the vernal phytoplankton bloom.

4.2 Phytoplankton

Phytoplankton (plankton algae and cyanobacteria) constitute the foundation of aquatic systems by being the basic component of the pelagic production, serving as food for both pelagic and benthic organisms (Olenina et al. 2006, HELCOM 2007). Hence, structure and dynamics (species composition, production and biomass) of the phytoplankton community are truly important for the whole ecosystem, although changes are not easily detected due to the naturally high temporal and spatial variability in phytoplankton (HELCOM 2007). Phytoplankton species composition and production is principally dependent on the availability of nutrients (nitrogen, phosphorous, silica) and the ambient salinity (Olenina et al. 2006, Suikkanen et al. 2007), and also on the light conditions (light intensity and water transparency) (Andersson et al. 1996, Sommer & Lengfellner 2008). Temperature and wind can also affect phytoplankton assemblages, for example, by initiating (increased temperature) and dislodging (wind) cyanobacterial blooms (Kanoshina et al. 2003) and by attenuating phytoplankton spring bloom (increased temperature) (Sommer & Lengfellner 2008). Different phenomena in the

seawater environment can indirectly influence the phytoplankton community by affecting the state of some of the essential requirements. Such phenomena are for instance stratification of the water column (development of a halo- or thermocline) (Cushing 1989, Hajdu et al. 2007) or an increased runoff from land (HELCOM 2007), the former leading to a nutrient depleted euphotic zone and the latter possibly to increased nutrient availability as well as decreased salinity and transparency. Changes in the community structure and biomass of phytoplankton can reflect both the effects of eutrophication and climate change, which are often interconnected and not easily separated (HELCOM 2007).

In spite of the numerous phytoplankton studies conducted in the coastal western GoF (Niemi 1973, 1975, 1978, Tamminen & Leskinen 1985, Huttunen & Kuparinen 1986, Kononen & Niemi 1986, Kuosa 1986, 1988a,b, Kuparinen 1987, Grönlund & Leppänen 1992, Uitto et al. 1997, Raateoja et al. 2005), no long-term surveys on the phytoplankton community structure (composition and abundances of species) could be found in the literature. However, long-term data on chl-a values, representing phytoplankton production biomass, do exist and have been published. A survey of 30-year (1972–2002) monitoring data concerning the chl-a concentrations in the outer archipelago area in western GoF south off Tvärminne, showed an increasing overall trend in the 1970's and 1980's mainly caused by strengthened vernal blooms, which illustrates a growing phytoplankton production during that time (Raateoja et al. 2005). The increase did not continue in the 1990's, and the seasonal phytoplankton biomass maxima since then has begun to show some bias toward the late summer, although the spring bloom is still more important than the late-summer bloom for the total chl-a levels. The early increasing trend in chl-a reflects the state of eutrophication, while the later changes in seasonal maxima of phytoplankton blooms probably indicates decreased nitrogen availability, which limits the magnitude of the spring bloom, saving the phosphorous reserves for the late summer (Raateoja et al. 2005). Another chl-a monitoring from 1993 to 2003 conducted summertime around the SW Hanko peninsula did not reveal any changes (Holmberg & Jokinen 2004), which confirms the findings made by Raateoja et al. 2005. Chl-a monitoring from the middle and inner archipelago areas during 1997–2006 does not show any general trend, except from a slight increase in one eutrophied inner bay area (Dragsviksfjärden) (Holmberg et al. 2008).

4.3 Zooplankton

Zooplankton is a diverse group of pelagic heterotrophic consumers consisting mainly of cladocerans, copepods, rotifers and pelagic larvae of benthic organisms (e.g. HELCOM 2007). The species composition and of zooplankton is mostly regulated by salinity and temperature (e.g. Flinkman et al. 1998, Dippner et al. 2000). Changes in salinity and temperature during the last decades have resulted in a zooplankton community dominance shift in the open Baltic Sea (Möllman et al. 2000) and the coastal zooplankton community has also showed a dependency to these environmental factors (Viitasalo et al. 1990, Vuorinen et al. 1998). However, hydrographical factors also influence trophic dynamics, which in some case are the direct regulators of zooplankton and thus explain the noticeable relationship to salinity and temperature (Viitasalo 1994, Koski 1999). Zooplankton grazes upon phytoplankton, which explains the annual zooplankton maximum occurrence usually falling after the phytoplankton spring bloom

(e.g. Johansson 1992). This phenomenon might be more obvious in the open sea than in coastal areas, where zooplankton often consume considerable amounts of bacterioplankton instead of phytoplankton (Koski 1999). Zooplankton is predated mostly by fish but also by mysids (Hansson et al. 1990).

Surveys concerning zooplankton in the coastal western GoF have been conducted (Kivi 1986, 1996, Viitasalo 1994, Uitto et al. 1997, Katajisto et al. 1998, Koski 1999), also including some long-term studies (Viitasalo et al. 1995a,b). An 18-year time series from 1967 to 1984 in Tvärminne Storfjärden showed changes in the zooplankton community structure and dynamics as well as alterations in copepod growth and body size (Viitasalo et al. 1995a,b). The copepod biomass, mainly consisting of *Acartia bifilosa* and *Eurytemora affinis*, increased during the study period (Viitasalo et al. 1995a). Results from the same study showed also an increasing trend in the abundances of *Pseudocalanus minutes elongatus* and *Balanus improvises* larvae, as well as a decrease in *Synchaeta baltica*, *Centropages hamatus* and Lamellibrachia larvae. The total mesozooplankton biomass was positively affected by temperature rise and negatively by salinity increase, and the timing of the seasonal peaks of some of the dominant species (*Bosmina maritime*, *Podon polyphemoides* and *E. affinis*) varied in accordance to water temperature (Viitasalo et al. 1995a). A statistically significant increase in the body size of *Acartia bifilosa* over the study period was found (Viitasalo et al. 1995b). This increase was not correlated with temperature but possibly with food conditions, while in turn the timing of the seasonal decline in copepod body size and the inter-annual variations in female *E. affinis* body size was affected by water temperature. It was suggested that temperature and food conditions are the most important factors for cladocerans and rotifers (and *E. affinis*), while salinity and predation would be the main factors for the larger copepods (except *E. affinis*) (Viitasalo 1994), which can lead to the conclusion that zooplankton are directly or indirectly highly dependent on hydrographic variations and hence, prone to impacts from climatic change.

4.4 Soft-bottom flora

The soft-bottom flora consists of macrophytic vegetation (both phanerogams and algae) that functions as important primary producers, nutrient cyclers and habitat facilitators (e.g. Munsterhjelm 2005, Ehlers et al. 2008). Soft-bottom vegetation assemblages serve as important reproduction areas for many coastal fish species (e.g. Snickars et al. 2009). Changes in the soft-bottom macrophyte community can be caused by natural succession due to e.g. land up-lift and accumulation of sediments or by anthropogenic influence like eutrophication and mechanical disturbance (Munsterhjelm 2005). Additionally, light, temperature, wave exposition and salinity are generally considered essential for coastal aquatic vegetation (Raffaelli & Hawkins 1996). Macrovegetation competes with phytoplankton for nutrients and light, which might in shallow soft-bottom areas lead to alternative stable turbid (phytoplankton dominated) or clear (macrophyte dominated) states and thus affect the macrophyte community and its surroundings (Blindow et al., 1993). Long-term surveys from the Baltic Sea coasts have shown changes in the macrophyte community due to patterns in salinity as well as ice conditions (Kovtun et al. 2009) and because of eutrophication effects (Blindow 2000), while experimental studies have proved negative effects of rising temperature on the only marine seaweed in the Baltic, the eelgrass (*Zostera marina*) (Ehlers et al. 2008).

Soft-bottom macrovegetation has been well studied in the coastal western GoF, starting from the early pioneering work of Häyrén (1912) followed by Luther (1951a,b), continuing to the more recent studies, where also long-term surveys are included (Munsterhjelm 1985a,b, 1987, 2005, Heinonen 1986, Oulasvirta & Leinikki 1993, 1995, Wallström et al. 2000, Boström et al. 2002, Peuraniemi 2005, Ranta 2005, Henricson et al. 2006, Pitkänen 2009, Rosqvist et al. 2010). The studies conducted by Munsterhjelm (2005) use recent long-term observations (1978–2003) as well as all available earlier documentations from the area to identify and describe occurred changes in the soft-bottom macrophyte assemblages. In these studies declines were found in several charophyte species and especially in the stonewort *Chara tomentosa* from sheltered areas. Most of the decrease had already occurred in the 1960's probably as a consequence of eutrophication, while some decline took place not until the 1980's mainly due to mechanical disturbance (dredging, motorboating, etc.). Simultaneously, turbidity (due to increase in phytoplankton) and filamentous algae increased which attenuated the light conditions and thus was considered the main reason for the declines in charophytes. The decline, in terms of disappearance and decrease in coverage, in *C. tomentosa* and in other charophytes was replaced by other species (e.g. *Myriophyllum spicatum*, *Ceratophyllum demersum*, *Vaucheria dichotoma* and *Potamogeton pectinatus*) with higher tolerance for eutrophication effects such as turbidity. Another study from the middle archipelago area looked for changes in the macrophyte vegetation over a 70-year period by comparing the results from Luther (1951a,b) with recent observations (Pitkänen 2009). The main findings were: the depth distribution of macrophytes in general has declined; eutrophication-favored species like *M. spicatum*, *C. demersum* and *Ranunculus circinatus* have increased, while species like *Eleocharis acicularis*, *E. parvula*, *Ranunculus reptans* and *Potamogeton filiformis* have decreased; eight species earlier present were now absent, such were e.g. *Limosella aquatic* and *Callitriche hermaphroditica*; and the common reed *Phragmites australis* has increased and expanded in coverage considerably, probably due to eutrophication. Some long-term changes have also occurred in the outer areas, where for example *M. spicatum* has increased in eelgrass meadows since the late 1970's (Munsterhjelm 2005). In another study from an eelgrass meadow, comparing results from 1968–1971 to more recent (1993) results, no clear changes neither in the macrophyte assemblage nor in *Z. marina* biomass could however be found (Boström et al. 2002).

4.5 Hard bottom flora

Hard-bottom flora comprises all the macrophyte vegetation living on rocky shores or other hard substrates and consists of annual and perennial green, brown and red macroalgae (e.g. Eriksson & Bergström 2005). The macroalgae serves as food and shelter for invertebrate epifauna as well as shelter and breeding ground for fish species (e.g. Oulasvirta et al. 1985, Schaffelke et al. 1995). One of the most important species in the rocky shore macroalgal assemblage is the marine bladderwrack *Fucus vesiculosus*, which is the only perennial brown macroalgae in the Baltic Sea, constituting a major part of the total benthic plant biomass (Katsky & Kautsky 1995). *F. vesiculosus* is limited by light and salinity and affected by wind explosion and eutrophication (Kiirikki 1996, Ruuskanen 2000). Eutrophication is known to have affected *F. vesiculosus* negatively in the Baltic Sea by decreasing the maximum growth depth (e.g. Kautsky et al. 1986) as well as by locally causing complete disappearance (e.g. Kangas & Hällfors 1985). This

was due to increased eutrophication, i.e. elevated nutrient concentrations, which stimulated the growth of filamentous algae and epiphytes (Ruuskanen 2000). The increase in filamentous algae benefited invertebrate grazers developing also a bigger grazing pressure on *F. vesiculosus* that already were suffering from the shading effect from the epiphytes.

Studies on the hard-bottom macrophyte assemblage in the coastal western GoF have been conducted by Kangas et al. 1982, Hällfors et al. 1984, Russel 1985, Kangas & Hällfors 1985, Bäck et al. 1992, Kiiirikki 1996, Ruuskanen 2000, Holmberg & Jokinen 2004, Ranta 2005 and Pitkänen 2009. The study of Pitkänen (2009) is the same already described in the previous section of soft-bottom flora. The results of this survey, concerning the hard-bottom vegetation, revealed that the present *F. vesiculosus* occurrence did not differ markedly from the earlier situation, despite other factors still indicating ongoing eutrophication effects. This result could confirm the general development of a recent recovery after the declines in the 1980's and 1990's seen in other Baltic Sea coastal areas (Nilsson et al. 2005), thus suggesting the possibility of locally enhanced water quality in the area. Monitoring studies from 1986 to 2003 in the area around the SW Hanko peninsula showed a slight general increase *F. vesiculosus* and a general decrease in the amount of eutrophication favoured *Chorda filum* brown algae as well as in the green algal *Enteromorpha* species (Holmberg & Jokinen 2004). However, the red algae *Ceramium tenuicorne*, an indicator species for good water quality, has decreased both in the outer and the inner hard-bottom areas (Holmberg & Jokinen 2004, Ranta 2005).

4.6 Soft-bottom zoobenthos

Soft-bottom zoobenthos comprises all the invertebrate fauna living both in (i.e. infauna) as well as at the surface (i.e. epifauna) of the bottom sediment (e.g. Karlson et al. 2002). Benthic fauna serve as food for many fish species as well as facilitate important biologic-chemical processes such as mineralization of settling organic matter and nutrient fluxes between water and sediment (e.g. Conley et al. 2009). Soft-bottom zoobenthos follows a natural succession over a gradient of depth and distance from mainland (Bonsdorff et al. 2003). Beside of that, the large-scale distribution of soft-bottom macrofauna in the open Baltic Sea is mostly affected by the combined effects of salinity, oxygen concentration and the organic matter content in sediments (Laine 2003), while the local distribution in archipelago areas are determined by the same factors except of salinity and with the addition of temperature (Bonsdorff et al. 2003). The responses to different environmental disturbances vary between different benthic taxa (Norkko et al. 2010), but generally the zoobenthic community is strongly harmed by oxygen depletion in many areas reaching from stratified deep-water bottoms (e.g. Laine et al. 2007) to shallow bays covered by hypoxia causing drifting algae (Norkko & Bonsdorff 1996a,b). Changes in macrozoobenthos in Baltic Sea coastal areas have been linked to local eutrophication effects (Perus & Bondsdorff 2004), such as e.g. nutrient loads from fish farms (Kraufvelin et al. 2001).

Soft-bottom zoobenthos have been studied thoroughly in the coastal areas of the western GoF, starting with the early pioneering works of Segerstråle (1933a,b, 1937) and continuing more recently with field studies, experiments and monitoring (Karjala &

Lassig 1985, Pekkarinen 1986, Sarvala 1986, 1987, Aschan 1990, Uitto & Sarvala 1991, Lindström & Fortelius 1992, Norkko et al. 1993, 2010, Englund & Heino 1994, Miettinen 1994, 1998, Bonsdorff et al. 1995, 2003, Stigzelius et al. 1997, Kangas et al. 2001, Kotta et al. 2004, Holmberg et al. 2008, Saarikari & Miettinen 2008, Valanko et al. 2010). A survey of a long-term (1964–1997) bottom fauna dataset from Tvärminne Storfjärd (20 m depth) showed considerable changes in the species composition, abundances and biomasses for the zoobenthic community during the study period (Kangas et al. 2001). The population of the amphipod *Monoporeia affinis* was strong until the 1970's but severely decreased thereafter to become nearly absent in the late 1990's, whereas the bivalve *Macoma balthica* and the priapulid *Halicryptus spinulosus* increased since the 1980's. *M. balthica* started to dominate, especially considering the biomass, since the early 1990's. Additionally, the density of the oligochaete worms decreased as from the 1970's, whereas chironomide midge larvae increased in the 1990's. These changes were coupled to the combination of eutrophication and natural intra- and interspecific regulation (Kangas et al. 2001). Monitoring studies from the outer archipelago area around SW Hanko peninsula showed general decrease in *M. affinis* from the beginning of 1980's to 1993 (Miettinen 1994) and the abundances were still very low (if *M. affinis* occurred at all) throughout a period 2001–2006 (Saarikari & Miettinen 2008). A further comparison between these periods reveals not only the general decrease in *M. affinis* abundances but also suggests that the species have moved out (i.e. disappeared) from the shallower areas, as it earlier was very abundant at all depths down to 24 m but was only found in one occasion from a depth below 24 m during 2001–2006. According to the same monitoring data, *M. balthica* populations have naturally been fluctuating but generally dominating the soft-bottom zoobenthos since the beginning of 1990's. Further, the invasive polychaete *Marenzelleria viridis*, first observed in 1990 (Norkko et al. 1993, Stigzelius et al. 1997), became permanent, rapidly increased and presently is one of the dominating species (Bonsdorff et al. 2003, Saarikari & Miettinen 2008). A similar increasing trend for *M. viridis* was also found in the monitoring of the middle and inner archipelago areas, being the main change seen in those results (Miettinen 1998). A study concerning long-term (1968–71 to 1993) changes in shallow soft-bottom *Z. marina* meadows near Tvärminne, has also been conducted (Boström et al. 2002). The results showed an overall increase in zoobenthos abundance and biomass, mainly attributed to significant increases of *M. balthica*, the *Hydrobia* spp. mudsnails and oligochaetes. In dense *Z. marina* patches the mean number of taxa also increased from 16 to 20. The main cause of all the observed changes in the soft-bottom zoobenthos is suggested to be a combination of eutrophication effects, oxygen conditions and natural variability, but the relative importance of these factors have not been determined (Miettinen 1994, 1998, Kangas et al. 2001, Boström et al. 2002, Saarikari & Miettinen 2008).

4.7 Blue mussels

The blue mussel *Mytilus edulis* (Bivalvia) is generally the most important species in the Baltic Sea hard-bottom zoobenthos and is therefore chosen to exclusively represent the rocky shore faunal community in this review. Blue mussels dominate the hard bottom seascapes of the Baltic, regarding both abundances and biomass, with densities exceeding 0.15 Me m^{-2} on favourable sites (Kautsky 1982) and biomasses constituting 80–90% of the total animal biomass (Kautsky et al. 1990). Because of their dominance,

blue mussels are considered as a keystone species in the Baltic, affecting the state of the entire coastal ecosystem by being important filtrators, food and facilitators (Westerbom 2006). It has been estimated that Baltic blue mussels annually filtrate a water content equivalent to the total volume of the Baltic Sea and thereby reduces turbidity as well as participate in the nutrient circulation (e.g. Kautsky & Kautsky 2000). Blue mussels at all life-stages serve as food for many predators, including the sea ducks and most of the non-piscivore fish (Hairio & Öst 2002, Lappalainen et al. 2004, Westerbom 2006). Furthermore, blue mussels act in the process of structure-forming facilitation (e.g. Westerbom 2006), which generally is considered to be an important mechanism on rocky shores affecting e.g. species diversity, abundance and distribution (Bruno & Bertness 2001). Salinity is the most important abiotic factor driving the dynamics of distribution and abundance (e.g. Westerbom et al. 2002), among other factors like wave exposure (Westerbom & Jattu 2006) and sedimentation (Westerbom et al. 2008). The overall effects of predation and interspecific competition have been regarded negligible, despite abundant molluscivorous vertebrate predators and local outcompeting by the shallow sub-littoral *F. vesiculosus* (Kautsky 1981, Kiirikki 1996). Intra-specific competition can, however, be an important factor controlling the blue mussel in crowded areas (Kautsky 1982). The depth distribution of blue mussels in the northern Baltic Sea is limited only by suitable substrate, whereas no major invertebrate predators exist (Westerbom 2006).

Some surveys concerning blue mussels have been conducted in the coastal areas of the western GoF (Sunila 1980, 1981, Öst & Kilpi 1997, Pimiä et al. 1998, Lappalainen et al. 2005, Westerbom 2006). Studies from the Tvärminne area have shown considerable changes in the blue mussel population (Westerbom 2006). Abundances, measured as mean density, first strongly increased from 1997 to 2001 and then decreased with slight fluctuations until 2006. The mean biomass has changed likewise, rapidly increased from the lowest values in 1997 to the highest in 2000 where after a decreasing trend occurred until 2005. The rapid increase in the blue mussel population was caused by a strong pulse of new recruits preceded by exceptionally high spring water salinity in 1997. However, similar changes were not observed at another sampling site west of Hanko, where the population seemed to be quite stable with a constantly high biomass (Westerbom 2006). The difference between the two sampling sites could though possibly be explained by the fact that the site west of Hanko is located in proximity to the open sea and hence; has a better import supply of mussel larvae from other regions via an offshore larval pool (Westerbom 2006), is to a lesser extent negatively affected by sedimentation due to less turbidity and a greater exposure to wave action (Westerbom & Jattu 2006, Westerbom et al. 2008), and is less affected by fish predation which is locally substantial in the archipelago areas with abundant cyprinid populations (Lappalainen et al. 2005). Bottom fauna surveys from 1973–1993 in the outer archipelago area around SW Hanko peninsula noticed substantial inter-annual fluctuations in blue mussel abundances but no clear trend what so ever (Miettinen 1994). A plausible assumption of a long-term change in blue mussel size distribution has been presented from Tvärminne (Öst & Kilpi 1997). This assumption rests upon an observed diminished mussel size from 1978–1979 to 1996, linked to salinity decline and selective predation from the common eider (*Somateria mollissima*).

4.8 Fish

Fish are important consumers in coastal ecosystems, populating a broad range of different habitats, from littoral to benthic to pelagic environments, from sheltered to exposed areas and from the inner to the outer archipelago (e.g. Koli 1990). The coastal areas of the northern Baltic Sea inhabit both marine and freshwater fish species, but are dominated by the latter group (Nellen & Thiel 1996, Lappalainen et al. 2000). Fish are in general economically important for human fisheries but also ecologically of even greater importance through crucial functions providing the maintenance of a natural balance in the ecosystem (e.g. Pauly et al. 2005). Fish affect the ecosystem by being both prey (for other fish, seabirds and marine mammals) and predators (for zooplankton, benthic invertebrates and other fish) (Koli 1990, Froese & Pauly 2009), and further through effective habitat coupling due to their mobility (Polis et al. 1997). The distribution and success of fish species are dependent on both abiotic (e.g. temperature, salinity, oxygen and turbidity) and biotic (e.g. prey availability, concurrence, predation, life histories) factors (Fréon & Misund 1999) of which salinity and temperature are considered the most important determinants for coastal fish species in the Baltic Sea (e.g. HELCOM 2006). Anthropogenic factors with impacts on the structure and dynamics of the fish community are e.g. fisheries and eutrophication (Bonsdorff et al. 1997b, Ådjers et al. 2006). Recently reported changes in coastal fish communities comprise for instance increases in roach and perch populations along the Finnish coast probably as an effect of eutrophication (Ådjers et al. 2006), but also severe recruitment failures of coastal fish species along the Swedish coast possibly caused by altered zooplankton food availability (Nilsson et al. 2004).

Fish species and the fish community have been studied in the coastal western GoF by Koli et al. 1985, 1988, Oulasvirta et al. 1985, Rask 1989, Sundell 1994, Lappalainen et al. 2000, 2001, 2004, 2008, Lappalainen & Urho 2006, Engström-Öst et al. 2005, 2007, Lehtiniemi et al. 2005, Westerborn et al. 2006, Candolin et al. 2007, 2008, Engström-Öst & Mattila 2008, Härmä et al. 2008, Lehtonen et al. 2009, Salonen et al. 2009, Kallasvuo 2010, Salonen & Engström-Öst 2010. The results from a gillnet fish sampling survey comparing catch data from 1975 and 1997, showed a pronounced increase in the roach (*Rutilus rutilus*) population, attributed to eutrophication effects (Lappalainen et al. 2001). In the same study perch (*Perca fluviatilis*) catches were unchanged but flounder (*Platichthys flesus*) had decreased. The growth rate of adult roach had also decreased, possibly as a consequence of increased intra-specific concurrence. A survey concerning long-term (1939–2007) changes in the pike (*Esox lucius*) catches from an outer archipelago area showed a drastic decrease since the beginning of the 1980's (Lehtonen et al. 2009). This decrease was attributed to large-scale eutrophication mediated environmental change and consequent changes in water turbidity and macro-vegetation as well as in food availability and quality. According to catches and fish stock estimations from local fishermen, cyprinid fish in general and bream (*Abramis brama*) in particular have increased from 1995–1999 to 2007, probably because of eutrophication effects and possibly also due to the slight decline in salinity (Valjus & Holmberg 2010). Decreased fish species were especially flounder, perch and herring.

4.9 Birds

Seabirds and coastal birds constitute an important part of marine and coastal ecosystems, usually as predators at the top of the food chain (Rönkä 2008). They are connected to the ecosystems at several trophic levels (Tasker and Reid 1997). Seabirds and coastal birds constantly live in proximity to the water, generally obtaining their food therefrom, and comprise major groups like the gulls (Laridae) and seaducks (Anatidae). Seabirds and waterfowl in the Baltic Sea feed on e.g. molluscs and fish (Öst 2000, Svensson et al. 2006) and thereby affect the sea-ecosystem. Birds are obviously not directly concerned of the hydrographic conditions in their surroundings, but do indirectly depend on water temperature, salinity, etc. through effects on the water living prey organisms (e.g. Westerborn 2006). However, changing air temperature can influence birds directly (e.g. through increased nestling survival) or through other patterns coupled to mildness of the winter, ice break-up and onset timing of the spring (e.g. Lehikoinen 2009). For example, advancement in spring arrival have generally been observed among migrating birds (Jonzén et al. 2006), potentially leading to implications such as e.g. mistiming in breeding (Lehikoinen 2009). Additionally, the mildness of the winter and early ice break-up favours many waterfowl species, whereas eutrophication affects negatively some of the species (Rönkä et al. 2005). Other anthropogenic activities, like pollution and hunting, can also influence different sea- and coastal birds (e.g. Rönkä 2008). The overall long-term development of some of the main sea- and coastal bird groups reveals a constant increase in the sea-ducks and in the gulls from the 1930's to 1990, where after the gulls continue to increase but the sea-ducks abruptly decrease until 2000 as a consequence of population decline in the common eider *S. mollissima* (Hario & Rintala 2008).

Studies concerning sea- and coastal birds have frequently been conducted in the coastal areas of western GoF (Kilpi & Lindström 1997, Öst 2000, Kilpi et al. 2001, 2003, Hario & Öst 2002, Öst et al. 2002, 2003a,b, 2005, 2007a,b, 2008a,b, Öst & Bäck 2003, Jonzén et al. 2006, Lehikoinen et al. 2006, 2008, Steele et al. 2007, Hario & Rintala 2008, Waldeck et al. 2008, Öst & Steele 2009, Jaatinen et al. 2010), including also the monitoring activity of HALIAS. During the period 1986–2007 a large-scale decline in the common eider populations along the entire S coast of Finland including the western GoF has been obvious since 1990–1995 (Hario & Rintala 2008, Nevalainen 2010). This development could be an effect of the climate change affecting indirectly through food availability of the eiders (Westerborn 2006). A survey concerning the common eider migration data from 1979–2004 at the SW end of Hanko peninsula showed a strong positive trend towards earlier migration over the time period, as a result of milder winters and advanced ice-break (Lehikoinen et al. 2006). Breeding adult common eider females have suffered from increased predation induced mortality in the Tvärminne archipelago during 1990–2006, which could explain the observed (during the period 1979–2005) shifting trend towards male bias in the sex ratio of migrating eiders and the decline in overall breeding success (Lehikoinen et al. 2008). A highly obvious change since the 1990's is also the rapid population increase in the great cormorant (*Phalacrocorax carbo*), which can probably be attributed to eutrophication through increased production of roach and other prey, and of course to an overall strengthening of population size in Europe (Lehikoinen 2005, Nevalainen 2010). Additionally, HALIAS bird observation data from the SW end of Hanko peninsula during 1979–2007, considering the yearly amounts of spring and fall migrants for numerous species, are

available as a graphic tool on the VACCIA internet site of Tvärminne Zoological Station (Nevalainen 2010).

5 Synthesis

5.1 Difficulties interpreting climate change effects

Many natural and human mediated forces act upon the Baltic Sea ecosystem, continuously changing both abiotic and biotic conditions. It would be convenient to be able to separate the anthropogenic changes from those occurring naturally as an ongoing succession after the last ice-age or as a result of normal climatic fluctuations (HELCOM 2007). This is, however, a difficult if not an impossible task to accomplish, because both the causes behind the changes and the changes themselves are interconnected in complex manners depending on causalities and interactions. Thereby it is also a great challenge trying to distinguish between the effects of the two major topical driving forces, i.e. eutrophication and climate change. Eutrophication cannot affect climate change, but the opposite interaction is possible and probable. Enhanced river runoff due to climate induced precipitation increment increases the nutrient load to the sea, thus aggravating the state of eutrophication, leading to more primary production that sedimentate to the sea floor, consumes the oxygen and causes hypoxia. Hypoxia influences negatively the biota and attenuates the nutrient mineralization processes, causing a vicious circle of eutrophication. Moreover, the river runoff also flushes organic matter to the sea, which ultimately also enhances eutrophication through increased oxygen consumption and hypoxia related nutrient release from bottom sediments. However, the river runoff consists of freshwater, thus diluting the seawater salinity, which again reduces the stratification and thereby enhances the mixing of the water column, finally leading to better near-bottom oxygen conditions. All these intermediate stages of the eutrophication process and the direct climate change effects affect the biota, which again further interacts with other biota and also back with the abiotic compartment. This description offered possible outcomes for the interplay between eutrophication and climate change, illustrating the complex reciprocal nature of these forces in the current state of the Baltic Sea. Thereby let us conclude that climate change impacts on the ecosystem can be observed both as direct effects (e.g. through weather, temperature and salinity) and as indirect eutrophication induced effects, even if the relative significance of the directly human induced (not primarily climate change forced) eutrophication and the climate forced eutrophication cannot be interpreted.

5.2 Major changes and possible consequences

The major abiotic climate induced changes in the study area were the slight decrease in salinity, strongly increased turbidity, locally more frequent and severe hypoxia as well as the advancement of the ice break-up. The majority of the identified biotic changes were attributed to eutrophication even if no nutrient enrichment had been apparent since the late 1980's. Some changes in zooplankton, zoobenthos and birds were coupled with

temperature, whilst the salinity decline was linked to changes in zooplankton, blue mussel and fish, these being the only directly climate forced changes observed.

5.2.1 Bacteria

Even if no documented changes in the aquatic bacterial community were found, the climate change still could induce severe alterations in the nutrient-phytoplankton-bacteria balance. There is a competition between bacteria and phytoplankton for inorganic nutrients (Chrzanowski et al. 1995), but during normal conditions phytoplankton tend to win that battle. However, the situation might become different with the changing climate. Climate forced increase in temperature and in carbon rich runoff may benefit the bacteria before the phytoplankton, especially in early spring. Bacterial production grows with temperature and the availability of carbon substrate (Autio 2000, Hoikkala et al. 2009), while phytoplankton are not that temperature-favoured and will probably suffer from the increased turbid runoff (HELCOM 2007, Sommer & Lengfellner 2008). If bacteria could better utilize the available nutrients in the spring before the phytoplankton, they would then possibly competitively suppress the phytoplankton growth. Since the initiation of spring time phytoplankton bloom is light-limited and if the phytoplankton at the same time suffers from elevated temperatures (Sommer & Lengfellner 2008), then the effects could be detrimental. This could lead to a dominance shift from phytoplankton production to bacterial production in near-coast systems, with oxygen depletion (from bacterial oxygen consumption) (Tuomi et al. 1999) and food-web cascades (shortage or poor quality of phytoplankton as primary food source for zooplankton, and so forth) as a consequence.

5.2.2 Phytoplankton

The major change found in phytoplankton is the shifting trend in the phytoplankton maximum from the spring bloom towards late summer, which could be a change of great influence on the whole ecosystem and the coastal production (Raateoja et al. 2005). The reason for this shift is the change in the nutrient balance and especially the availability of nitrogen, possibly due to reduced vertical mixing in the spring. A potential absence of a spring turnover would be the result of milder winter temperatures affecting the temperature dependent water density (crucial for vertical mixing) and the stabilisation of the water column through the severity of the ice conditions (HELCOM 2007). The reduction in the spring phytoplankton production could cascade as production failure through the entire food-web from zooplankton to juvenile fish and further to seabirds.

5.2.3 Zooplankton

The observed temperature and salinity induced shifts in the zooplankton community can have affected their predators, i.e. mainly zooplanktivorous fish (e.g. herring (*Clupea harengus*) and any juvenile fish), in terms of changes in food availability and food quality (Viitasalo 1994). Such changes have been seen in the open Baltic Sea, severely impacting sprat (*Sprattus sprattus*), herring and cod (*Gadus morhua*) stocks, contributing to large-scale ecosystem dominance shifts, with observable changes even in the condition of seabirds (Österblom et al. 2006, 2007).

5.2.4 Soft-bottom flora

The major changes found in the soft-bottom macrofauna were the sharp turbidity induced decline in charophyte vegetation (especially *Chara tomentosa*) in shallow areas and the expansion of the common reed *P. australis*, which both are effects of eutrophication but possibly even influenced by turbid runoff (Munsterhjelm 2005). The decline in the charophyte vegetation indicates worsened water quality and likely involves the disappearance of important reproduction areas of many fish species. The ongoing expansion of the reed belts is poorly studied and documented, even if it is a common development along the entire S and SW coast of Finland (Roosaluste 2007). Dense reed belts are important and favoured reproduction areas for many freshwater fish species, e.g. pike *Esox lucius* as well as roach and other cyprinids (Kallasvuo 2010). The reproductive success of roach is especially susceptible to salinity (preferably < 4 psu), which makes it strongly dependent on sheltered, low-saline, reed-covered shores of the innermost bay areas. An expansion of the reed belts could thereby enhance roach production, which has been observed, and alter the dynamics of the coastal fish community thus affecting both upper and lower trophic levels.

5.2.5 Hard-bottom flora

No major long-term changes were observed in the hard-bottom macrophyte assemblage (Pitkänen 2009). There has though most likely been a decline in both the horizontal and vertical distribution of the bladderwrack *F. vesiculosus* in 1980's and 1990's, in accordance with the widely observed general pattern along the northern coasts of the Baltic Sea, followed by a more recent recovery (see Nilsson et al. 2005). A recovery of the bladderwrack could indicate a slight enhancement in water quality and could implicate a revival of important habitats for several fish species in the middle and the outer archipelago (see Lehtonen et al. 2009 and references).

5.2.6 Zoobenthos

The major change in zoobenthos has been the eutrophication mediated strong decrease of the amphipod *M. affinis* and the increase and dominance takeover of the bivalve *M. balthica* (Kangas et al. 2001, Saarikari & Miettinen 2008). Simultaneously a successful invasive polychaete *M. viridis* has increased and is spread over vast areas in the coastal western GoF as well as in other areas. These major changes in the zoobenthos can affect other trophic levels through altered feeding conditions for the benthic predators (mainly fish). Different bottom fauna species comprise also different functions, e.g. different degrees of bio-turbation affecting benthic sedimentation, oxygenation and nutrient fluxes.

5.2.7 Blue mussel

The blue mussel, *M. edulis*, populations have decreased in the coastal areas of western GoF since year 2000, probably as a consequence of salinity decline and possibly further due to increased sedimentation and increased predation pressure from adult roach (Westerbom 2006), which can be considered as a major change with potentially large implications for the whole ecosystem. Firstly, a decline in the blue mussel populations would obviously severely reduce the water filtering function supplied by this organism, which could further aggravate the already strongly turbid state of the coastal waters. Secondly, the decline in blue mussels would affect the facilitating function provide in

the otherwise bare rocky bottoms and cliffs. Thirdly, many fish species, particularly specialist feeders e.g. the flounder, would endure a loss if the blue mussel population decreases. Fourthly, the common eider, being a blue mussel specialist feeder, would suffer from reduced blue mussel availability.

5.2.8 Fish

The main changes in the coastal fish community in the study area comprise a strong increase in cyprinid fish species, especially regarding the roach and bream (Lappalainen et al. 2001, Valjus & Holmberg 2010). Furthermore, a decrease in the flounder as well as the pike (Lehtonen et al. 2009) populations in the outer archipelago was observed. The increase in roach and bream has been attributed to eutrophication and salinity decline, whereas the decrease in flounder can be an effect of salinity decline and hypoxia in the breeding grounds, or even an implication of reduced food availability on account of decreased blue mussel populations. The decrease in the pike population was a consequence of large-scale eutrophication mediated environmental change, including increased turbidity, impaired state of macro-vegetation and changed food conditions. The increase in roach and other cyprinids will alter the coastal fish community through amplified food competition and through increased prey availability for predatory fish (Kallasvuo 2010). An increased roach population will also affect the zoobenthos and macrophyte epifauna by increased predation pressure, which can cascade further in the food-web and for example lead to mass-occurrences of filamentous macroalgae through the released predation control from invertebrate grazers (Eriksson et al. 2009). An increase in roach predation can further affect the success of the blue mussel populations in the study area (Westerbom 2006), as roach freely can thrive especially in the outer areas in the absence of large predatory fish like pike.

5.2.9 Birds

One major change in the sea- and coastal birds has been the rapid decrease in the common eider population, possibly influenced by the decreased food availability due to the recent reduction of the blue mussel populations (Hario & Rintala 2008, Nevalainen 2010), and the advancement of eider spring migration in relation to temperature increase (Lehikoinen et al. 2006). A second major change is the rapid increase of the great cormorant, which is likely strongly mediated by the enhanced prey fish availability especially due to the abundant roach population (Lehikoinen 2005, Nevalainen 2010). The decrease in the common eider population would obviously affect positively the blue mussels through decreased predation pressure, even if the impact of this release could be minor. The great cormorant eats fish and thus has the potential to locally affect coastal fish populations. The true impact of the cormorant on its prey fish populations is still somewhat unclear, but a highly debated issue.

6 Conclusions

Climate-induced changes in coastal marine ecosystems include both abiotic and biotic changes complexly interconnected with each other and with other ongoing processes descending from additional anthropogenic or natural forcing mechanisms. It is

particularly difficult to distinguish between pure eutrophication effects and the climate induced effects, created or influenced via the mechanisms of eutrophication.

The main findings of this report concerning major potentially climate induced changes in the coastal ecosystem of the western GoF were:

- Slight long-term decline in seawater salinity
- Sharply increased water turbidity
- Advanced sea ice break-up
- Phytoplankton annual biomass maximum shift from spring towards late summer
- Decreased charophyte vegetation in shallow areas
- Increased reed cover and distribution
- Dominance shift in benthos from the amphipod *M. affinis* to the bivalve *M. balthica*
- Increase and a successful spreading by the invasive polychaete *M. viridis*
- Recent decline in blue mussel populations
- Strong increase in roach and other cyprinid fish
- Decrease in pike and flounder in outer archipelago areas
- Rapid decline in common eider population
- Rapid increase of great cormorant
- Advanced spring migration of bird species

Consequently, it can be concluded that several major potentially climate induced changes in the coastal ecosystem of the western GoF have occurred and have been identified. These changes might drastically affect the ecosystem structure, function and services in the coastal areas, and should therefore be noticed, evaluated and incorporated as a basis in management decision-making.

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