Rapport Report

Impact of climate change and ocean acidification on ocean-based industries and society in Norway

Observed and future impacts, mitigation and adaption actions

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Summary

This report presents a review of the scientific literature on how key ecosystems, ecosystem services and ocean-based industries in Norway are affected by climate change and ocean acidification today and under future scenarios. The project has also compiled knowledge on how ocean-based actions can help mitigate and reduce the magnitude of climate change, ocean acidification and environmental problems. Further possible trade-off related to ocean-based action were identified as well as how climate change and ocean acidification may potentially affect these ocean-based opportunities. Finally, the report presents published findings on possible future impacts on society and implications for policy and management.

The literature review has revealed that there are **already observed effects from climate change and ocean acidification on ocean-based industries**. Future impacts on ocean-based industries will be related to physical and biophysical changes and the ecological effects of climate change and ocean acidification. The extend of these impacts will depend on what greenhouse gas emission scenarios will be followed. **Impacts are projected to be more or less severe depending on human's ability to apply mitigation** (actions that are taken to reduce and curb greenhouse gas emissions) and **adaption** (actions that are based on reducing vulnerability to the effects of climate change).

While changes in human behaviour and ambitious mitigation and adaption are all needed, **the ocean provides major opportunities** both by mitigation and adaption actions **to reduce climate change and ocean acidification** globally and their associated impacts on vital ecosystems, ecosystem services, ocean-based industries and societal goals. However, climate and ocean acidification related impacts on ocean ecosystems and ecosystem services will reduce ecosystems ability to provide local solutions and possibilities for action.

Ocean-based industries sensitive to climate change and ocean acidification such as fisheries and aquaculture, oil and gas deposits as well as maritime industry, **provide the basis of much of the industrial production and employment in Norway**. Therefore, socio-economic consequences of climate change and ocean acidification will be dependent on the ability to quickly implement mitigation and adaptation strategies within the country. Literature on how society will be affected is scarce, however some studies have shown that **choosing a more sustainable option vs a "a business as usual" emission scenario will be economically valuable to society**. However, this value may not benefit this generation, and the next generation might stand to lose, while generations beyond will clearly gain.

None of the present mitigation efforts in operation will prevent climate change and ocean acidification to occur within the next few decades due to the time lag of the effects. Consequently, implementation of **adaptation is critical to minimize the negative impacts and reduce societal vulnerability**. Norway is perceived to be well prepared to adapt to both gradual and abrupt changes in climate and ocean acidification, as it scores well on a number of factors associated with adaptive capacity including "wealth, technology, education, information, skills, infrastructure, access to resources, and management capabilities". However, it is underlying social and economic conditions that shape adaptive capacity. The adaptive capacity is not equally distributed in society and **vulnerability to climate change and ocean acidification is highly differentiated between regions and sectors in Norway**. These barriers to adaptation may exacerbate negative impacts in certain sectors and regions. It has overall been shown that well planned, early adaptation action saves money and reduce impact on society.

Norway as an "ocean nation" has a range of emerging ocean-based industries. However, the level of development of these new industries is low, and recent literature suggests that ocean-based actions

needs to be scaled up. However, for these industries to grow, present and future challenges must be addressed and considered. If **new and current industries should be scaled up** this must be done **in an environmentally sustainable way**, as ecosystems are already under pressure from numerous of human activities.

Literature suggests that there are many controversies and uncertainties around many of the current ocean-based solution measures and new ocean-based industries. There is a **need for a better scientific understanding of the costs, benefits and suitability of different governance arrangements to inform political decision making**. Several scientific studies highlight the **need for urgent investments in local, regional, and global ocean research, monitoring, and observing systems** to help detect and project threats related to climate change and ocean acidification on ocean industries and society. Among the suggestions for research priorities, a better understanding of the ocean's role as a major carbon sink, how to develop "climate-ready" fisheries and how to improve nature-based approaches to adaptation. Scientists also point to the need for more robust ocean observation systems (including the Global Ocean Observing System and the Global Ocean Acidification Observing Network), mechanistic understanding of the impact on species and ecosystems, technology development and policy development for ocean actions.

As there potentially are many societal challenges related to solutions, the science community also highlight the need for a **greater involvement from the social sciences in order to understand factors that hinder or promote effective and fair governance of ocean-based solutions and new ocean-based industries**. For society to effectively implement ocean solutions and manage climate change and ocean acidification impacts, it is important to recognize the need to mitigate and adapt. Literature suggests that this requires **increased ocean literacy and an efficient and targeted communication strategy** to prepare the public toward changes in behaviour as well as acceptance to policy changes. Citizens' ocean literacy is the "understanding of the ocean's influence on you and your influence on the ocean". Being ocean literate implies being able to address ocean-related issues in order to develop solutions and actions adapted to our culture and values. This requires knowledge about what hinders and drives collective action and adaption. A collective action problem is normally described as a situation in which short-term self-interest conflicts with longer-term collective interests, generating a substantial risk that the collective benefit is not produced at all. This is crucial for a balanced consideration of new ideas, reducing social conflicts, and to provide politicians and managers with a robust knowledge base for decision-making.

Finally, literature suggests that it is key that **scientists effectively engage with the general public and decision makers**, especially discussing the potential feasibility, trade-offs and social preferences of specific measures and industries, and the consequences of failing to deploy solutions on time. This will simplify the development of a mutual understanding of problems and solutions as well as avoiding the confusion and misunderstanding regarding the realized and future impacts of climate change and ocean acidification on the ocean, ocean industries and society.

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Preface

The Norwegian Environment Agency is working on commissions from the Norwegian Ministry of Climate and Environment (KLD) to compile knowledge on the effects of climate change and ocean acidification on ocean, coasts, ocean-based industries and society. The Norwegian government has expressed a need for a good and comprehensive assembly that summarizes the part of the extensive literature on the subject that is of relevance to Norway. The Norwegian Environment Agency asked for a literature study specifically including the following themes:

1) **How effects of climate change and ocean acidification influence society and ocean-based industries in Norway**. This should include both documented consequences of climate changes and ocean acidification on ocean-based industries as well as future consequences expected under different future emission scenarios.

2) **The ocean as a contributor to address climate change.** As the Norwegian Environment Agency states: "What does the knowledge base say about how the ocean and the ocean natural resources can contribute to solve environmental problems and climate change. And how do climate changes and ocean acidification influence these possibilities?"

3) A summary of the most relevant knowledge on the **most relevant findings to consider effects of climate changes and ocean acidification** in a Norwegian social perspective.

4) A summary of the **most important knowledge gaps** on how climate change and ocean acidification influence ocean-based industries in Norway.

This present report is the product of this project. It was funded by The Norwegian Environment Agency and was led by Akvaplan-niva in cooperation with Sam Dupont at the University of Gothenburg.

The report aims at providing a summary of the relevant scientific literature on the present and possible future effects of climate change and ocean acidification on ocean ecosystems and ocean-based industries in Norway. The report also presents information on how ocean-based actions can help mitigate and reduce the magnitude of climate change and ocean acidification. It identifies trade-offs that needs to be considered while investigating their potential, today and under future scenarios. Finally, it summarizes the relevant literature on possible future impacts on society as well as implications for policy and management. This report also highlights the most important knowledge from the last years assessing socio-economic effects from climate change and ocean acidification in Norway. Based on these findings, this report aims at identifying knowledge gaps and future research needs.

It must be pointed out that this report is not an exhaustive literature review given the short time frame of the project (approximately six weeks) and the broad research area. The report can be described as a fast report based on a critically selected literature representative of the subject.

This report provides a basis for the identification of national and international research priorities and science-based decision making as well as keys to allow Norway to reach its goal of being a modern and responsible ocean nation.

Trondheim 30.11.2019

Maj Arnberg

Project manager

1 INTRODUCTION

The world's oceans and coastal areas are changing due to man-made greenhouse gas emissions (IPCC 2019). The target of the Paris Agreement of limiting global surface warming to 1.5-2 °C as compared to pre-industrial levels will still heavily impact the ocean (Gattuso et al. 2018). Oceans represent a vital part of the global ecosystem. It hosts a large proportion of the biodiversity, plays a major role in regulating the weather and climate of the planet, is vital to the world’s economy, directly and indirectly impacts our health, and contributes to food security. Oceans provide us with a multitude of goods such as food, energy, carbon storage, medicines and recreational services including swimming, boating and wildlife watching. Our welfare and well-being depend on these goods and services, often labelled ecosystem services.

Severe impacts on key marine ecosystems and ecosystem services are expected as a response to the future increase in global mean temperature and concurrent ocean acidification, decline in oceanographic oxygen content and sea-level rise (Hoegh-Guldberg et al. 2014, Pörtner et al. 2014, Gattuso et al. 2015, Nagelkerken and Connell 2015, IPCC 2019). These impacts will depend on the carbon dioxide (CO_2) emission scenarios and will be worse under a high emissions scenario than with a scenario that limits the temperature increase to 2°C relative to the pre-industrial levels (Bopp et al. 2013). In addition, the world's oceans and coastal zones are under pressure due to other environmental influences such as the decrease in marine biodiversity and stressors like pollution and littering, increasing the overall strain on the ocean ecosystems and the ecosystem services they provide. Ecosystem services form the basis for value creation in several of the ocean-based industries and impacts on these ecosystems will have consequences for these industries.

The key question is: What will our emissions of CO_2 and other pollutants be in the years to come? To keep the global temperature increase below 2°C in 2100 relative to pre-industrial level, and to reach the targets of the United Nations Sustainable Development Goals, the emission pledges made under the 2015 Paris Agreement are insufficient (Rogelj et al. 2016). Emissions are depending on human’s ability to apply mitigation (actions that are taken to reduce and curb greenhouse gas emissions). On the other hand, adaption strategies are actions that aim at reducing vulnerability to the effects of climate change and ocean acidification. Increased ambition and additional actions are therefore required to limit the temperature below 2°C and limit the impacts at the local scale (Gattuso et al. 2018).

Policy responses to climate change and its impacts have largely been focused on land-based actions (Field and March 2017) and relatively little attention have been given to the potential for ocean-based action (Rau 2011, Billé et al. 2013). Ocean- based actions are ocean-related climate mitigation and adaptation measures such as protection of mangroves, tidal marshes, and seagrasses that are critical to global carbon sequestration and storage. The ocean is already absorbing about 25% of the anthropogenic CO_2 emissions (Le Quéré et al. 2018) and it has the potential to remove and store much more (Rau 2014). The magnitude and rate of ocean warming, ocean acidification, sea-level rise and their subsequent impacts on ocean ecosystems could be reduced significantly by ocean-based actions. Ocean-based actions could also play an important role in reducing global warming and its impacts on land. They can also play a role in a greater utilization of marine and coastal resources in order to achieve the UN's sustainability goals related to food, energy and health.

All these measures have trade-offs, and there may be associated risks to ocean life and people. Presently, there is a lack of guidance for prioritising ocean-based interventions since there have been relatively little research and development in this field (Gattuso et al. 2018). There is therefore a need for a comprehensive assessment of their potential, including issues like effectiveness in countering changes in climate drivers and impacts, possible spatial and temporal scales of deployment, associated positive and negative climate, environmental, economic and societal impacts (Russell et al. 2012, Gattuso et al. 2018), and implications for ethics, justice and governance (Williamson and Bodle 2016). Many of these factors cannot yet be reliably quantified, however it is important that 'cost' includes both market and non-market values like cultural and recreational values (Williamson and Bodle 2016).

Norway's coastline is one of the longest in the world and Norwegian waters covers an area that is more than five times larger than the land area. Norway is an "ocean nation" and have lived by and of the ocean for thousands of years. Norway is different from most countries having a significant part of its value creation and employment in and in relation to ocean-based industry. The seafood industry, shipping, offshore oil and gas and their associated land-based supplier industries employ hundreds of thousands of Norwegians, and account for almost 70 percent of Norwegian export revenues.

The Norwegian government has great ambitions for an increased value creation from utilizing ocean resources both in existing and emerging industries (Blå muligheter 2019). Among the new ocean industries that are emerging are marine biotechnology, lower trophic level harvesting, biochemicals, bioprospecting, offshore wind, seabed minerals and harvesting and production of new marine species. "The Ocean space" has been highlighted by Innovation Norway, as one of six potential areas for business development and growth. SINTEF, a Norwegian research institution, has estimated that Norway can multiply by five the value creation from the sea by 2050 (Olafsen et al. 2012). Due to its economic reliance on ocean industries, Norway is more vulnerable to negative impacts on ocean ecosystems than many other European countries. A degradation of goods and services provided by the ocean can result in a welfare cost to the Norwegian society. In addition, Norway has an open economy, with a high degree of exports and import of goods and intake factors for domestic production in industries like aquaculture. This means that Norway can also be affected by negative impacts from climate change and ocean acidification in other countries (CICERO/Vestlansdsforskning 2018).

In order to reach the goal of the Norwegian government to be an "Ocean nation" and a responsible manager of the ocean, it is important to use existing knowledge on future effects of climate change and ocean acidification on key ecosystems, ecosystem services and ocean-based industries. Furthermore, it is important to increase our knowledge on how ocean-based action can help address climate change, ocean acidification and their effects on ocean ecosystems, and how these different actions can be affected by future ocean warming and acidification.

Figure 1. Fish in blue mussel (Photo credit: NORCE)

1.1 Aim and structure

The report is divided into eight chapters.

Chapter 1 introduces the subject and the report structure.

Chapter 2 presents projections of regional abiotic effects of climate change and ocean acidification relevant to Norwegian waters. It provides a background to understand how these observed and projected changes in ocean conditions can affect ecosystems and ocean-based industries in Norway.

Chapter 3 is a summary of both observed and possible future abiotic and biotic impacts from climate change and ocean acidification on three main ocean-based industries in Norway: seafood, maritime and petroleum industry. The chapter starts with the methodology and definitions of ocean-based industries and the different categories of the climate vulnerability. This methodology is then used for each industry, summarizing key findings on present and future changes for each climate vulnerability category.

Chapter 4 provides a summary of observed and possible future abiotic and biotic impacts of climate change and ocean acidification on emerging new ocean-based industries.

Chapter 5 describes the ocean as one key to achieve climate and societal goals. Different ocean-based solutions (or action) are presented based on four recent key reports. Their potential, associated challenges and trade-offs are discussed. Finally, knowledge gaps are identified.

Chapter 6 compiles the relevant literature up the impact of climate change and ocean acidification on marine industries and society under different mitigation and adaption scenarios. It also includes a section on future policy and management.

Chapter 7 summarizes the main conclusions, the most relevant knowledge gaps and research needed in the future

This report is based on published peer-review articles as well as grey literature (e.g. reports from consultancy companies, management and industry). Literature was compiled through searches in scientific databases such as the "ISI web of knowledge", “Climate Change Library", "Ocean Acidification International Coordination Centre (OA-ICC) bibliographic database" and “Google Scholar" and through general internet searches. In addition, we performed a search in the project database of the Research Council of Norway (https://prosjektbanken.forskningsradet.no/) as well as relevant other projects such as BIOACID, clime fish and fish exchange. We also collected information directly from Norwegian R&D institutions (see methodology in appendix). Key researchers were contacted, and, in some cases, media articles are mentioned when they directed us to unpublished key findings. Some results and methodology from a survey sent to R&D institutions are presented in the appendix.

2 CLIMATE CHANGE AND OCEAN ACIDIFICATION - ABIOTIC EFFECTS AND REGIONAL CLIMATE PROJECTIONS RELEVANT TO NORWAY

2.1 Regional abiotic climate projections

Climate and ocean acidification risk for ocean-based industry is a product of their effects as well as societal response. Different risk factors apply in different parts of the world. Norway is an elongated country with large local climate differences (Forsgren et al. 2015). It is expected that Norway will experience a warmer and wetter climate due to man-made greenhouse gas emissions with more frequent extreme precipitation events, glacier melting and ocean warming and acidification (Hanssen-Bauer et al. 2017). The level of changes both globally and in Norway will depend on future man-made emissions, the sensitivity of the climate system and future natural climate variations. Impacts will be considerably worse under higher emissions scenario (Bopp et al. 2013). In the fifth report of the UN Climate Panel (IPCC) (IPCC 2014), so-called “development trajectories” or “Representative Concentration Pathways” (RCPs) have been proposed. They describe consequences of different emission scenarios. Development paths under different emission scenarios are largely dependent on the world's population growth, technology development, business development and political framework conditions (Hanssen -Bauer et al. 2015). Three RCPs scenarios (RCP 8.5 - high emissions, RCP 4.5 / RCP 6 - medium emissions and RCP 2.6 - low emissions) are described proposed.

RCP 8.5 - high emissions scenario: Continuous increase in greenhouse gas emissions. This is often referred to as the 'business as usual' scenario as the increase in greenhouse gas emissions is to a large extent following the same development that we have had in recent decades. Under RCP 8.5, global temperature would rise by more than 4°C by the end of the century relative to the preindustrial period.

RCP 4.5 – medium emissions scenario: Stable / slightly increasing emissions till 2040 followed by reduced emissions. This scenario describes an energy efficient world where most countries adopt an ambitious climate policy. Under this scenario, it is estimated that the temperature increase will reach around 2.5°C towards the end of the century, relative to the period 1850-1900.

RCP 2.6 - low emissions scenario: sharp reduction from 2020. This is the only scenario most likely to result in less than 2°C warming by the end of the century.

Present understanding on the relationship between CO_2 emissions and climate does not allow to provide certain projections but gives an indication of how climate is expected to change under different emission scenarios (Flæte et al. 2010, Stocker et al. 2013). According to Hanssen-Bauer et al. (2015), this also apply for the calculations of the future marine climate in Norwegian marine areas.

For this report, we have used models developed for Norway. We used the three RCPs scenarios but mainly focused on the worst-case scenario for the national climate projections (RCP 8).

Rising seawater temperatures due to man-made greenhouse gas emissions, are altering the ocean’s circulation and oxygen levels, melting sea ice, and flooding of coasts (IPCC 2019). In addition, the acidity of the global ocean’s surface waters has increased by 30 % as compared to before the industrial revolution (IPCC 2013). These changes pose a significant risk not only to Norway but to global food security, tourism, transportation, and maritime security and governance (IPCC 2019). Food security is already challenged by increased ocean temperature as marine species distribution is modified (Barange et al. 2018) and tougher weather limits suitable and safe areas for the location of ocean-based aquaculture installations (Barange et al. 2018).

Surface waters (0 to 700 m deep) warmed globally by an average of 0.7°C per century from 1900 to 2016 (Huang et al. 2015). Ocean temperature trends over this period vary in different regions but are positive over most of the globe, although the warming is more prominent in the Northern Hemisphere, especially the North Atlantic (Barange et al. 2018). An increase in surface temperature as a result of global warming and a decrease in salinity due to ice melt and increased rainfall could lead to changes in the vertical stratification or density distribution in the sea (Hanssen-Bauer et al. 2017). The study by Hanssen-Bauer et al. (2017) suggests a general increase in sea surface temperature along the entire Norwegian coast under the scenario RCP 4.5. The largest increase is expected over the next 50 years in the Oslo fjord and Skagerrak, with an increase up to 3-4°C in winter. The North Sea have been thoroughly described and increases by 1-3°C towards the end of the 21st century is projected. In the Barents Sea, a temperature increases by 1 to 2°C is projected for the same period. A climate projection for the ocean areas (for medium emissions) suggests an average warming of surface waters around Svalbard of about 1°C from 2010–2019 to 2060–69.

Lind et al. (2018) shows that a sharp increase in ocean temperature and salinity is apparent from the mid-2000s in the north Barents Sea. Authors suggest that it can be linked to a recent decline in sea-ice import and a corresponding loss in freshwater, leading to weakened ocean stratification, enhanced vertical mixing and increased upward fluxes of heat and salt that prevent sea-ice formation and increase ocean temperature. Lind et al. (2018) suggest that the northern Barents Sea may soon complete the transition from a cold and stratified Arctic to a warm and well-mixed Atlantic-dominated climate regime. Changes in the vertical stratification or density distribution in the Barents Sea may affect many ecosystem processes.

A substantially decreased sea ice concentration in the northern Barents Sea has been observed in the last 30 years (Parkinson et al. 1999). The latest IPCC (2019) report projected reduction in the spread of sea ice in the Arctic towards the end of this century, although the spread in model results from global climate models is large. There are also major differences between runs when different emission scenarios (RCP) are compared. The definition of an "ice-free Arctic" is not the complete absence of ice, but that there is less than 1 million km^2 of sea ice left in the summer (around 17% of observed sea ice in September 2014). Climate models show a large spread in when this can occur; ranging from the year 2011 to 2098 under the high scenario RCP 8.5. In a warming climate, projections from the large ensemble simulation with the Community Earth System Model show a winter ice-free Barents Sea for the first time within the time period 2061–2088. The large spread in projections of ice-free conditions highlights the importance of internal variability in driving recent and future sea ice loss (Onarheim et al. 2017).

Globally, there is a concern for deoxygenation (reduced oxygen concentration due to rising sea temperatures) (Schmidtko et al. 2017) as oxygen is declining in the global ocean and coastal waters (Breitburg et al. 2018). As a result of reduced sea ice, an accelerating trend in the years to come is expected. Less sea ice causes larger amounts of algae and organic matter in the surface water to sink into the deep sea. The algae and organic matter will decay and consume oxygen. A recent study by Aksnes et al. (2019) demonstrates that the oxygen content of a deep fjord, Masfjorden (on the west coast of Norway near Bergen), has dropped over the last four decades. In the same period, the temperature of the oxygen-rich North Atlantic Water (NAW), which ventilates Masfjorden as well as other fjords, has increased by about 1ºC. As a consequence of this warming, NAW has become less dense, and therefore less able to sink and thereby bring new oxygen into the basin of Masfjorden. This suggests that deep Norwegian fjords are prone to a warming-induced decrease in ventilation and associated deoxygenation, Authors concluded that further oxygen decline if NAW becomes less dense a consequence of warming, but an oxygen increase if density should increase.

Marine heat waves can affect ecosystem goods and services, such as fisheries landing and biogeochemical processes (Smale et al. 2019). In the central west Atlantic, the northeast Atlantic and the northwest Pacific Regions rapid increases in the annual number of marine heatwaves (MHW) days overlap with existing high-intensity non-climate human stressors (Smale et al. 2019). These regional pressures include overfishing and pollution. Interaction between regional stressors and MHW will lead to an amplification of impacts.

Increased CO_2 in the atmosphere leads to greater absorption of CO_2 in the oceans. To date, the ocean has absorbed about a quarter of CO_2 emitted to the atmosphere (IPCC 2013). Increased CO_2 concentration in seawater changes its chemical balance and leads to a perturbation of the carbonate system including a lower pH, so-called ocean acidification. The average pH in the surface of the world's oceans has decreased by 0.1 pH unit from around 8.2 before the industrial revolution to the present average of around 8.1 (Orr et al. 2005). The pH scale is logarithmic, so this is a considerable change, corresponding to a 26 % increase in hydrogen ion concentration (IPCC 2013). As cold water absorbs more CO_2 than warm water, ocean acidification is a greater challenge in Norwegian marine areas than in warmer parts of the world.

In the Norwegian Sea, monitoring has shown that the pH values in the sea surface are declining (Skjelvan et al. 2014). In parts of the Norwegian Sea, the pH has decreased by 0.13 units in the sea surface, which is more than the global average decline of 0.1. This corresponds to a 30 percent increase in acidity since the 1980s. A recent study showed that the sea areas west and north of Svalbard absorb more carbon dioxide (CO_2) over the year than they emit (Chierici et al. 2019). Model forecasts also show that the Norwegian coastal areas are sensitive to acidification. Acidification is not only a function of atmospheric CO_2 but also other local sources such as organic carbon and nutrients through run-off from land and aquaculture, as well as increase in supply of fresh water (Dannevig et al. 2019). It was found that areas of the Nordic seas with corrosive surface seawater are increasing.

Towards the end of the century, results suggest an increase of 7% in runoff on an annual basis, especially for the high emission scenario (RCP8.5) (Hansen Bauer et al. 2017). For Norway, increases in runoff are mostly expected in the spring and autumn. In spring, a large increase is expected at high altitudes because of snowmelt shifting from early summer to spring. At low altitudes, spring runoff is expected to decrease, as there will be no snowmelt contributing to spring runoff (Hansen Bauer et al. 2017). Measurements in Oslo have shown that rainfall increased by 18% as compared to 115 years ago. Strongest rain showers occurring in the summer have become almost twice as strong. After heavy rainfall, rivers discharge sewage into the Oslo Fjord, as rains exceed sewage capabilities.

Furthermore, increased runoff can increase a process called coastal darkening. Increased dissolved organic matter of terrestrial origin, also known as browning, has caused the observed reduction in North Sea water clarity in the later years (Opdal et al. 2019). In the future, climate warming is expected to further increase browning in lakes and rivers due to increases in terrestrial greening and leading to increased dissolved organic matter, ultimately reducing water clarity in coastal areas where there are freshwater drains.

For some areas along the Norwegian coast, measurements show moderate sea level rise. For example, the relative sea level is already rising in both Kristiansand and Stavanger (Kartverket 2018). Projections of sea level in Norway indicate for all scenarios that most of Norway will experience an increase in sea level relative to the country level before the end of this century

(Hanssen-Bauer et al. 2015). For scenario RCP 8.5, sea level is projected to increase from 15 to 55 cm, depending on location.

It is uncertain how winds affect the wave height and if storm activity will increase the next hundred years (Hanssen-Bauer et al. 2015). On an annual basis, projections show a very slight decrease in the median value for the wind speed, which is exceeded in 1% of the time for both RCP4.5 and RCP8.5. The trend towards lower values is strongest in spring and summer. In winter, however, there is a tendency for increasing values for both median and high projection. In winter, the entire distribution of winds is shifted towards higher values, while the opposite is the case in spring and summer. For the absolute maximum values there is an increase for all seasons; and for winter and summer an increase of over 20% for some projections (Hanssen-Bauer et al. 2015).

A combination of strongest storms, and increased sea level would lead to an increase in storm surge in most places along the coast, with the largest projected for the Trøndelag coast, Troms and Finnmark (Hanssen-Bauer et al. 2015). Increased storm surge will have an impact on erosion and sediment deposition on the seashore.

The biological implications of the future abiotic effects will be discussed in depth in the following sections describing the present and possible future effects of climate change and ocean acidification on different ocean-based industries.

3 IMPACT OF CLIMATE CHANGE AND OCEAN ACIDIFICATON ON EXSITING OCEAN-BASED INDUSTRIES

3.1 Methodology

This chapter presents a summary of current knowledge on the observed and possible future abiotic and biotic impacts from climate change and ocean acidification on ocean-based industries. The three main ocean-based industries in Norway, the seafood industry, the maritime industry and the petroleum industry have one section each (3.3 - 3.5). These sections have the following sub-categories:

1. Observed effects

2. Possible future impact

New industries and processes based on the ocean and marine resources are emerging, such as marine biotechnology, lower trophic level harvesting, biochemicals, bioprospecting, offshore wind, seabed minerals and harvesting and production of new marine species. Impacts on these will be described in a separate chapter (Chapter 4).

Figure 2. Fishing boat. Photo credit Mark Berry

3.2 Definitions of ocean-based industries and climate vulnerability

3.2.1 Defining ocean-based industries

In this report, we define ocean-based industries as industries that directly depend on the ocean and/or ocean resources. This definition follows the updated ocean strategy from the Norwegian government "Blå muligheter" (2019) and the publication by Menon economics (Menon economics 2016).

In the Menon economics report the petroleum industry is defined as operating companies (oil companies) and associated supplier industries. Maritime industry is defined as any business that owns, operates, designs, builds, supplies equipment or specialized services to all types of ships and other floating entities. The seafood industry is defined as fisheries, fish farming (aquaculture), and their related processing export businesses. In this report, the land-based value chain of ocean-based industries in Norway was not included, however some transportation chains are discussed.

3.2.2 Defining climate vulnerability

Ocean-based industries will be directly impacted by increased ocean temperature, ocean acidification and lower oxygen levels but also by more frequent extreme weather (storms, waves), changing currents, rainfall/runoff, introduction of alien species, times of algal blooms, leaching of pollutants from landfills and contaminated land (CICERO/Vestlandsforskning 2018). Other human activities at sea and land will also contribute to degradation of marine ecosystem including pollution and littering, loss of marine natural diversity due to habitat destruction of over-exploitation of resources. The combination of local (e.g. overfishing, oil spill) and global (e.g. ocean warming and acidification) stressors may amplify the negative consequences of marine ecosystems (Arnberg et al. 2018). It is therefore key to have a comprehensive understanding of all these factors to evaluate impacts on ocean-based industries.

Industries related to fisheries and aquaculture are already directly exposed to physical climate changes (e.g. extreme weather, diseases). However, governments, private investors, insurance companies and banks have seen that industries can also be influenced economically by climate change related policies, including several Norwegian companies and industries (Norsk klimastiftelse 2018). This involves ocean-based industries such as the oil and gas industry that can be indirectly affected by government regulations (e.g. CO_2 tax, emission allowances, energy efficiency requirements). At the same time, new industry possibilities can be opened both in short and long-term and it is important to understand new trade-offs with exposure to climate change and ocean acidification.

The climate-vulnerability of an actor, industry, municipality or region depends on exposure, sensitivity, and adaptive capacity. Evaluate potential impacts require the understanding of natural vulnerability (exposure to climate change and occurrence of natural processes affected by climate change), societal vulnerability (the degree to which processes, infrastructure and industries affected by climate change is important for this actor/region), and institutional vulnerability (the institutional capacity there is to handle climate change and its implications, to carry out adaptive measures). To be able to determine the climate and ocean acidification related financial impacts on the ocean-based industry and society, one therefore needs a look at new broader climate risk analysis as impact is what will happen if the risk occurs.

In this report, we used the approach suggested by the G20 (or Group of Twenty) Task Force of Climate related Financial Disclosures (TCFD) on how climate risk should be reported and analysed (https://www.fsb-tcfd.org/wp-content/uploads/2017/06/FINAL-TCFD-Report-062817.pdf). This approach has recently been used in another Norwegian report describing climate risk (Norsk klimastiftelse 2018). According to this TCFD, risks can be divided into physical and transitional risk.

The physical risks resulting from climate change and ocean acidification can be acute (short-term and event driven) or chronic (long-term).

- Acute physical risks refer to those that are event-driven, including increased severity of extreme weather events, such as cyclones, hurricanes, or floods.
- Chronic physical risks refer to longer-term shifts in patterns (e.g., sustained higher temperatures and ocean acidification) that may cause sea level rise or chronic heat waves.

The transition risks. Transitioning to a lower-carbon economy may entail extensive policy, legal, technology, and market changes to address mitigation and adaptation requirements related to climate change and ocean acidification. Depending on the nature, speed, and focus of these changes, transition risks may pose varying levels of financial and reputational risk to industries. These risks can further be divided into regulatory, technology, market and reputation risks.

- *Regulatory risks*. Policy actions around climate change continue to evolve. Their objectives generally fall into two categories - policies that attempt to constrain actions contributing to the adverse effects of climate change or policies that seek to promote adaptation to climate change. Some examples include implementing carbon-pricing mechanisms to reduce GHG emissions, shifting energy use toward lower emission sources, adopting energy-efficiency solutions, encouraging greater water efficiency measures, and promoting more sustainable ocean-use practices
- *Technology Risks*. Technological improvements or innovations that support the transition to a lower-carbon, energy efficient economic system can have a significant impact on industries. For example, the development and use of emerging technologies such as renewable energy, battery storage, energy efficiency, and carbon capture and storage will affect the competitiveness of certain organizations. To the extent that new technology displaces old systems and disrupts some parts of the existing economic system, winners and losers will emerge from this “creative destruction” process.
- *Market Risks*. The ways in which markets could be affected by climate change are varied and complex and one of the major ways is through shifts in supply and demand for certain commodities, products, and services as climate-related risks and opportunities are increasingly considered.
- *Reputation Risks*. Climate change has been identified as a potential source of reputational risk tied to changing customer or community perceptions of an organization’s contribution to or detraction from the transition to a lower-carbon economy.

3.3 Impact on the seafood industry

Figure 3. Aquaculture installation. Photo credit: Mark Berry

Norway is the world's second largest seafood exporter after China, and the industry represents the second largest export industry in Norway after oil and gas. Norway exports seafood for a value of around NOK 53 billion every year. Of the total value of Norwegian seafood exports in 2017, 72% came from aquaculture and 28% from the fisheries sector (https://en.seafood.no/). Measured in volume, the distribution was 40% from aquaculture and 60% cent from fisheries. Furthermore, the Norwegian government aims at facilitating further sustainable growth in the seafood industry, as the it has great ambitions for increased value creation from the ocean (Blå muligheter 2019).

Marine fish and invertebrates have become an increasingly important source of food as the human population has grown (Barrnge et al. 2018) and seafood is expected to play an increasingly important role in the future. Earth's biological production is roughly equally divided between land and sea, however only 2% of caloric intake and 15% of human protein intake come from the sea (Torrissen et al. 2018). This is no longer sustainable given the nutritional needs of a growing population and over-consumption of land-based resources (Torrissen et al. 2018). Given the current trends, total food demand is projected to increase by 60% by 2050 unless demand can be managed more effectively (SAPEA 2017). A shift to diets toward low carbon marine sources such as sustainably harvested fish, seaweed, and kelp as a replacement for emissions intensive land-based sources of protein, has been proposed as one of the ocean-based actions to lower future greenhouse emissions (Hoegh-Guldberg et al. 2019, chapter 5).

Fisheries depend entirely on healthy ecosystems in the ocean, and aquaculture are highly dependent on the biophysical conditions in the ocean. Recent climate projections suggest that warming will affect economies relying on the production of seafood and the utilization of marine ecosystems (Hollowed et al. 2013). Temperature variability, ocean warming, ocean acidification and broader environmental regime shifts are important variables when considering impacts on ecosystems, fisheries and aquaculture. For example, studies show that spawning locations and stock distribution are partially correlated with changes in ocean temperature (Sundby and Nakken 2008). Marine fisheries are typically affected by large scale oceanic processes, while ocean-based aquaculture may be more affected by local processes such as precipitation and topography (Brandner 2007).

3.3.1 Fisheries

Figure 4. Fishery catch. Photo credit: Mark Berry

The term "fisheries sector" in Norway is understood to encompass value chains based on the harvesting of cod varieties, pelagic species, flatfish and other benthic fish species, shellfish and other molluscs (Olafsen et al. 2012). In the past 30–40 years, the development has gone from virtually free fishing towards more efficient and highly regulated fishing, with fewer fishermen and vessels (The Norwegian Directorate of Fisheries 2016). The pelagic value chain is characterised by a few vessel operators, a highly structured industrial link, and large production volumes of simple products passing through the system. The white fish sector operates with a more complex fleet structure made up of many fleet groups, a filleting industry in which the market share in processing is in decline, and a conventional sector (dried fish, salted fish and stock fish) which is increasing its market shares. In recent years, shrimp harvesting has been in decline, and there are only a few processing factories left (Olafsen et al. 2012). According to the Norwegian Seafood Council, 1,900t of king crab worth NOK 548m ($64.5m) were fished in Norway in 2018 and exported (https://en.seafood.no/). There has also been a shift of paradigms through the evolution within fisheries management, from protection of the fishery (first by protecting the fisher, later the resource base of the fishery), to protection of the environment (Eide et al. 2014). Furthermore, there has also been a shift from a single species management to ecosystem-based management (Gullestad et al. 2017).

Key findings:

- **Fish stocks will likely move north** and east due to temperature increases, but this will also depend on i.e. availability of food (match/mismatch in space and time), and alternative spawning grounds for the smaller species of fish. **Production may increase**, but this will depend on the effects of climate change and ocean acidification on the whole ecosystem.
- Changes in stock availabilities affect cost of harvest. **New fisheries may emerge** while **others may vanish** in some areas due to ecological changes (shift in migration patterns and distribution areas).
- Changes in weather conditions **change the cost of effort** (for example more extreme weather may increase costs).
- Climatic change may also **change the demand** for fish and fish products regionally and globally due to increased environmental concern and consumer caution.
- Transnational expansion may lead to **international (re-) negotiations on quotas** and fishing rights. The societal effects based on highly uncertain ecological effects, are even more uncertain.

3.3.1.1 Observed changes

Aquatic systems that sustain fisheries are undergoing significant changes as a result of global warming and projections indicate that these changes will be accentuated in the future (Barange et al. 2018). These changes have been clearly demonstrated in Norwegian marine areas, such as the North Sea and the Barents Sea. In the North Sea increased temperature have caused changes in the zooplankton community leading to a less productive ecosystem and local fish species are displaced by other species migrating from the south (Arneberg et al. 2018). Similarly, warming and loss of sea ice in the Barents Sea has caused the Arctic species to be largely displaced by southern species, significantly altering ecosystems in the northern Barents Sea (Fossheim et al. 2015, Arneberg and Jelmert 2017).

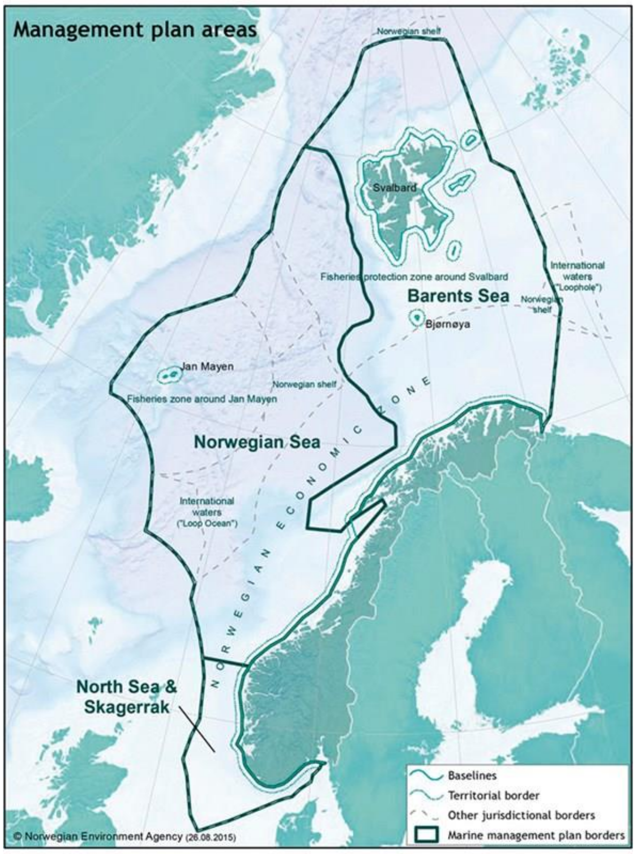

Figure 5. Map of the different sea areas in Norway (source: Norwegian Environment Agency)

More subtle changes attributed to climate change have been documented in the Norwegian Sea.

Southern zooplankton species common in the North Sea or further south have been increasingly observed in the Norwegian Sea since 2006. Furthermore, there has been a significant reduction in the amount of the two key zooplankton species in subarctic water in the south-western Norwegian Sea from 2003, probably due to less inflow of subarctic water from the west (Kristiansen et al. 2015). Consequences of these changes in zooplankton communities for the ecosystem are currently unknown. However, zooplankton are a key food source for many of the commercially important fish stocks in the North Atlantic such as the herring. Toresen et al. (2019) show that for Norwegian spring-spawning herring estimated recruitment and mean winter temperature show a significant positive correlation for the period 1921–2004. However, this positive correlation did not continue from 2005 onwards as the winter temperature increased and herring recruitment decreased and has remained low. In the past, spawning grounds outside Møre were the most important. Today, it is the generations born in the north that are the most successful through the first phase of their life. Herring itself is not directly affected by the fluctuations in ocean temperature but indirectly through the zooplankton that they eat. The density of zooplankton in the drift route of the herring larvae dropped significantly after 2004, and their centre of gravity shifted northwards. Toresen et al. (2019) analysis indicated that the presence of food and overlap with high food concentrations are likely important regulators of survival in herring larvae. As a consequence, herring may move north in the decades to come.

Changes in migration patterns of the northeast Atlantic mackerel is likely influenced by changing climate and ocean temperature. This migration led to intergovernmental dispute. The interstate conflict started after the mackerel moved northwards. Due to this change in distribution, Icelandic and Faroe fishers got better access to the stock and therefore wanted to secure their fishing rights. The Faroe Islands wanted to enlarge their mackerel quota, while Iceland wanted to become an accepted Coastal State member to secure their quota share. The conflict between the EU/Norway and the Faroe Island dissolved in 2014 with a new management agreement, which allocated a substantially larger mackerel quota to the Faroe Islands. The conflict between Norway and Iceland persists today (Spijkers and Boonstra 2017).

3.3.1.2 Expected future consequences

Projecting the response of fished species to future climate change and ocean acidification is of great interest for scientists, fishing communities and governments. Healthy ocean ecosystems systems play a critical role in supporting fisheries. Observations, experiments and models suggest that climate change and ocean acidification have the potential to impact primary productivity, shifts species distribution and change the potential yield of exploited marine species, resulting in impacts on the economics of fisheries (Sumaila et al. 2011). For the fisheries sector, it is important to keep an eye on how fish stocks distribution will evolve in future oceans (Norsk klimastiftelse 2018).

Physical risks

Acute: More extreme weather such as wind, storms, storm surges and waves can influence the safety at sea and limits the number of days at sea. This can have negative consequences for the fishermen (Hovelsrud 2011, Noone et al. 2013). Local knowledge of ocean conditions is not necessarily sufficient under new weather conditions (Hovelsrud 2011). A more widely distributed, distant and possible different target fish stock (see chapter below) is likely to require increased vessel capacity investment, both with regard to

Figure 6. Fishing boat with net. Photo credit: Mark Berry

safety (rougher seas, and fishing further from shore) and gears, in order to reach deeper and a more varied catch composition (Eide et al. 2014).

Chronic: Marine ecosystems can be defined as the sum of the biological community and its physical environment. Environmental conditions affect the species composition, their distribution and primary production (Eide et al. 2014). The IPCC identifies four principal climate drivers that affect marine ecosystem structure, functioning and adaptive capacity: pH, temperature, oxygen and food. The resulting ecological impacts associated with climate change and ocean acidification will be complex, including changes in productivity, food web structure, losses of native species, and the introduction of non-native species. For example, ocean acidification and increased temperature can have a dramatic effect on the size of fish stocks, which will have major negative consequences for the fishing and fishing industry (IPCC 2014). Recent studies have sought to characterize how climate-related drivers alter species' distributions and community size structures, with increased attention allocated toward interactive effects, early developmental stages, community size structure, and genetic and phenotypic adaptation (Weatherdon et al. 2016 and reference therein). Each of these aspects is likely to affect the availability and abundance of fish stocks (Sumaila et al. 2011), with regional variation accompanying climatic trends.

Changes in environmental conditions strongly affect the spatial distributions of marine fishes and invertebrates (Sumalia et al. 2011). Higher ocean temperature drive changes in ocean circulation and stratification, decrease of oxygen concentrations, and shifts of primary productivity. Ocean acidification can also affect organisms, food and habitat availability (BIOACID 2018). As a consequence, marine fish populations are experiencing large-scale redistributions, increased physiological stress, and altered food availability (Barange et al. 2018).

The number of fish reaching fishery size every year is critically dependent on the match or mismatch between the occurrence of the fish larvae and the availability of their zooplankton food (Cushing 1982). Climate change and ocean acidification may have important consequences on the seasonal timing and the magnitude of blooms of phytoplankton and or zooplankton at high latitudes (Henson et al. 2017). Global scale modelling of phytoplankton has projected large shifts in the seasonal timing of blooms throughout subpolar waters of the north Atlantic and polar waters of the Artic (Henson et al. 2017). Coastal darkening as reduced water clarity in coastal areas where there are freshwater drains are expected to increase and can contribute to a shift in the timing of phytoplankton blooms (Opdal et al. 2019).

Zooplanktons are key diets of early life stages of fish (Barange et al. 2018). In the northeast Atlantic, major biogeographical shifts in zooplankton have already been observed in response to warming, including poleward increase in warm water species and a reduction in cold water species in the same area. Even small alterations at the base of the food web can have knock-on effects for higher trophic levels (BIOACID 2018). The decline of a key prey item (the copepod *Calanus finmarchicus*) has been correlated with recent failures in cod recruitment in the North Sea (Beaugrand et al. 2003).

As temperature, oxygen and acidity levels are causing habitats to be restricted, several species of fish are moving. In recent years a northwards expansion of the distributional range of several fish species has been driven by warming, sometimes also including a contraction of their southern distributional range (Perry et al. 2005, Fossheim et al. 2015). The change in distribution of stocks leads in turn to shifts in local fisheries (Barange et al. 2018, Bonanomi et al. 2015, Pecl et al. 2017). Countries or regions in the southern part of the distributional range of a species may lose access to the resource while countries or regions in the northern part might benefit from a northward shift of its distributional range (Barange, et al. 2018). The effect of temperature rise may be positive for the commercial fish species which Norway currently exploits. Large scale redistribution of maximum fisheries yield potential is projected by 2050 under a business as usual scenario including a 30 to 70% increase in yield of high latitude regions such as Norway's Exclusive economic zone (EEZ) (Barange, et al. 2018). For example, pelagic fish have the potential for rapid abundance and distribution shifts in response to climatic variability due to their high adult motility, planktonic larval stages, and low dependence on benthic habitat for food or shelter during their life histories. It is expected that more anchovies and sardines will be distributed in the North Sea, while herring and mackerel are expected to spread further north (Montero-Serra et al. 2015). Cod and other cold-water species are doing worse in the southern parts of the North Sea today than 30 years ago. The cod is moving slowly north, as the temperature is rising. Studies show that if average bottom temperature in the North Sea is above 5.6 °C in the first quarter of the year, there is lack of good cod recruitment. The institute of marine research (IMR) suggests that higher temperatures during the spawning period is an important reason for the reduced cod recruitment for the cod stock in the North Sea (https://www.imr.no/hi/nyheter/2019/juni/kraftig-nedgang-for-torsk-i-nordsjoen).

A shift between Arctic to Boreal (Atlantic shallow water) fish communities dominated by American plaice, Atlantic cod and haddock occurred between 2004-2012 in the Barents Sea (Fossheim et al. 2015). In 2014, the UN Climate Panel estimated that marine fish species move at approximately 40 kilometres per year. Fossheim et al. (2015) found that fishing communities in the Barents Sea moved up to four times as fast over the period 2004–2012. The increased access to Arctic waters due to the ongoing retreat of the summer sea ice has accelerated a growing interest in exploiting Arctic marine ecosystems and expanding fisheries also in the Arctic ocean. In the future, an Arctic fishery may broadly rely on two groups of fishes, i.e. those which are already commercially harvested: native and boreal fish fauna native. Lam et al. (2016) projected that total fisheries revenue in the Arctic region may increase by 39% (14–59%) by 2050 relative to 2000. Ocean acidification is expected to reduce the potential increases in catch. However, the effects of ocean acidification on total fisheries revenues will lower than the expected future benefits in the Arctic.

Several fundamental questions arise when boreal fishes invade Arctic waters (Christiansen et al. 2014). Many commercial fish (e.g. cod, capelin, herring, mackerel, blue whiting) are now found north of their traditional distribution areas. The expected increase in the abundance of boreal fish in Arctic waters is likely to disrupt existing and create novel trophic links. Furthermore, question remains: how do native and boreal fish interact, and how does that affect the population dynamics for both groups of fish? (Christiansen et al. 2014). It is anticipated that this could result in the local extinction of some arctic fish species, such as the Polar cod (https://climefish.eu/c4f-barents-sea). The suitability of present spawning habitat for both Atlantic cod and Polar cod are expected to decrease by 2100 under RCP 8.5 scenarios (Dalke et al. 2018). Christiansen et al. (2014) suggest that precautionary management practices by the Arctic coastal states are urgently needed to mitigate the impact of industrial fisheries in Arctic waters.

Not all fish species have the ability to move to new ecosystems as temperatures rise (https://forskning.no/fangst-klima-havforskning/klimaendring-pavirker-globale-fiskefangster). For example, bottom fish such as cod and haddock often depend on a specific habitat and cannot replace a shallow continental shelf with deep water. Pelagic fish that live freely in the water masses much of the year may also depend on special conditions for spawning. For example, capelin is spawning outside Finnmark and Norwegian or herring spawning in Spring use banks from Møre and north as spawning grounds. These species cannot easily find new habitats further north. They may migrate further north to colder seas to graze but will have to migrate back to spawn.

Invertebrate species are also migrating North because of increased temperature. Pelagic larvae of the commercially important Northern shrimp are particularly sensitive to temperature changes. This translates into negative effects in southern areas and positive in northern areas (Ouellet et al. 2017). Temperature, substrate, salinity and depth are all factors that control the distribution and density of Northern shrimp along the Norwegian coast. Predation and fishing pressure also affect density, while stock size may affect distribution. The shrimp in the Barents Sea have already moved northeast as the sea has become warmer. According to scientists, shrimp in the North Sea and the Skagerrak could become climate refugees in northern Norway and can disappear from their southern habitats in Norway (https://www.harvestmagazine.no/artikkel/en-historie-om-rekene).

Concurrent with long-term persistent warming, discrete periods of extreme regional ocean warming (marine heatwaves, MHWs) have increased in frequency (Oliver et al. 2018). Smale et al. (2019) identified the northeast Atlantic as a region with rapid increases in the annual number of MHW days and overlap with existing high-intensity non-climate human stressors. As a consequence, these regions may be particularly vulnerable to MHW intensification as existing regional pressures, including overfishing and pollution, have the potential to exacerbate MHW impacts. The physical attributes of prominent MHWs varied considerably, but all had deleterious impacts across a range of biological processes and taxa, including critical foundation species (corals, seagrasses and kelps). MHWs can also change the distributions and abundances of commercial fisheries species (Mills et al. 2013), and widespread shifts in coastal biota (Sanford et al. 2019). For example, in the northwest Atlantic high temperature in Summer 2012 moved lobsters closer to the shore. This led to an increased catch size, a subsequent lowering the prices and a collapse of lobster fisheries (Mills et al. 2013). Similar events will become more frequent as MHWs intensify.

Several studies have indicated that climate change has already affected fish size (Forster et al. 2012). In response to climate-induced changes in temperature and oxygen, fish size might decrease. The smaller body sizes being projected for the future are already detectable in the North Sea. The size of North Sea fish such as cod and flounder, decreased the yield-per-recruit of these stocks by an average of 23% over the past 40 years (Baudron et al. 2014). Cheung et al. (2012) estimated that under high-emissions scenarios, warming oceans will cause a 14-24% reduction in the average body mass per fish worldwide in the first half of the 21st century. Overall, this could reduce commercial catches by up to 3.4 million tonnes annually per degree of heat increase (Pauly and Cheung 2018). While laboratory experiments support Cheung's model, few studies have tested it in wild populations, and some researchers remain sceptical of the model’s applicability in the real world.

Increase in water temperature could affect fish size because of the reduction in oxygen content in the water. As the water's dissolving capacity decreases in higher temperatures, global warming will result in the ocean absorbing less oxygen. Some research indicates that fish stocks may have difficulties adapting to a changing oxygen level, which may limit fish's overall growth. Stendardo and Gruber (2012) examined oxygen trends over five decades in the North Atlantic and identified declines in almost all regions during the period from 1960 to 2009. Whether or not these changes in dissolved oxygen are a result of long-term climate change remains unclear, and it is also unknown whether such changes will impact commercial fish and commercial fisheries (Townhill et al. 2017). However, Deutsch et al. (2015) suggest that projected climate and oxygen conditions has the potential to restrict the distribution of marine fish poleward, as equatorward waters become too low in oxygen to support their energy needs. Furthermore, even the more-poleward waters will have reduced oxygen levels. The combination of temperature increases and reduced oxygen levels in fish habitats could contribute to reduce total cod habitat by up to 20 percent globally and as much as 50 percent in northern areas by 2100 (Deutsch et al. 2015).

While there is certainty in the direction and magnitude of ocean pH decline, and of its largely negative impacts on many marine organisms (Kroeker et al. 2017), most models do not incorporate the potential impacts of ocean acidification (OA) on fish and fisheries. This may be a consequence of the lack of monitoring and models for the carbonate chemistry on the coastal zone as well as a limited understanding of the impact of OA on commercially important species. However, a strong body of evidence shows that OA can have a major impact on marine life, including seafood such as mussels, clams and other shellfish. OA can have consequences on habitats such as corals and coastal vegetation, which in turn will affect populations of small fish and fish food (IPCC 2014, Colburn et al. 2016, BIOACID 2018). Recent research has also shown that fish species (especially in the early development phase) can be negatively affected by OA (levels that are predicted to occur in the near future, but have already been observed in many coastal areas) including effects on their behaviour through modification of their senses and central brain function (e.g. Porteous et al. 2018). Combined ocean acidification and warming may also reduce the survival rates of early life stages of some fish species and will likely reduce recruitment of fish stocks and ultimately fisheries yield (Dahlke et al. 2018). Direct and indirect (through habitat restructuring and food interactions) can reduce the size of cod stocks in the Barents Sea and the Baltic Sea up to a quarter of the current level in 2100, assuming a CO_2 increase in line with that in RCP 8.5 (BIOACID 2018).

Although some fish move toward the poles, absolute stocks will nevertheless be at risk of being reduced, as suitable fish habitat may also be threatened by climate change and ocean acidification. In marine ecosystems, habitat-forming species (HFS) such as reef-building corals and canopy-forming macroalgae alter local environmental conditions and can promote biodiversity by providing biogenic living space for a vast array of associated organisms including commercially important species (Teagle and Smale 2018).

Cold water corals (CWC), with all their small cavities and formations, provide fine habitats for fish fry and benthic animals. They are regarded as hot spots for biodiversity and carbon cycling. Along the Norwegian coast there are thousands of coral reefs, especially on the continental shelf. *Lophelia* is one of the most common coral species in Norwegian reefs and plays a key role in benthic ecosystems in Norwegian waters (Järnegren and Kutti 2014). *Lophelia* ecosystems have come under increasing anthropogenic pressure due to releases of suspended particles from the aquaculture, oil and gas, mining and bottom trawling industry (Järnegren and Kutti 2014). Changes in ocean temperature and ongoing acidification will act as additional stressors on *Lophelia* ecosystems. Ocean acidification is considered the most serious threat. However, laboratory studies have shown that *Lophelia* from Norwegian populations are only slightly impact by OA. More serious effects have been observed under specific conditions and it is urgent to better understand the effects of multiple stress factors and long-term exposure to stressful conditions. Most of the habitat formed by *Lophelia* is made of dead coral (calcium carbonate structures) that are threaten by the chemical changes associated with OA. Of all known *Lophelia* occurrences in the world, 30% are from the Norwegian shelf. Norway has then a special responsibility in managing this species and the ecosystem it creates. Functional connections between CWCs and fish stocks are suspected, and there is evidence of the utilization of CWCs by fish larvae, mainly those of redfish (*Sebastes* spp) (Baillon et al. 2012).

Macroalgae (e.g. *Laminaria hyperborea* and *Saccharina latissima*) are important habitat forming species (Teagle et al. 2017) that create large underwater forests. Under the canopy of these forests, several brown, red, and green algae of various sizes thrive, some even growing on the kelp itself (epiphytes). These algae communities' function as habitat for invertebrates such as bivalves, echinoderms such as sea urchins, crustaceans such as crab, and benthic fish such as cod and wolf fish. They dominate lower intertidal and shallow subtidal reefs along temperate and subpolar coastlines including Arctic coastlines in the Northern Hemisphere (Teagle et al. 2017). Seagrass meadows and kelp forests are sensitive ecosystems at high risks for projected global warming exceeding 2°C above pre-industrial temperature and other associated climate-related hazards (IPCC 2019). Interactive effects of ocean warming and acidification can lead to kelp degradation and disease-like symptoms, with detrimental effects on photosynthetic efficiency (Qiu et al. 2019).

According to Araújo et al. (2016), kelp forest distribution and abundance are decreasing in Europe except for an increase of some populations in some localities in Norway and Svalbard. In Norway, grazing by sea urchins has been regarded as the most important stressor affecting kelp species, especially in the northern and mid part of Norway where recovery of kelp forests is in progress after the intensive grazing period (Norderhaug and Christie 2009). The *L. hyperborea* kelp recovery in the southern part of the grazed area (i.e. mid Norway) has expanded northwards since the 1990s due to reduced sea urchin populations (Norderhaug and Christie 2009, Rinde et al. 2014). The reduction in sea urchins is linked directly to warming by a resulting reduction in sea urchin recruitment (Fagerli et al. 2014, Rinde et al. 2014) and indirectly through increased predation from crabs expanding their range (Fagerli et al. 2014) and changed water masses in recent decades (Wiltshire et al. 2008).

Kelp species thrive in cold water, and their general health is reduced under warmer conditions. This makes them less resilient towards additional stressors like eutrophication, pollution, foreign species, harvest and extreme weather events (Filbee-Dexter and Wernberg 2018). Most of the kelp forests (80 %) along the Norwegian coast towards Skagerrak has disappeared since 2002, due to increased temperature and runoff, together with other human influences. They have been replaced by communities of opportunistic and ephemeral filamentous algae, resulting in a much lower species richness and abundance (Christie et al. 2009). Turf-covered reefs are lacking the three-dimensional structure of a kelp forest, where an immense richness of crustaceans, fish and snails live and hide. These shifts to turfs represent widespread global loss in structural habitats and a new "battlefront" as kelp forests move away from traditional urchin-grazing (and overfishing) dynamics toward climate- and nutrient-driven replacement by turf algae (Filbee-Dexter and Wernberg 2018). Furthermore, as waters warm and sea ice retreats, more light will reach the seafloor, which will benefit marine plants. Researchers predict a northern shift of kelp forests as ice retreats (Krause-Jensen and Duarte 2014). There is a major knowledge gap concerning the effects of changes in kelp forests on fisheries at the European level.

In an ever-changing marine environment, organisms must respond to their environment in order to survive and reproduce. This involves migration, acclimation and/or adaptation. However, the current rate of change is extremely fast and strong. For example, sea surface temperature is projected to increase by approximately 3°C by the year 2100 (Collins et al. 2013). As a consequence, many species will rapidly be exposed to conditions they never experienced in the past. Many seafood species have long generation time and will only have a few generations to adapt to these changes completely depending on existing genetic variability. In over-exploited ecosystems, pelagic species that are smaller and have faster turnover generally increase in dominance (Cheung et al. 2007). Although species with higher turnover rates may theoretically have more capacity to adapt evolutionarily to environmental changes (Cheung et al. 2018), the scope and rate of such adaptive response for most fishes are unclear (Munday et al. 2013). Also, over-exploited fish stocks with largely reduced abundance may also have reduced genetic diversity and variability, and consequently the population will have a reduced scope for adaptation under climate change and ocean acidification (Munday et al. 2013).

There are strong interactions between global and local drivers. For example, fishing interacts with climate change and ocean acidification. As fishing reduces fish age, size, and distribution as well as ecosystems biodiversity, fish and their associated ecosystems are more sensitive to additional stressors such as ocean acidification and climate change (Brander 2007). Climate change will likely also hinder efforts to rebuild overfished populations (Brander 2007). Reducing fish mortality in the majority of fisheries, which are currently fully exploited or overexploited, is the principal feasible means of reducing the impacts of climate change and ocean acidification. Free et al. (2019), suggest that prompt improvements in fisheries management could maintain global wild-capture fisheries yields and profits into the future. It is essential to prevent overfishing and develop management strategies that are robust to temperature-driven changes in productivity (Free et al. 2019). In addition to overfishing, multiple interacting stressors can have negative impact on fisheries (Toft et al. 2018). It is therefore key to build a comprehensive understanding of the overall burden of human activity ecosystems and the fishery industry, especially in the vulnerable northern areas (Boyd et al. 2018).

Transition Risks

Regulatory risks/Technology Risks:

The global fuel use and greenhouse gas (GHG) emissions from the global wild capture fisheries accounts for 4% of global food system production emissions (Hoegh-Guldberg et al. 2019). Reductions in emissions from wild capture fisheries can be achieved through technical and behavioural changes and solutions, optimising fish catch efficiency (Hoegh-Guldberg et al. 2019). For example, new trawlers can be equipped with battery packs that enable diesel-electric propulsion, and each new generation of boats can be made more energy efficient (Norsk klimastiftelse 2018). Vessels with low or zero emission are under development. Therefore, the fishing fleet is likely to face increasingly stringent emission requirements and possible new regulations.

Climate change and ocean acidification will change the distribution and abundance of fish species in Norwegian waters. This can have a significant impact on small-scale coastal fisheries and fishing tourism. New fisheries regulations may be essential to prevent overfishing and develop management strategies that are robust to temperature and pH-driven changes in productivity (Gourlie 2017). Responsive harvest control rules provide inherent resilience to adverse effects of climate change (Kritzer et al. 2019). Precautionary fisheries policy has been also been suggested by the IPCC (2019) to global international fisheries, which suggests that one should avoid taking risks when consequences are highly uncertain but maybe result in permanent losses of biodiversity or sustainable stocks or other unacceptable damages to present or future generations.

Market risks/reputation risks:

Demand for fish and other seafood is expected to grow strongly in the future, and ocean food may play a role in emission reductions efforts if the production is sustainable (Hoegh-Guldberg et al. 2019). However, the sustainability aspect is increasingly being questioned (Norsk klimastiftelse 2018). When it comes to climate footprint and sustainable production, air transport is an issue. Carrying fresh fish by aircraft over long distances has significantly greater footprint than other methods of transport (Norsk klimastiftelse 2018).

There are suggestions of significantly altering the behaviours of a broad section of the society, through possible food related taxes that embed broader environmental and social costs (external costs) of different food choices and thus motivating lifestyle changes (Hoegh-Guldberg et al.

2019). Wild fish might come out well in regard to carbon and environmental footprint compared to meat and farmed fish (Norsk klimastiftelse 2018).

3.3.2 Aquaculture

Figure 7. Aquaculture site. Photo credit: Mark Berry

Fish farming is an important industry in Norway. The annual revenue of the aquaculture industry in the country is 30 billion NOK and the industry offers 21,000 man-labour years. Salmon dominates the farming industry and although several other species are farmed such as cod, halibut, wolffish, turbot, these account for only less than 2‰ total fish farming in Norway. Aquaculture is the second largest export industry in Norway, after petroleum and it is a national goal to 5-fold the production by 2050.

Climate change and ocean acidification can have direct and indirect impacts on the Norwegian aquaculture industry, both in short- and long-term. Short-term impacts include losses of production and infrastructure arising from extreme events, increased risk of diseases, parasites and harmful algal blooms (HABs), and reduced production due to negative impacts on farming conditions (Barange et al. 2018). Changes in temperature, precipitation, ocean acidification, incidence and extent of hypoxia and sea level rise, amongst others, will have long-term impacts on the aquaculture sector at scales ranging from the organism to the farming system (Barange et al. 2018). The aquaculture industry depends on water quality and weather circulation conditions in the fjords along the Norwegian coast. An increase of ocean temperatures and a higher frequency of extreme weather are believed to have the greatest impact. Also, ocean acidification and changing water salinity due to increased freshwater inflow into the fjords may affect the industry in the long run (https://www.climatechangepost.com/news/2016/9/21/norways-aquaculture-needs-more-focus-long-term-cli/). In comparison with other seafood producing countries, Norway and Chile has been identified as being the most vulnerable to climate change, reflecting the high production and the concentration of production on few species (Barange et al. 2018).

There may however be some positive effects from climate change for the aquaculture industry such as faster growth rates and higher feed conversion ratio, longer growing season, and new production areas as a result of decreases in ice cover (Holmyard 2014). Furthermore, it may also become possible to use species with preferences for higher temperature. These possibilities will be described in more detail in the chapter new ocean-based industries (Chapter 4).

Key findings:

- Short-term impacts of climate change and ocean acidification on the aquaculture industry include **losses of production and infrastructure** arising from extreme events such as MHW, increased risk of diseases, parasites and harmful algal blooms (HABs), and reduced production because of negative impacts on farming conditions.
- As temperature increase due to climate change, **optimal salmon production areas will move northward** along the Norwegian coast. This is a consequence of optimal temperature for growth of the salmon itself, but also temperature rise aggravating existing problems linked to parasites (including salmon lice) and pathogenic organisms. On the other hand, ocean warming may provide **opportunities for farming new species**.
- Predicted reduced ice coverage in the arctic as a result of climate change can also **open up new production areas**.
- **Production of feed for aquaculture can have indirect negative effects** on the industry as they require fish capture and agriculture production. Shortage of fish oils suitable for fish feed is expected in the near future, and climate change risks associated with crop failure may occur at the same time in important soy producing countries.

3.3.2.1 Observed changes

Impacts of climate change and ocean acidification on aquaculture to date have been difficult to discern from natural environmental variability, and the pace of technological development in aquaculture often overshadows effects of these changes. There is little existing evidence of impacts on aquaculture that can be attributed to climate change. However, hatchery failures and survival of larval groups of Pacific oysters in an US hatchery was linked to increased CO_2 and ocean acidification (Barton et al. 2015). Furthermore, several effects have been observed that could be related to a changing climate such as increased shellfish contamination, harmful plankton events and the establishment of non-native species, but it is not clear that a changing ocean climate is responsible for these effects (Gubbins et al. 2006). Both diseases and lice have become more common on fish farms in recent years, with experts blaming warming sea temperatures associated with climate change (Callaway et al. 2012). A recent event (September 2019) in the east coast of Canada of mass mortality of salmon in open-net pens operated by Mowi Canada East's Northern Harvest Sea Farms. This led to an economic loss of 50 million NOK. Unusually warm water over an 11- to 13-day period led to low oxygen levels that caused a mass die-off of farmed Atlantic salmon. Temperatures ranged from 18 C to 21 °C throughout the entire water column, meaning there was nowhere for the fish to go to cool off. The aquaculture company Mowi expresses its concern that these events are not treated as a new normal (https://www.intrafish.com/aquaculture/1856007/mowi-calls-for-climate-change-action-after-massive-farmed-salmon-die-off-in-newfoundland).

3.3.2.2. Expected future consequences

Physical risks

Acute: More extreme weather (stronger winds, storms, storm surges and waves) may increase the requirements of all constructions in the ocean. The most common aquaculture site failure events occur in connection with severe storms, especially in autumn and winter. When an aquaculture site is failing, and nets are broken, fish can escape. Not only this is a financial burden but also an environmental risk from escaped farm fish mixing with wild populations. Genetic pollution can weaken the wild stock resilience (Bergh et al. 2007). More intense and more frequent storms are projected and will necessarily incur increased costs for the aquaculture industry in the form of larger investments. Furthermore, more extreme weather might also be an environment health and safety challenge to employees working on sea-based fish farms (Norsk klimastiftelse 2018).

Chronic: The aquaculture may be affected by long-term chronic biophysical changes in the water conditions in the fjords along the Norwegian coast. The variations in biophysical conditions along the Norwegian coast as well as the variation in biophysical conditions over the years may have an impact on the production of Norwegian fish farming, which can affect prices and the profitability for the industry (Thyholdt 2014). Both growth and health of fish and shellfish are dependent on variables such as water temperature, salinity, oxygen content and water quality (Mydlarz et al. 2006). Physical processes associated with waves, currents, tides, ice and river input may also influence the farming conditions (Callaway et al. 2012).

Marine life is sensitive to temperature changes, and most species perform poorly outside their optimal temperature range (Hiddink et al. 2015). Fish often have an optimal temperature for growth and temperature and deviating from this optimum restricts growth and therefore reduce harvest. Salmonids have a relatively narrow range of temperature for optimal growth and thrives in the temperature range between 9-14°C. Hevrøy et al. (2013) showed for Atlantic salmon that the most efficient growth was achieved at a water temperature of 13°C. Furthermore, the study showed that salmon farmed at temperatures of 15 and 17°C grew efficiently in the first two weeks but exhibited reduced feed intake and growth over the rest of the study period. Salmons living at 19°C reduce their feed intake by 50% as compared to salmon living at 14°C (Hevrøy et al. 2013) and reduced growth at the same rate as observed for 3°C. Temperature above 20°C lead to physiological breakdown (Lorentzen 2008). Therefore, periods with higher than usual temperature can lead to faster growth of farmed salmon in the North and Central regions, while leading to slower growth in the South region of Norway. In 2012, optimum conditions for salmon farming were documented at latitude of 62-64º (from Stadt to Fosen) along the Norwegian coast (Hermansen and Troell 2012). For the farms currently located at optimum or higher temperature, ocean warming has the potential to decrease the production. For salmon farms located North of the optimum as well as in the Artic will likely experience improved productivity (Hermansen and Troell 2012). This was demonstrated by Thyholdt (2014) showing that an increase in temperature positively affected salmon growth in the Northern and Central Norway, while an increase in temperatures negatively affected the growth in the Southern region. Ocean temperature changes may therefore influence the area available for farming. As temperature increases new areas might be available. Predicted reduced ice coverage in the arctic as a result of climate change can also open new areas, as cage cultures requires more or less ice-free conditions year-round, as ice can cut nets release fish (Hermansen and Troell 2012). In the arctic, suitable areas might be constrained by the minimum water temperature that allows economically sustainable farming (Hermansen and Troell 2012). A study by Anttila et al. (2014) demonstrated that Atlantic salmon has a remarkable cardiac plasticity which is largely independent of their natural habitat. They suggest that this strategy may aid salmon to cope with global warming. Other species such as cod and halibut, have narrower temperature tolerance. Similarly, increases in temperature can have both positive and negative influence on growth and productivity depending on existing temperature regime at farm sites and (Hermansen and Troell 2012).

An aquaculture-based study has reported that ocean acidification can also impact fish physiology and have substantial effects on behaviours linked to sensory stimuli (smell, hearing and vision) both having negative implications for fitness and survival (Ellis et al. 2017). Ellis et al. (2017) showed that the aquaculture industry has been farming aquatic animals at high CO_2 levels that exceed end-of-century projections (sometimes >10 000 μatm) long before the term 'ocean acidification' was coined, with limited documented detrimental effects reported. The study highlights that its therefor vital to understand the reasons behind this apparent discrepancy. Potential explanations include the environment used in aquaculture (abundant food, disease protection, absence of predators) as compared to the wild, selection of aquaculture species based on their natural tolerance to the intensive culturing conditions, including CO_2 levels or the breeding of species within intensive aquaculture having further selected traits that confer tolerance to elevated CO_2.

Increased temperature can also have indirect effects, such as increased risk for diseases or pathogens and lice infections, lower oxygen content in the waters, and increased harmful algal blooms (HABs).

Previous studies have shown decline in dissolved oxygen of the ocean basins. Aksnes et al. (2019) study of the deep Norwegian fjord Masfjorden basin showed that dissolved oxygen (DO) declined over the last four decades. This is likely the consequence of a decrease in high-density intrusions and reduced ventilation associated with ocean warming. Furthermore, this study also showed that high fish farming activity can also contribute to the DO decline and that reduced basin ventilation decreases the holding capacity for fish farming. As the ventilation mechanism of many Norwegian fjord basins is similar to Masfjorden, these results can likely be extrapolated to the entire Norwegian coast. Increased temperature combined with low dissolved oxygen concentration is one of the most challenging environmental conditions farmed fish experience (Vikeså et al. 2017). As the metabolic rate of the fish exposed to higher temperature increases, they consume more oxygen. Combined with a reduced oxygen availability, this can have significant impact on carry capacity of an aquaculture sites along the coasts. Farmers may have to adapt fish densities so that oxygen demand does not exceed the available oxygen and sites with poor water exchange may have to significantly reduce density of fish (Hermansen Troell 2012).

Abrupt changes in biophysical conditions also increase the production risk and can lead to considerable variations in industry profit levels (Tveterås and Almaas 1999). Discrete periods of extreme regional ocean warming (marine heatwaves, MHWs) have increased in frequency for the northeast Atlantic (Oliver et al. 2018). If these extremes are close to the fish tolerance, and occur in combination with oxygen depletion, this can result in extreme physiological stress and increased susceptibility to disease (Gubbins 2006). This has recently been seen in Canada, where a prolonged increased temperature event killed salmon (see observed changes 3.3.2.1). High temperature can also affect disease progression through direct negative effect on host immune system function or through a direct effect on the parasite replication rate (Miller et al. 2014). Furthermore, there is an increased distribution expansion of various marine species and their associated pathogens across ocean basins (Post et al. 2013).

This leads to risk for a shift in the distribution of pathogens, possibly leading to introduction of exotic diseases and removal of others.

Parasite infections is a major problem in aquaculture. The occurrence and growth of parasitic organisms are temperature dependent, as shorter generation time is associated with increased temperature (Hermansen and Troell 2012). The most common parasite in salmon farming is sea lice. This parasite is more common in southern waters than in the Arctic and ocean warming can contribute to increase its prevalence in the north. It is likely that infections will be more frequent as the temperature increase with associated increased costs for fish treatments to avoid or reduce mortality of farmed fish, as well as limiting infestations on wild salmon (Bergh et al. 2007).

Harmful algal blooms (HABs) also have negative consequences for the aquaculture industry. For example, a recent HABs events both in the north (Nordland county) and south (Troms county), 11,600 tonnes of farmed salmon died and there was a considerable economic loss of estimated 720 million NOK (https://www.fiskeridir.no/Akvakultur/Nyheter/2019/0519/11-600-tonn-doed-laks-i-nord).

Climate models project increased precipitation that will likely lower the salinity of coastal water, strengthening the stratification and influencing the availability of nutrients for algae. In addition, many coastal areas are prone to eutrophication. Many eutrophic habitats that host recurring HABs already experience extreme temperature, low dissolved oxygen, and low pH, making these locations potential sentinel sites for conditions that will become more common in the future as global changes progress (Griffith and Gobler 2019). Excessive nutrient loading and prolonged residence times can promote many types of HABs. Increase temperature can also favour HABs via accelerated growth and an expanded realized niche. Reduced pH can increase the toxin production of several harmful algae (Hattenrath-Lehmann 2015a, b; Griffiths et al. 2019). In addition, recent ocean warming has caused bloom favourable conditions for several HABs allowing them to establish earlier and persist longer. This increases the risk and/or duration of exposure to aquaculture from certain HABs (Gobler et al. 2017). Identifying combined impacts of these stressors is critical for high-production aquaculture facilities/locations contributing large quantities of organic matter to the water column (Burkholder and Shumway 2011) that can deteriorate water quality (e.g. acidification, hypoxia, and HABs) and may prolong algal blooms (https://www.imr.no/en/hi/news/2019/may/aquaculture-didnt-cause-the-algal-bloom). Given that caged organisms are unable to avoid HABs, aquaculture operations may be particularly vulnerable to the co-exposure to these stressors. The study of Griffith and Gobbler (2019) highlights critical gaps in our understanding of HABs as a climate change co-stressor that must be addressed in order to develop management plans that adequately protect fisheries, aquaculture, aquatic ecosystems, and human health.

Aquaculture industry is dependent on feed. Today, 30% of salmon feed is of marine origin while 70% is land based such as soya. Both these sources are dependent on climate conditions. Climate change may affect the abundance of pelagic fish such as anchoveta used for fishmeal production, an ingredient in salmon feed. For example, lower catches of anchoveta in southern America in 2012 resulted in a decline in fishmeal and fish oil production, and an associate price rise (Holmyard 2014). Several factors will likely limit the access of fish oils suitable for fish feed in the near future such as requirements for sustainable harvesting, over-fishing of the marine raw materials at the global scale, and an increase in the consumption of the raw materials (Winther et al. 2013). A decrease in natural feed availability leads to reduced fish growth and quality. For example, a fishmeal/oil-free feed impacts flesh composition and may reduce nutritional value, in particular with regards to n-3 polyunsaturated fatty acids (PUFAs)

(Barange et al. 2018). There is extensive R&D on developing alternative and more sustainable feed.

Transition Risks

Regulatory risks/Technology Risks:

Like other sectors, the aquaculture industry may gradually face stricter regulations on greenhouse gas emissions. The largest source of emissions is related to feed production (Norsk klimastiftelse 2018). Hoegh-Guldberg et al. (2019) propose a framework to evaluate price based on a full lifecycle assessment of emissions from new feeds, targeted investments, information and certified campaigns that could help prioritise low-emissions feed options. For example, airfreight transportation of farmed salmon to markets can be more costly than locally wild caught because of the CO_2 cost of travelling (Norsk klimastiftelse 2018).

The aquaculture industry is investing in R&D, both in land-based and offshore facilities. Land based sites may be more energy demanding as a result of the need for Recirculating Aquaculture Systems (RAS). Except for feed and airfreight, salmon farming is not a very energy intensive industry, but as the production sites are often located at a great distance from the power grid, there is considerable use of diesel generators (Norsk klimastiftelse 2018). Renewable energy can reduce the environmental impact of energy production. For example, a transition to onshore power or hybrid solutions is considered in addition to the electrification/hybrid solutions for boats (Norsk klimastiftelse 2018).

Market risks/reputation risks:

The global need for protein is increasing. There is a challenge for agriculture to supply enough food while shifting diets to include more low-carbon sources of ocean-based proteins as a solution to reduce greenhouse gas emissions (Hoegh-Guldberg et al. 2019). Norwegian farmed salmon is mainly an export product and transportation to markets is therefore an issue (Norsk klimastiftelse 2018). Air freight significantly increases the climate footprint. Both increased CO_2 taxes on air cargo and negative consumer reactions can be a threat for increased other market (Norsk klimastiftelse 2018). The key may lie in getting consumers to accept frozen fish and freezing technologies that preserve quality (Norsk klimastiftelse 2018). Furthermore, criticism of the aquaculture industry has been raised both from media, researchers and environmental and recreational NGO's. These criticisms relate to issues of local pollution, feed production and emissions from transportation to markets (Norsk klimastiftelse 2018) as consumers, to an increasing extent, demand that seafood satisfies their preferences for responsible environmental management.

3.4 Impact on maritime industry

Figure 8. The research vessel Johan Hjort. Photo credit: Mark Berry

Shipping is one of Norway's oldest business sectors. The industry employs around 90,000 peoples, generates an economic value for a total of NOK 140 billion (https://www.regjeringen.no). Norwegian ships and sailors sail on all world's oceans, Norwegian maritime producers deliver components and equipment to ships under construction throughout the world and Norwegian maritime service providers offer their skills to customers on the global markets (DNV 2016). The Norwegian government's overall goal for the maritime industry is sustainable growth and value creation. Calculations based on the maritime fleet activities show that domestic Norwegian shipping makes up 9% of all Norwegian greenhouse gas emissions (DNV 2016). The global shipping industry is under pressure to cut climate-altering greenhouse gases and find sustainable shipping solutions. Reduction of greenhouse gas emissions (chapter 5) by implementing available technologies to increase energy efficiency (e.g. improved hull design) and support the development of low-carbon fuels is one of the "ocean action" aiming at contributing to the broader decarbonisation of ocean industries and energy supply chains, including port facilities.

Key findings:

- Climate change can create **opportunities for new transport routes**, especially in the northern areas, where higher temperatures reduce sea ice and lead to a gradual opening of northern trade routes in both the Northeast and Northwest passages. These changes will have important economic, strategic, environmental, and governance implications for the region.
- To achieve climate targets, **changes in economic activity** that will affect trade patterns and the need for ocean-based transport might be required. Trade in new forms of energy such as biofuels and hydrogen can grow rapidly. Norwegian ship equipment producers have taken leading positions in markets that could prove vital in reaching the world's climate goals.

3.4.1 Observed changes

In 2017, more icebergs have drifted into the North Atlantic shipping lanes than usual. Michael Mann, director of the earth system science centre at Pennsylvania State University, argues that this trend will increase in the future. He also points to the risk for changed wind patterns (https://www.theguardian.com/science/2017/jan/19/sea-levels-could-rise-by-six-to-nine-metres-over-time-new-study-warns).

3.4.2 Expected future consequences

The maritime sector will meet stricter regulations to reduce climate change. The industry must also expect indirect effects if other industries cut emissions, and if physical climate change modifies transportation needs and trade patterns (Norsk klimastiftelse 2018). Compared to other environmental phenomena, observed and projected changes in wave and wind climate are expected to have the largest impact on maritime structure designs and operations. An increase in storm activity (intensity, duration and fetch) in some ocean regions, and changes to storm tracks, may lead to secondary effects such as an increased frequency of extreme wave events (abnormal waves, also called rogue or freak waves) (Bitner-Gregersen 2016).

Physical risks

Acute: Physical consequences of climate change can affect the ability to transport goods between countries, especially through extreme weather events that can affect infrastructure and make goods transport more difficult, both on land and at sea (Norsk klimastiftelse 2018). The latter is particularly important as about 80 percent of world trade is transported at sea.

Chronic: Climate change can create opportunities for new transport routes, especially in the northern areas, where higher temperatures will reduce sea ice cover and lead to a gradual opening of northern shipping routes in both the Northeast and Northwest Passages. The new Trans-Arctic shipping routes may be navigable by mid-century (RPC 8.5) (Smith and Stephenson 2013). This enables increased ship traffic in the Arctic and shorter transportation routes between Europe, North America and Asia (EY 2019). Although numerous other no climatic factors also limit Arctic shipping potential, these changes will have important economic, strategic, environmental, and political implications for the region (Smith and Stephenson 2013).

Future rising sea levels, erosions of coastlines or destruction through extreme weather can also result in reduced port capacity in the future emission scenario (IPCC 2019). A complete opening of shipping in the Arctic Ocean between Europe and Asia could lead to a sharp increase in shipping traffic and strengthen Norwegian trade with Asian countries by up to 7% (EY 2019). Northern Norway can become a favourable place for port activity and other ship services (EY 2019). However, increased ship traffic will also possibly result in increased pollution of air and sea in highly vulnerable natural areas, along with an increased risk of environmental disasters associated with oil and gas transportation (EY 2019). This will in turn strengthen the need for international environmental cooperation in the Arctic.

Transition Risks

Regulatory risks/Technology Risks: Both near shore shipping and international shipping can expect the introduction of new emission regulations or a strengthening of current regulations (Norsk klimastiftelse 2018). International shipping is regulated through the International Maritime Organization (IMO). IMO has also adopted an ambitious climate action plan. This plan aims to reduce emissions from international shipping by 50% by 2050 (Hoegh-Guldberg et al. 2019). Considering planned growth in the industry, this will require up to 80% reduction in greenhouse gas emissions (Hoegh-Guldberg et al. 2019).

The energy intensity and absolute GHG emissions from ocean-based transport, can be reduced by technical and operational interventions to reduce energy consumption per tonne of transported goods and substitution of low and zero carbon fuels (e.g. hydrogen and biofuels) for diesel and bunker oil (Hoegh-Guldberg et al. 2019).

The Norwegian national transport plan proposes to transfer more transport work from road to sea. This is regarded as a climate measure as CO_2 emissions from near shore shipping is lower than for trucks on land. Near shore shipping is covered by Norwegian climate policy for the non-quota sector and must expect national requirements to reduce emissions in line with Norway's international climate obligations. As a consequence, stricter climate policy can have positive effects on the industry. The introduction of political incentive schemes for low-emission technology, and penalties for ships that are less environmentally friendly, can reinforce the need to seek zero-emission solutions, such as biofuels and hydrogen (Norsk klimastiftelse 2018).

Market risks/reputation risks: To achieve climate targets there is a need for changes in trade patterns and increase ocean-based transport. New forms of energy such as biofuels and hydrogen can grow rapidly. Within the near shore shipping and offshore segment, new opportunities may emerge including ocean based renewable energy (Norsk klimastiftelse 2018). Increased pressure to develop environmentally friendly solutions and effects of digitalisation will also challenge the industry to innovate. Norwegian ship equipment producers have taken a lead position in markets that could prove vital in reaching the world’s climate goals. Norway is developing into a stronghold for production of battery-driven ship equipment, and Norwegian equipment suppliers are well positioned for the boom in LNG-fuelled ships and other alternative fuels (DNV 2016).

Increasing regional and coastal marine transport to support the exploration and extraction of oil, gas and hard minerals, coupled with increase in Arctic tourism, have brought a complex set of users to the Arctic. This increases the demand for changes in legal and regulatory frameworks for marine safety and environmental protection (https://pame.is/index.php/projects/arctic-marine-shipping). These challenges will also require strong cooperation among the eight members of the Arctic Council (AC) as well as broad engagement between AC and the many non-Arctic stakeholders within the global maritime industry.

There is already increased focus on the importance of climate-friendly shipping from various stakeholders, such as banks, shareholders and civil society. In the first instance, increased reporting requirements and transparency regarding emissions profiles for ships and shipping companies can be expected. In the long term, this could potentially cause changes in capital costs and pressure on freighters to choose the most environmentally friendly shipping services (Norsk klimastiftelse 2018).

3.5 Impact on the petroleum industry

Figure 9. Oil platform. Photo credit: Mark Berry

Oil and gas are very important to the Norwegian economy. Petroleum activities have played a key role in the development of today's welfare state in Norway. Norway is the World's 15th largest producer of oil, the 11th largest exporter and the 3rd largest producer of gas in the world (EIA 2019). Since production on the Norwegian continental shelf began in the early 1970s, petroleum activities have contributed over NOK 14,000 billion to Norway's gross national product measured in current value. At the same time, climate policy is increasingly leading the way for the industry both globally and in Norway. The petroleum industry is increasingly being criticised for its role as one of the main contributors to climate change and ocean acidification (Grasso 2019). Many commentators have highlighted the contradiction at the heart of the Norwegian approach to climate change. On the one hand, a political consensus that Norway should take a leading role in climate policy; on the other hand, a policy of continuing petroleum production and maintaining a strong petroleum industry (Lahn 2019). Understanding 'the Norwegian paradox' may also be relevant beyond its specific national context. The goal of the Paris Agreement to keep global temperature rise below 2°C and pursue efforts to limit it to 1.5°C, challenges all fossil fuel-producing nations with new questions regarding their future contributions to the global energy mix (Lahn 2019). Climate targets may result in changes in both energy production and consumption and in the transition to more renewable energy sources in the global energy mix. The cost of extracting oil can be affected by climate policy, but it has been argued that it is unlikely that it will lead to major changes in the industry. According to NOU (2018), it is more likely that future changes in Norwegian international climate commitments will affect the scope and orientation of Norwegian oil and gas production. (NOU 2018).

Key findings:

- At the global level, the trajectory of **international climate policy cooperation** will determine the extent to which Norway will be able to reconcile its oil and gas production with its climate leadership ambitions. If limiting the supply side of fossil fuels were to become a more established part of the international response to climate change, whether through regulations or norms, this will likely **increase the pressure on Norway oil policy**.
- For the petroleum industry, climate impact can be directly a question about future market prices. In recent years, strong oil demand has been observed. It is the speed of the transition to other energy sources that constitutes the main threat to the petroleum industry. The **development of technology will be crucial to the pace of transition**. In the recent years there has been a strong oil demand, resulting in a slower pace in the development of new technology. This may be altered in the future.

3.5.1 Observed changes

Oil and gas companies are already grappling with the risks posed by climate change, from the physical threats of extreme weather to the challenge of switching to cleaner energy. The industry also has a new item appearing on their agenda: liability lawsuits. For example, the US industry is being met by an increasing number of legal cases from cities and counties that are seeking compensation for climate change related damages (https://www.ft.com/content/d5fbeae4-869c-11e9-97ea-05ac2431f453). In Norway, the oil and gas industry are being challenged by the "Arctic climate lawsuit", the first Norwegian climate court case in history. Norwegian authorities have opened for oil exploration in the Arctic, and environmental organizations have taken the Norwegian state to court to challenge this policy. The climate lawsuit deals with ten new oil exploration permits in the Barents Sea, allocated by the government in 2016. Norwegian environmental organizations have sued the state for violation of the Constitution's environmental clause, section 112, which is to safeguard the right of present and future generations to a liveable climate (http://www.xn--klimasksml-95a8t.no/om-saken/).

Figure 10. Platform in sunset. Photo credit: Mark Berry

3.5.2 Expected future consequences

The world's largest oil and gas companies must cut combined production by 35 % by 2040 if nations are to meet the collective ambitions of the Paris Agreement and limit global warming to below 2°C. Therefore, demand for oil and gas may be reduced accordingly.

Climate-related issues reinforce several risk factors facing by the petroleum sector (Norsk klimastiftelse 2018). Potential changes in the longer term will depend, among other things, on international developments in climate policy as well as oil and gas markets. Existing political tensions around the question of how Norway should reconcile its petroleum industry with its climate ambitions may however provide some insights into future Norwegian petroleum and climate policy (Lahn 2019).

Physical risks

Acute: Although extreme weather might be more common and occurring more frequently, there is little evidence that this will result in any significant change in the Norwegian petroleum industry's existing operations (Norsk klimastiftelse 2018).

Chronic: Climate change has played an important role in expanding access to that untapped storage of oil and natural gas in the Arctic (Eurasia and Woodrow2014). Further, decline in Arctic sea ice is projected to continue in the near-term (2031–2050) due to rising surface air temperature (IPCC 2019) and this could potentially open even more areas to oil and gas exploration. Norway faces production decline at its developed fields in the North Sea and Norwegian sea. Therefore, there has been an increased focus on the unexplored resources in the Barents Sea over the later years. This is partly due to the 2010 Russia-Norway border agreement, which has allowed Norway to open the southern part of the formerly disputed area. Over the past few years, Norway has attracted more than $9 billion in investments in far northern fields (Eurasia and Woodrow 2014). Currently, most of the Norwegian Continental Shelf is open for licensing, with the exception of the areas off Lofoten, Vesterålen and Senja in Northern Norway, the Northern part of the Barents Sea, the area surrounding the Svalbard archipelago as well as some other coastal areas that are defined as ecologically sensitive areas (Lahn 2019). The 2016 licensing rounds with ten new oil exploration permits in the Barents Sea was controversial (Lahn 2019). This led to the mobilization from environmental organizations, the fisheries industry and other stakeholders. The opposition towards petroleum activities outside Lofoten, Vesterålen and Senja islands in Northern Norway has been particularly strong (Kielland 2017, Sæther 2017). These protests are explicitly tied to climate change but also to worries for the marine environment in case of oil spills. They call for a "managed decline" of the oil and gas industry as a whole in Norway (Lahn 2019). The most high-profile recent initiative to protest further oil and gas licensing in Norway is the lawsuit brought by the environmental NGOs.

Also, some governmental agencies in Norway has pointed to the potential climate consequences of future licensing and the need to reconsider licensing in light of climate policy targets (Lahn 2019). In the 2016 and for the first time in Norwegian petroleum history, the Norwegian Environment Agency argued for caution in further licensing for climate policy reasons. In doing so they highlighted the economic risk of expanding oil production in the Barents Sea in a situation where fossil fuel reserves will have to be left undeveloped and thus may become "stranded assets". In the 2019 licencing round, Norwegian Environment Agency were joined by the Norwegian Institute of Marine Research (IMR), who pointed to the findings of the 2018 IPCC report statement that oil and gas consumption will have to be significantly reduced in order to keep global temperature rise below 1.5°C (Lahn 2019). These institutes have not found backing in the Norwegian government and Norwegian licensing policy therefore remains unchanged.

The transition Risks

Regulatory risks/Technology Risks

For the Norwegian oil and gas industry, there seems to be considerable uncertainties associated with the development of policies and regulations at national, European and global levels. If climate change consideration is tightened against the oil sector, activity in the Norwegian petroleum industry will be adversely affected (Norsk klimastiftelse 2018). There is uncertainty in how the Norwegian petroleum policy will develop in the coming years. There are also uncertainties regarding the development of European and global climate policy (Norsk klimastiftelse 2018).

At the national level there are uncertainties regarding new exploration licenses, and the development in ecological sensitive areas such as Lofoten. In addition, the petroleum industry may be facing new regulations such as the government's direct involvement in ownership in licences, changes in the tax regime and increased costs in CO_2 emissions (Norsk klimastiftelse 2018). As the oil industry accounts for around ¼ of Norwegian greenhouse gas emissions (Lahn 2019), higher production-related emissions costs can have a significant influence on the industry. High emission projects may therefore not be realised if the costs for emission is too high for the industry (Lahn 2019).

EU climate policy will directly impact Norwegian climate regulation due to increasing policy integration in this sector. It will also possibly have a major indirect impact on the Norwegian oil and gas industry by determining European demand for natural gas in the decades to come (Lahn 2019). Furthermore, proposals of total ban on drilling in the Arctic have been proposed by the European parliament (https://thebarentsobserver.com/en/industry-and-energy/2017/03/european-parliament-calls-for-ban-oil-arctic).

At the global level, the trajectory of international climate policy cooperation will determine the extent to which Norway will be able to reconcile its oil and gas production parallel with its climate leadership ambitions. If limiting the supply side of fossil fuels were to become a more established part of the international response to climate change, through regulations or norms (Newell and Simms 2019), this will likely increase the pressure on Norway to further revise its present approach (Lahn 2019).

The oil and gas industry face increasing competition from low- and zero-emission energy resources. It is the speed of the transition to other energy sources that constitutes the main threat to the petroleum industry. The development of battery technology, and the response of the automotive industry, will be crucial to the pace of transition. For heavier vehicles and ships, hydrogen can also be an option (Norsk klimastiftelse 2018). In the recent years there has been a strong oil demand, resulting in a slower pace in the development of new technology (Norsk klimastiftelse 2018).

Market risks/reputation risks:

The petroleum industry is facing a substantial market risk as a lower demand due to climate policies and a possible future transition to new energy solutions will result in lower oil prices and therefore decreased profitability for the industry. This may change the focus towards resources or reserves that has the lowest development costs. These will be the "safest" to explore if oil demand and prices decline (Norsk klimastiftelse 2018). Compared to the global oil market the market for gas is more regional and dependent on the European market and European policies. In the short term there will probably be an increase in demand for gas, but with EU long-term climate emission reduction goals, demand of gas may also be reduced in the European market (Norsk klimastiftelse 2018)

The petroleum industry is increasingly being criticised for its role as one of the main contributors to climate change and ocean acidification. As a consequence, there is an increasing number of lawsuits that is raised against the industry or the policy of oil producing countries, including Norway with the “Arctic climate lawsuit”. The oil industry in Norway is dependent on broad political will and therefore societal acceptance to be able to run its business. The fact that constraints on future greenhouse gas emissions may limit the demand for oil and gas in the coming decades has been accepted as a potential economic risk in Norway. At the same time, the realization that stricter climate targets mean less demand for oil and gas can also be signalling new questions about the future of Norway’s main industry – thus, potentially, pointing towards bigger policy changes ahead (Lahn 2019). However, the most important influence on how the debate about the future of Norwegian oil and gas proceeds are likely to be policy developments on the international arena (Lahn 2019).

4 IMPACT OF CLIMATE CHANGE AND OCEAN ACIDIFICATON ON NEW OCEAN-BASED INDUSTRIES

Figure 11. Fish catch. Photo credit: Mark Berry

4.1 Methodology

New ocean-based industries are emerging industries with future potential value in Norway. These were selected on the base of four Norwegian reports: “Forward-looking food production in coast and fjord” (Torrissen et al. 2018), “Value created from productive oceans in 2050” (Olafsen et al. 2012), “Sektoranalyse for de marine næringene i Nord-Norge” (Winter et al. 2013), and “Verdiskapning i næringene” (Verdiskapning i næringene 2019).

4.2 Background

There ocean is expected to play an increasing role in future production of sustainable seafood (see section 3.3 on sustainable low carbon ocean-based proteins) and energy production. There is also a need for new ocean-based measures (chapter 5) to reduce greenhouse gas emissions. Consequently, the global community must cooperate to ensure the right of future generations to a healthy and productive sea (Torrissen et al. 2018). One example is the sustainable production and capture of low-trophic level seafood as the way to increase global food production (SAM 2017, Torrissen et al. 2018, Hoegh-Guldberg et al. 2019).

For fisheries, the development is expected to be relatively stable, but the emergence of new business activities such as harvesting at lower trophic levels, harvesting of snow crabs, and a better utilization of leftover produce from the seafood industry, could provide greater value creation for Norway (Olafsen et al. 2012).

For this section, we focussed primarily on bio-based industries such as: (i) Marine Ingredient Industry that includes utilization of marine raw material for the production of ingredients (e.g. omega-3, marine biochemical); (ii) Unborn marine industry, including harvest at lower trophic level, upwelling, low-trophic production of marine species, etc.; (iii) Exploitation of wild caught and cultivated of seaweed and kelp. Other industries include wind farming and seabed mining industry.

Key findings:

- **Harvesting and increased production of new species could significantly increase value creation and valuable local employment in the future**. A dietary shift toward low carbon marine sources such as sustainably harvested fish, seaweed, and kelp can be a **replacement for emissions intensive land-based sources of protein** (chapter 5).
- When harvesting new species, rapid climate change with associated nonlinear adjustments (distribution and abundance) on keystone species, poses challenges for the management of ecosystems. **Precautionary approaches** should apply in order not to reduce fishery stocks and avoid the risk of ecosystem damage.
- Climate change and ocean acidification are expected to impact many marine species. **Selection of future species for food** and or biomass production should therefore consider species' sensitivity to expected changes in the environment.
- Increased sea temperature is likely to benefit pathogens and promote their spread. Thus, **the risk of disease problems** for cultured organisms may increase in the future.
- Biodiversity is deteriorating worldwide. Ocean acidification and climate change can lead to the local extinction of some species. This can strongly **limit the prospects for marine bioprospecting**.
- **Scaling up renewable marine energy** have been identified as a key global ocean action. This includes offshore floating and fixed wind installations, tidal and wave power, etc. As this has the potential for high mitigation potential, this industry can have significant value potential (se chapter 5).
- **Seabed mining is a new industrial frontier**. However, consequences for carbon sink and impacts on biodiversity must be carefully considered and investigated.

4.3 Harvesting of new marine species

It has been suggested to harvest on different trophic levels to meet increasing global food demand. Furthermore, there is a need for new feed ingredients for the aquaculture industry. Species on lower trophic levels include phytoplankton, zooplankton, mesopelagic fish, sea cucumbers, micro and macro algae, periwinkle, molluscs, polychaete, sea urchins and many more. There is presently little harvest of these species in Norway (Almås and Ratvik 2017).

4.3.1 Wild capture

Macroalgae:

Wild species of kelp are harvested along the Norwegian coast, with an average of 160,000 - 170,000 tonnes of kelp per year and a turnover value of approximately 1.4 billion NOK (Breimo et al. 2018). Kelp is harvested mainly to produce alginate and brown-hued seaweed for seaweed flour. In addition, kelp has the potential to be utilised in the production of fertilizer and biofuel (Gundersen et al. 2017). Sensitive ecosystems such as seagrass meadows and kelp forests are at high risks if global warming exceeds 2°C above pre-industrial temperature, combined with other climate-related hazards (IPCC 2019). As the kelp forest recovers to some shores in northern Norway after the intensive grazing period from sea urchins, there is an increasing interest in expanding the harvesting area northward. This has led to concern, as the consequences of kelp on local ecosystems are unknown. Fishermen in Norway are worried about reduced catches as they blame kelp harvesting for the disappearance of coastal fish species. Kelp is also a potential important player in the blue carbon budget. It contributes to the regulation of the global climate by capturing carbon dioxide (CO_2) and represents a significant part of the carbon sequestered in marine sediments and the deep ocean (Krause-Jensen and Duarte 2016). Furthermore, kelp forests form important habitats supporting high biodiversity. In temperate and boreal regions, such as Norway, the conservation, restoration and sustainable management of kelp forests and seagrass meadows can contribute to climate change mitigation efforts. The high productivity and biodiversity of kelp forests and seagrass meadows make them important providers of various ecosystem services, of which some are similar to those for tropical blue forests (https://www.hi.no/hi/nyheter/2018/juni/blaaskog). The wild harvesting of kelp has sustainability implications for the species and associated ecosystem. Over-exploitation could lead to negative impacts on marine biodiversity, loss of nursery grounds for juvenile invertebrates and fish, reduced contributions to the marine carbon cycle, disrupted transfer of organic materials between ecosystems and reduced coastal protection from erosion and flooding (Morrison 2018). Conservation of kelp might be very important in future and may come in conflict with kelp harvesting.

Zooplankton and mesopelagic fish:

The potential for large-scale harvesting of zooplankton and mesopelagic species is unknown (Verdiskapning i næringene 2019). However, lower trophic level resources constitute enormous biomasses. For example, the production of the zooplankton species *Calanus* in the Norwegian Sea is estimated to be 190-290 million tonnes (Broms et al. 2016). Norway started sustainable harvest of *Calanus* with a quota of 254,000 tonnes for 2019 and 300,000 tonnes of Antarctic krill are fished each year by Norway accounting for about half of this fishery. Most of the krill and *Calanus* catch goes to flour production and functional ingredients, which in turn is used for fish feed and fish farming. As the aquaculture industry needs new sources of omega-3 rich feed ingredients, the theoretical potential and value creation for this activity is high.

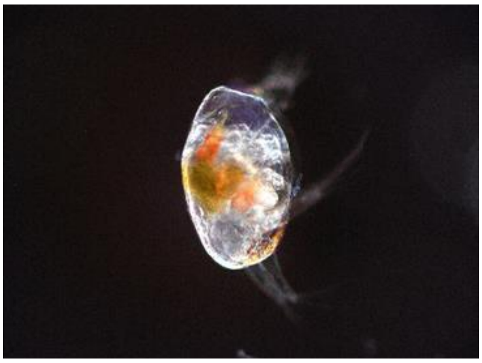

Figure 12. Krill larvae. Photo credit: NORCE

Global warming and ocean acidification as well as restoration of seal and whale population may reduce the potential for krill and *Calanus* exploitation (https://www.dagbladet.no/mat/skulle-bli-rokkes-nye-gull-sa-bestemte-den-seg-for-a-reise/70697544). According to a new study from Atkinson et al. (2019), krill has moved 440 kilometres closer to the South Pole over the past 90 years. *Calanus* has also changed its distribution in Norwegian waters. For example, there has been a significant reduction in the amount of *Calanus finmarchicus* in the Norwegian Sea (Arneberg et al. 2018).

Both krill and *Calanus* are key species in the Norwegian Sea, for example as a major source of food for wild fish. *Calanus* is an important food for krill, herring, mackerel, fish larvae and fry but also endangered seabird species. Increased research on the link between fished zooplankton populations, harvesting, ocean acidification and climate change is required to ensure that fishery is done in a sustainable way. Fishing bans and precautionary approaches should apply in order not to reduce the output of traditional fisheries but to avoid the risk of ecosystem damage (SAM 2017). Norway must also apply the same standards when harvesting in Antarctica as in its own waters (https://framsenteret.no/arkiv/mer-forskning-i-antarktis-5315790-146437/Norway).

Mesopelagic fishes

Mesopelagic species is a collective term for species that live in the water column between 200- and 1000-meters depth. Norwegian vessels only harvested mesopelagic species to a limited extend. However, there is an increased interest from the industry to increase the harvesting (Verdiskapning i næringene 2019). Mesopelagic fish feeding on zooplankton and not currently exploited have a large potential to contribute to the increasing seafood demand (see (SAPEA 2017). Mesopelagic fish species can be used to produce fish feed. However, fundamental knowledge gaps and technical limitations raise doubts about the short-term techno-economic viability. The most recent estimate of an exceptionally high mesopelagic fish biomass remains uncertain due to inadequate sampling methodology and other factors. Extensive utilisation of this resource would require improved biological knowledge of these stocks, and how these are influenced by climate change and ocean acidification.

Snow crab

Until recently, snow crab could only be found in Alaskan, Pacific Russian and Atlantic Canadian waters. Globalisation and growing human access to Arctic waters have expanded the species distribution. Increased marine traffic allowed the introduction of this species into the Barents Sea. Climate change is making it easier to fish the crabs as ice-free periods in the Barents Sea past longer. Norwegian vessels started catching snow crab in 2012, and the increase in catches has been rapid. The Norwegian and Russian authorities agreed to manage this resource with the aim of achieving the highest possible long-term and sustainable economic return on the stock (Verdiskapning i næringene 2019). Based on the average price in 2018, the snow crab quota for 2019 has a first-hand value of NOK 234 million.

In Norway, snow crab may have negative effects on native species and fishery resources. Among other things, cage fishing for snow crabs may conflict with other fishing gear, specifically shrimp trawling. The snow crabs advance into international waters also created a diplomatic dispute (Østhagen and Raspotnik 2019). In 2015, Norway and Russia agreed on a new set of regulations. They used a loophole in international laws to categorise the crab as seabed resource, basically equivalent to a mineral or oil, instead of a fishing resource. Reclassifying the crab allow Russians and Norwegians to deny vessels from other countries to fish as continental shelves define mineral resource boundaries, while distances to shore define fisheries boundaries. An international treaty from 1920 allows anyone to engage in commercial or scientific opportunities on Svalbard. There is now ongoing dispute between Norway and EU states regarding international permits to fish snow crab in Svalbard as the Norwegian continental shelf also extends there (http://polarconnection.org/snow-crab-climate-change/)

This example shows the potential of international conflicts of stocks redistribution. As climate change and ocean acidification contributes to the redistribution of species in and out of legal jurisdictions, it can be expected than these disputes will be more frequent. A new way of negotiating shared resources amongst interested local and global parties is required.

4.3.2 Aquaculture in fjords and along the coast

With one of the longest coastlines in the world, Norway has a lot of potential to expand seafood production and play an important role in food production for the world's growing population.

Alga

Marine algae include micro- and macro-algae that form the basis of the marine food chain. They harvest energy from sunlight through photosynthesis, absorb nutrients and fix carbon from dissolved CO_2 in seawater (Breimo et al. 2018). The growth potential of algae-based industry in Norway is large. The report "Value creation based on productive seas in 2050" from Wither et al. (2018) forecasts algae production to an economic value of NOK 8 billion by 2030 and NOK 40 billion by 2050.

Microalgae are single-celled organisms that grow in the epipelagic zone (0-200 m) of the sea. Large-scale industrial cultivation of marine microalgae is an environmentally favourable approach for meeting the climate goals. It can produce liquid hydrocarbon fuels required by the global transportation sector and supply proteins to feed a global population (Greene et al. 2016). In Norway, it can play an important role as a feedstock for aquaculture and a marine source of both protein and oil (omega 3 fatty acids). Norwegian salmon have already been produced on microalgae diet (BIOMAR 2017). Two Norwegian projects seek to identify the best types of algae suitable for industrial production, optimization of productivity and uncovering the profitability of production on land (http://www.co2bio.no/nasjonal-algepilot-mongstad/, https://goo.gl/u6nrUz).

Seaweeds and kelp have been utilized and harvested commercially in Norway for decades. However, the first commercial license for kelp cultivation in Norway came only in 2014. With cold and nutritious water, Norwegian waters are ideal for kelp cultivation, and the industry is expected to grow substantially (Hancke et al. 2018). A sustainable cultivation of kelp requires an understanding of specific impacts and potential consequences of tare cultivation (Hancke et al. 2018). In recent research project such as KELPPRO investigate the positive and negative effects. Hancke et al. (2018) state that future kelp cultivation industry requires an adaptive management strategy, and it is essential that the industry develops in close connectivity with research and environmental management efforts to succeed. In a modelling study by Broch et al. (2019), they demonstrate that there is higher production potential offshore than in inshore regions for kelp, which is mainly due to the limitations in nutrient availability caused by stratification more often found along the coast. Some suitable locations areas for kelp cultivation have also been identified in areas with high vertical mixing close to the shore (Broch et al. 2019). Cultivation of macroalgae is relatively area demanding, and there are many sectors and interests competing for space in coastal regions (Duarte et al. 2017). Cultivation of Kelp has also been suggested as an ocean measure to reduce greenhouse gas emissions (Chapter 5).

Sea ranching

Sea ranching is defined as the harvesting of marine production as a result of the release of organisms or physical devices that contribute to increased production and easier access to the resource in parts of the production cycle. This differs from farming or cultivation where the organisms are kept in enclosure throughout the production cycle or on a substrate for the purpose of controlling access and optimizing production conditions (Torrissen et al. 2018).

Sea ranching of low trophic organisms can be significantly increased and intensified by artificial upwelling nutritious deeper water layers in fjords. This is a new, unique and proven solution for increased low-trophic production with the potential for a relatively large contribution to increased food and biomass production in fjords. European lobster is currently at a minimum and has little commercial significance compared to approx. 70 years ago when the catches made up 30-40% of the total withdrawal in Europe. With its high market value, there has been great interest in the breeding and release of hatchery-produced lobster to rebuild the stocks and strengthen the fisheries. Lobster as a resource has an important and exclusive position in the coastal culture and increased production could contribute to a significant value creation along the coast (Torrissen et al. 2018).


Figure 13. Sea urchin. Photo credit: NORCE

Another potential candidate is sea urchin. The roe from the green sea urchin has a high market value and its use as feed is under development and production the international market has started (Torrissen et al. 2018).

Organic wastes from fish farming facilities can locally result in increased occurrence, biomass and production of benthic animals. Production of polychaete under aquaculture plants can be 50 times higher than natural production. Harvesting this production for biomass purposes can also reduce the impact of fish farming waste on the benthic environment. Similarly, culturing red sea cucumber under fish farming facilities recycles aquaculture waste and is a value resources on the Asian market (Torrissen et al. 2018).

Controlled supply of nutrients from deeper to upper layers in fjords has been shown to provide a basis for better production conditions for phytoplankton and thus culture-related harvesting through the cultivation of, for example, blue mussels and vase tunicate. Mussels grown in the deep-water influx area are shown to yield 24-95% higher yields of soft parts than mussels grown outside. Sea ranching through controlled influx of nutrient-rich deeper layers of fjords is a unique utilization of low-trophic production that can make a major contribution to realizing some of the largest production for food production along the coast (Torrissen et al. 2018).

The prospect for development for all these species in a long-time perspective (10+years) is promising and opens for other species and methods for cultivation. However, uncertainty as to whether ocean acidification and climate change will impact sea ranching should be considered. Increased sea temperature is likely to improve the conditions for pathogens and promote the spread of pathogens. The risk of diseases for cultured organisms will likely increase. Selection of future species for food and biomass production should include an assessment of the species' tolerance to expected climate and ocean acidification changes in the environment (Torrissen et al. 2018).

Marine fish Farming

Today, Norway has a large production of salmon and rainbow trout. Production of halibut is increasing while cod and spotted wolffish are farmed in some parts of Northern Norway. There is also a small but stable turbot production in Vest-Agder (Torrissen et al. 2018). It is projected that salmon will still dominate the aquaculture in Norway by 2050. However, Torrissen et al. (2018) suggest that cod fish (cod, saithe and haddock) may be the most appropriate species for large-scale production in the sea. They are all native species in Norway and have different feeding requirements. Cod already has a well-established breeding program. Flat fish species are considered as good new candidates to be farmed as products aimed for a northern European market. Norway have good knowledge and long experience in the production of flatfish, and this competence can be transferred into production of new species.

There is also an interesting potential for the farming of key species for the treatment of the lice problems in salmon farming, such as lump sucker and Ballan wrasse. Development of methods for these species is driven by salmon breeders.

4.4 Marine bioprospecting

Marine bioprospecting is a discipline under marine biotechnology that seeks knowledge of genes, biomolecules and properties of marine organisms that may have potential for commercial exploitation (Olafsen et al. 2012). These resources or compounds can be useful in many fields, including pharmaceuticals, agriculture, bioremediation, and nanotechnology. In Europe, marine biotechnology revenues are expected to reach one billion Euro by 2020, which in turn could result in 10,000 new jobs (ECORYS 2014).

Northern marine areas are characterized by many species that specialize in extreme and shifting conditions and are therefore of particular interest (Olafsen et al. 2012). For example, Arctic fishes have evolved an array of unique physiological and biochemical adaptations to sustain sub-zero temperatures (DeVries and Cheng 2005). Many compounds (e.g. biological antifreezes, lipids, enzymes) hold a great potential for marine bioprospecting and biotechnology. Norway's marine areas are large, and most of the biodiversity here is still unexplored. New technology and development of next generation sampling based on self-propelled underwater robots, provides access to organisms retrieved from new marine habitats. At the same time, the rapid development of genetic technology contributes to making the potential for value creation based on marine biological resources to appear more exciting than ever (Verdiskaping i næringene 2019). As biodiversity is deteriorating worldwide, goals for conserving marine diversity cannot be met under current emissions trajectories and associated climate change and ocean acidification (IPBES 2019). It is anticipated that this could possible result in the local extinction of some species, some with biotechnological potential (https://climefish.eu/c4f-barents-sea).

4.5 Residual raw materials

The marine ingredients industry is a collective term for companies that use residual raw materials from the fisheries and aquaculture industries to produce ingredients used in food and drink, dietary supplements and cosmetics (Nofima 2019). Parts of the seafood industry have experienced periods of low profitability, which has increased their interest in using more of the fish and thereby increasing the value of the residual raw materials. Meanwhile, growing environmental awareness has made it less acceptable to waste part of the fish (https://www.kbnn.no/en/article/waste-not-want-not-an-analysis-of-the-marine-ingredients-industry-in-northern-norway). In Norway, a directive promotes the conservation all waste marine raw materials. An efficient handling and logistical systems have been established even for the smallest vessels in the fisheries industry. As a consequence, land-based residual raw material handling industry will likely be established in Norway. Heads, livers, roe, milt and stomachs are directly used in consumer products or to produce ingredients with well-established markets. Currently, 170,000 tonnes of waste raw materials are dumped by the coastal and sea-going fleets. At an average price of NOK 5 per kilo, this is the equivalent of about 1 billion NOK. However, increases in economic value will be linked to the markets' willingness to purchase marine proteins and oils but Norway has the potential to assume a leading position in the global marine ingredients sector by 2050.

4.6 Offshore wind

Scaling up renewable marine energy (offshore floating and fixed wind installations, tidal and wave power, etc.) have been identified as one of the global ocean actions as it has the highest potential to mitigate carbon dioxide emissions (see chapter 5). Technology development, cost reductions and major international development have contributed to offshore wind power being the fastest growing form of renewable energy production in Europe (NORWEA 2017), including in seas bordering the Norwegian seas. In Norway, offshore wind developments have been slow. However, the Norwegian state-owned company Equinor just landed the world's biggest offshore wind contract and is building three wind farms off Britain. Furthermore, Equinor is investing in the Hywind Tampen development, deploying floating offshore wind farms to power its oil and gas production platforms in Norway. The project would consist of 11 wind turbines based on Equinor's floating offshore wind concept. It would be enough to meet about 35% of the annual power demand of the five platforms. However, there are concerns about the possible environmental problems caused by wind farms. For example, Broström (2007) found that generated upwelling by wind farms may be sufficiently enough that the local ecosystem may be influenced. Furthermore, Gattuso et al. (2018) suggest that renewable energy may lead to some local collateral damages on ecosystem services when these systems are deployed in coastal ecosystems, however this study suggest that these impacts may be largely moderated through careful planning and consultation.

4.7 Seabed minerals

The world has a growing need for minerals and metals. The green shift and renewable energy production technologies are also contributing to this demand (Breimo et al. 2018). When it comes to seabed minerals, three main types are considered to be of particular economic interest: massive sulphide ores, manganese nodules and manganese crusts (SPC 2013). For Norway, multi-metallic sulphides are present and possible to recover on the Norwegian continental shelf, but manganese crusts have also been found (Breimo et al. 2018). Extraction of seabed minerals have not started in Norway. However, it is estimated that the Norwegian continental shelf can contain minerals and metals for up to 1000 billion NOK (NTNU 2013). Wither et al. 2018, also suggest environmentally sound mineral resource extraction in the future could support the green transition.

Extraction of new minerals and metals, even at several thousand meters of sea depth, will have negative impact on marine ecosystems (Miller et al. 2017). The prospect of deep-sea mining has been met with warnings from scientists and prominent conservationists who have highlighted the risk of irreversible damage to ecosystems, including those that are poorly understand. They argue that mining with no net loss of biodiversity in the deep sea is an unattainable goal (Van Dover et al. 2017) and that opening a new industrial frontier in the largest ecosystem on Earth and undermining an important carbon sink carries significant environmental risks. Indeed, the mining activity itself could add to greenhouse gas concentrations in the atmosphere by disturbing carbon stores (Sweetman et al. 2018). In the light of the urgent threat from loss of biodiversity because of human activities, the Norwegian goals to conserve and sustainably use nature may be problematic in relation to deep sea mining. Miller et al. (2017) pointed out that improving consumer access to recycling and streamlining manufacturing processes can be a more efficient and economically viable method of sourcing metals than mining virgin ore. This could greatly reduce or even negate the need for exploitation of seabed mineral resources.

5 OCEAN SOLUTIONS TO ADRESS CLIMATE CHANGE AND OCEAN ACIDIFICATION - OPPORTUNITIES FOR ACTION AND TRADEOFFS

Figure 14. The ocean. Photo credit: Mark Berry.

The ocean is one key to achieve climate and societal goals. Ocean-based solutions and actions have different potential to reduce carbon dioxide levels and impacts of climate change and ocean acidification on marine ecosystems and associated services ecosystem services. Each solution is associated with challenges trade-offs and should be considered with caution. Moreover, ocean acidification and climate change can negatively impact their potential.

5.1 Methodology:

This section is based on four key studies/reports describing and comparing ocean solutions and actions. These reports/studies have different approaches and levels of industry focus.

1) Gattuso et al. (2018). Ocean solutions to address climate change and its effects on marine ecosystems. Frontiers in Marine Science, 5 (337).

2) Hoegh-Guldberg et al. (2019) The ocean as a solution for climate change: Five opportunities for action. World Resources Institute. Report. Washington, D.C. Available at www.oceanpanel.org/climate

3) The Global Climate Action Summit (2018). Ocean-Climate Action Agenda. https://www.oceanclimateaction.org/wp-content/uploads/Ocean-Climate-Action-Agenda_FINAL_8.16.18-2.pdf

4) United Nations Global Compact (2019). Global Goals, Ocean Opportunities. https://www.unglobalcompact.org/library/5711

5.2 Background

All people on earth depend directly or indirectly on the ocean (IPCC 2019). Key ocean ecosystems, associated services and marine industries are already being impacted by climate change and ocean acidification (IPCC 2019). Severe and irreversible impacts are projected in the near future (Gattuso et al. 2018, IPCC 2019). Future impacts are dependent on the different GHG emission scenarios with stronger impacts as they become more severe (Bopp et al. 2013). Although there is an increasing political and societal focus on climate change, the current emission reduction pledged under the 2015 Paris agreement have not been fulfilled, and the emission gap is larger than ever (Christiansen and Olhoff 2019). Unless mitigation ambition and action increase in the form of new or updated nationally determined contributions (NDCs), exceeding the 1.5°C goal can no longer be avoided, and achieving the well-below 2°C temperature goal becomes increasingly challenging (Christiansen and Olhoff 2019).

Strong policies and implementation of solution is critical to solve the climate issue. However, solving the global climate change crisis relies also on changing human behaviour (Williamson et al. 2018). Consumer choices regarding food, mobility, and housing, and more generally consumption patterns affect GHG emissions (Faber et al. 2012). Nearly two-thirds of global emissions are linked to both direct and indirect forms of human consumption (Williamson et al. 2018). Adoption of sustainable behaviours is a key component of solving the climate change challenge, and individual behaviour changes when taken up by billions of people can therefore make a decisive difference (Williamson et al. 2018).

Various social actors, both in politics and management, industry and finance, academia and civil society, must emphasize the climate risk when making decisions. (Norsk klimastiftelse 2018). Key enablers for implementing effective responses to climate-related changes in the ocean are the governing authorities (IPCC 2019). Governments have the power to enact legislation which could regulate industries and society to remain within sustainable emission limits and adhere to environmental protection standards. Furthermore business and industry has an impact through production processes and at the same time has the capability to facilitat e climate change mitigation and adaptation through implementing clean technologies (https://unfccc.int/files/na/application/pdf/module_1_7.business_response_to_climate_change_-_bcsdz.pdf).

To date policy responses to climate change have largely focused on land-based actions, while relatively little attention has been paid to ocean-based potential (Rau et al. 2011, Billé et al. 2013, Field and March 2017, Gattuso et al. 2018). However, the ocean also provides major opportunities for action to reduce climate change globally and reduce its impacts on vital ecosystems and ecosystem services (Gattuso et al. 2018, Global climate action summit 2018, Hoegh-Guldberg et al. 2019, UN Global Compact 2019). The ocean already absorbs 93% percent of the heat trapped by the rising anthropogenic CO_2 (Hoegh-Guldberg et al. 2019) and

Key findings:

- There is a battery of **existing and potential ocean-based solutions** that can contribute to mitigate CO_2 emissions and limit impacts of ocean acidification and climate change on marine species, ecosystems and their associated services.
- It is key to recognize **uncertainties and limitations of currently available ocean-based solution.** Technology development and research on potential impacts are urgently needed but some actions related to mitigation (renewable energy, decarbonize industry) and adaptation (protection and restoration of key ecosystems) should be urgently developed.
- Greatest benefit is derived by **combining local and global solutions**, some of which could be scaled up immediately
- **All measures have trade-offs** and multiple criteria must be used for comprehensive assessment off their potential
- Political consistency must be achieved through effective cross-scale governance mechanisms

removes about 25 to 30 % of the anthropogenic CO_2 (Le Quéré et al. 2018) that would otherwise remain in the atmosphere and increase global warming.

5.3 Ocean solutions

Gattuso et al. (2018) present 13 types of global and local scale measures to reduce the scale and impacts of climate change. These were divided into four types of actions: (1) reduction of atmospheric greenhouse gas concentrations, (2), solar radiation management, (3) protection of biota and ecosystems and (4) manipulation of biological ecological adaption. The first two actions were considered "global" and aim at reducing atmospheric CO_2 and its impacts on climate. Solar radiation management is not an ocean-based solution and aims at counteracting warming through increasing albedo in the atmosphere or at the earth's surface, thereby increasing the proportion of solar radiation that is reflected to space. The two other actions were referred as "local" and aim to reduce impacts of site-specific combination of stressors (global and local) and/or reducing the sensitivity of organisms and ecosystems to these drivers.

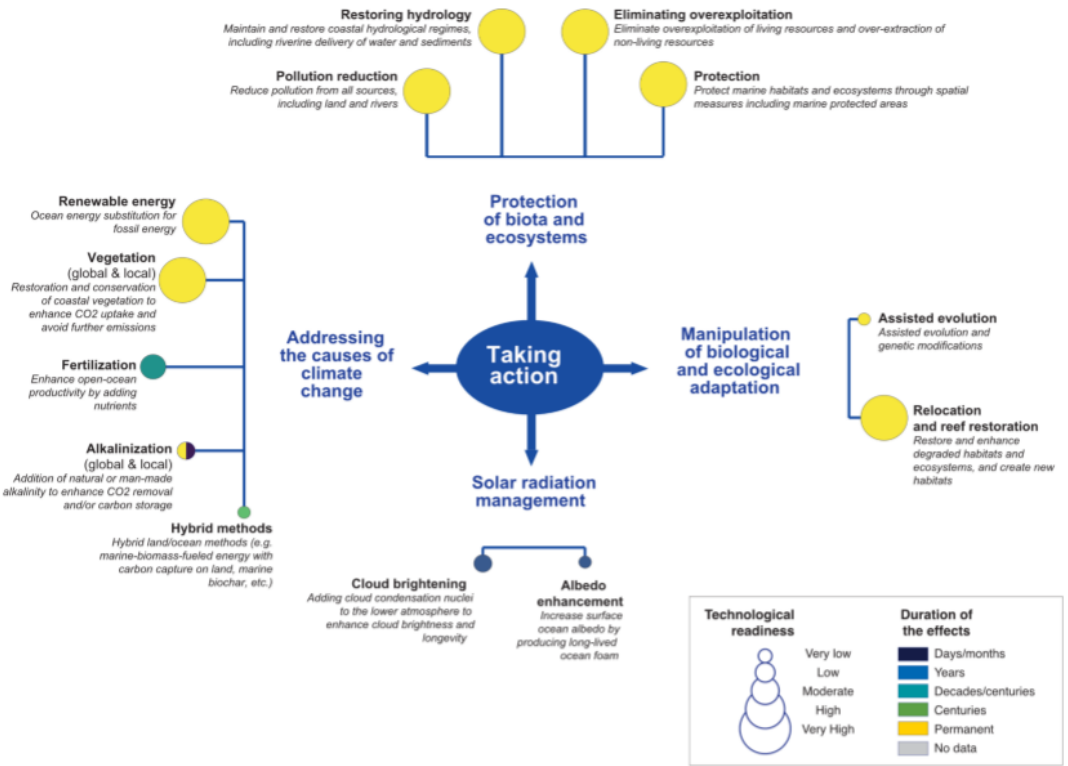

Figure 15: Potential solutions. Four main groups are considered: addressing the causes of climate change (i.e., reducing anthropogenic greenhouse gas emissions or increasing the long-term removal of greenhouse gases, primarily CO_2), solar radiation management, protection of biota and ecosystems (habitats, species, resources, etc.), and manipulation of biological and ecological adaptation (Gattuso et al. 2018).

Four "global" ocean-based solutions can contribute to a global decrease in CO_2 into the atmosphere and into the ocean. The first two options (development of alternative sources of energy and decarbonisation of the industry) aim at decreasing emissions while the next two (CO_2 captures by marine ecosystems and alkalinisation) aim at reducing CO_2 concentration into the atmosphere and the ocean.

1. The ocean can contribute to a decrease in CO_2 emissions from fossil fuels by offering **alternative sources of energy**. Ocean based renewable energy resources can offer alternatives to the use of fossil fuels. Marine-based renewable energy has an enormous energy potential as tides, waves, ocean currents and thermal stratification is estimated to well exceeding future human energy needs (Gattuso et al. 2018, United Nations Global Compact 2019). Hoegh-Guldberg et al. (2019) emphasize that it is critical to reduce barriers to scale up offshore wind (fixed and floating turbines) and invest in new, innovative ocean-based energy sources such as floating solar photovoltaics, wave power, and tidal power. These proposed actions could contribute to 5.4% of the emission reduction required by 2050 to limit warming to 2°C.

2. The Global Climate Action Summit (2018) and the United Nations Global Compact reports (2019) highlight the importance to **decarbonise the industry**. For the ocean-based transport, this could be achieved by the implementation of available technologies to increase energy efficiency (e.g. improved hull design) and support the development of low-carbon fuels as part of a broader decarbonisation of ocean industries and energy supply chains, including port facilities. This could start with decarbonising the domestic fleet, such as coastal ferries. These actions could contribute to 1.8% of the emission reduction required by 2050 to limit warming to 2°C (Hoegh-Gulberg et al. 2019). Such changes could also be implemented in fisheries and aquaculture related industries. A further reduction of the emissions by fisheries and aquaculture operations can be done by optimising wild catch and shifting to low carbon feed options, shift diets toward low carbon marine sources such as sustainably harvested fish, seaweed, and kelp as a replacement for emissions intensive land-based sources of protein. These actions could contribute to 1.2% of the emission reduction required by 2050 to limit warming to 2°C (Hoegh-Gulberg et al. 2019).

3. Part of the **CO_2** present into the atmosphere can be **captured by marine ecosystems**. Coastal wetlands such as tidal marches, mangroves and seagrasses are powerful "blue carbon" sinks that sequester up to 5 times more carbon per area that terrestrial forests. The **restoration and conservation of coastal vegetation** seeks to enhance their carbon sink capacity and avoid emissions from their existing large carbon stocks if degraded or destroyed. This measure does not only have benefits at the global scale (mitigation). Local implementation provides local mitigation (e.g. buffering of local variability) and adaption benefits (e.g. increase ecosystem health) as well as other co benefits (Gattuso et al. 2018). The report from the Global Climate Action Summit (2018) proposes an increase by 20% the global area of coastal wetlands critical to global carbon sequestration and storage (mangroves, tidal marshes, and seagrasses) as compared to 2018. These efforts can be complemented by the expansion of **farmed seaweed** (Hoegh-Gulberg et al. 2019). The potential of the ocean to capture CO_2 could also be artificially increased through **fertilization**. This involves the artificial increase in the ocean primary production and, hence carbon uptake by the open ocean. This can be achieved primarily by adding soluble iron to surface waters where it is currently lacking (Gattuso et al. 2018). These proposed actions could contribute to 1.4% of the emission reduction required by 2050 to limit warming to 2°C (Hoegh-Gulberg et al. 2019).

It is also critical to ensure long-term storage of carbon in the seabed. This can be compromised as a consequence of ocean acidification and climate change but also by emerging industrial activities (e.g. deep-sea mining). Hybrid methods are land-ocean hybrid methods, for example, by including the use of the ocean and its sediments to store biomass, CO_2 or alkaline substances derived from terrestrial sources. For example, crop residue storage on the seafloor, marine storage of CO_2 from land-based bioenergy, or from direct air capture of CO_2 and conversion of such CO_2 to alkaline forms for ocean storage. Hybrid methods also include techniques involving marine-to-land transfers, such as using marine biomass to fuel biomass energy with carbon capture and storage (BECCS) on land or using such biomass to form biochar as a soil amendment (Gattuso et al. 2018).

4. **Alkalinisation** describes the addition of a variety of alkaline substances into seawater to reduce CO_2 concentration by increasing the concentration of carbonate or hydroxide ions in surface waters. This would increase the oceanic uptake of atmospheric CO_2 and limit ocean acidification. Alkaline substances could be land-based mineral, synthetic chemical sources or locally available marine material (e.g. waste shells). This method would require preparation, transportation and distribution within the marine environment (Gattuso et al. 2018).

Four "local" ocean-based solutions aim at limiting negative impacts of ocean acidification and climate change (adaptation).

5. Marine ecosystems are locally exposed to a wide range of global (e.g. ocean acidification and warming) and local (e.g. overfishing, pollution) pressures. While each of these stressors contribute to the overall pressure on the ecosystem, it is the unique combination of these stressors that will determine its fate. **Management of local stressors** is often easier and can be based on existing regulatory framework. For example, reducing local pollution pressures that can directly harm ecosystems or exacerbate hypoxia and ocean acidification (Gattuso et al. 2018) can increase ecosystem resilience to climate change and ocean acidification. Similarly, restoring hydrological regimes (the maintenance and restoration of marine hydrological conditions, primarily in coastal waters, including both the tidal and riverine delivery of water and sediments) can alleviate local changes in global drivers (Gattuso et al. 2018).

6. Healthy and diverse ecosystems are more resilient to climate change and ocean acidification. This resilience is challenged by overexploitation of resources and habitats destruction. **Limit overexploitation** includes ensuring the harvest and extraction of living resources are within biologically safe limits for sustainable use by humans and to maintain ecosystem function and, in the case of non-living resources (e.g. sand and minerals), in levels that avoid irreversible ecological impacts and keep them resilient (Gattuso et al. 2018). The Global Climate Action Summit report (2018) advocates that global ocean fishing and aquaculture should be sustainably managed by 2025 to ensure food security in the face of climate change and ocean acidification.

7. Another way to ensure ecosystem health is the **protection of habitats and ecosystems**. This refers to the conservation of habitats and ecosystems, primarily through marine protected areas (MPAs). For example, increased abundance of marine species is expected to enhance productivity of the surrounding areas which can help buffer against climate impacts and increase resilience. The Global Climate Action Summit report (2018) sets the goal of at least 30%t of the global ocean included in effectively managed MPAs by 2030 to ensure food security, coastal protection, and biodiversity preservation in the face of climate change and ocean acidification.

8. There is a huge potential in **exploring genetic diversity** into the ocean to identify or select individuals more resilient to ocean acidification and climate change. These can be used for aquaculture or ecosystem restoration. Assisted evolution involves large-scale genetic modification, captive breeding and release of organisms with enhanced stress tolerance to future ocean acidification and climate change (Gattuso et al. 2018).

The potential of these ocean-based solutions depends on their contribution to two different attributes: (i) the effectiveness to reduce exposure to ocean acidification and climate change, and (ii) the sensitivity of ecosystems to changes in these drivers (Gattuso et al 2018). The first four "global solutions" are the most effective ones to reduce exposure to the global drivers but do not reduce sensitivity of the ecosystems. On the other hand, the four "local solutions" do not reduce exposure but increase health and resilience of coastal ecosystems and marine environments and this limit the potential negative impacts of ocean acidification and climate change. Consequently, a combination of global and local solutions has the greatest potential in addressing future global drivers and their effects on marine ecosystems and ecosystem services. Prioritization of ocean-based solution can also be based on local needs. For example, sensitive marine ecosystems or services with limited potential for increased resilience and associated services would benefit the most from the implementation of global measures. Proper management of resources can also lead to co-benefits for climate. For example, the most effective local scale interventions to maintain healthy conditions for fisheries and aquaculture is to eliminate overexploitation, restoring hydrology, reducing pollution vegetation and protection. Increasing stock abundance and productivity by effective management of fisheries is likely to compensate for the losses from climate change and ocean acidification (Costello et al. 2016, Cheung et al. 2017, Gattuso et al. 2018).

5.4 Challenges and cautions using ocean solution options and climate-related impacts that could reduce the ability to provide ocean solutions

Ocean based actions increases hope that reaching the 1.5°C target might be possible, along with addressing other societal challenges including economic development, food security, and coastal community resilience (Hoegh-Guldberg et al. 2019). Hoegh-Guldberg et al. (2019) suggest that deploying proposed actions (Ocean-based renewable energy, decarbonize ocean-based transport, management of coastal marine ecosystems, sustainable fisheries and aquaculture) could contribute to as much as 25% of the emission reduction required by 2050 to limit warming to 2°C.

However, there are uncertainties and associated risks with ocean-based solution. Presently, there is a lack of guidance for prioritising ocean-based interventions as there has been relatively little research, development and deployment in this field (Gattuso et al. 2018). It is then critical to determine the effectiveness of a given approach, possible spatial and temporal scales of deployment, trade-offs, associated positive and negative climate, environmental economic, and societal impacts, and implications for ethics, equity and governance (Russell et al. 2012, Preston 2013, Burns et al. 2016, Williamson and Bodle 2016, Gattuso et al. 2018). For example, the deployment of wind farms in coastal ecosystems can create collateral damages on some ecosystems. However, these impacts may be largely moderated through careful planning and consultation (Pelc and Fujita 2002, Gattuso et al. 2018). Decisions favouring any measure must therefore consider multiple criteria including effectiveness, feasibility, co-benefits, governmentality and cost effectiveness rather than only climate related effectiveness (Gattuso et al. 2018). For example, alkalinisation have high mitigation potential, but low technological readiness and governmentality.

Global measures are more effective than local ones in addressing the climate and ocean acidification problem, but they are in general more difficult to implement due to challenges in global governance. In contrast local measures have higher governance readiness, but they only offer local opportunities for mitigation.

The scale of development for most ocean solutions remains far below what would be necessary to effetely address climate change and drivers and impacts (Gattuso et al. 2018). Moreover, many measures are still too uncertain to be recommended (e.g. alkalisation, assisted evolution) until more research is conducted (Gattuso et al. 2018). However, it is urgent to develop the necessary knowledge to sustainably and safely implement ocean-based solutions. As ocean acidification and climate change progress, related impacts on ocean ecosystems and services will reduce ecosystems ability to provide local solutions thereby decrease the possibility for action (Albright et al. 2016, Cheung et al. 2017, Gattuso et al. 2018). For example, Cheung at al. (2018) suggest that potential fish catches will decrease by more than 3 million metric tons per degree Celsius of warming.

5.5 Knowledge gaps in relation to ocean solutions

A successful implementation of ocean-based solution requires a better scientific understanding of benefits, costs, trade-offs, impacts, uncertainties and suitable governance arrangements to inform industry, policy and decision making (Gattuso et al. 2018). There is an urgent need for more investment at local, regional, and global scales into marine research, monitoring, and observing systems to evaluate the biggest climate-related threats to society. For example, one need to better understand the ocean's role as a major carbon sink, how to upscale from physio-chemical changes to ecosystem and associated services impacts, understand how to develop "climate-ready" fisheries, and how to improve nature-based approaches to climate adaptation (The Global Climate Action Summit 2018, Hoegh-Guldberg et al. 2019).

More robust ocean observation systems such as the Global Ocean Observing System and Global Ocean Acidification Observing Network are vital to document and project climate change and ocean acidification as well as understand complex local conditions. This is critical to evaluate how related shifts in ocean conditions will impact regional communities around the world and develop efficient adaptation options. Technological development is also needed (Hoegh-Guldberg et al. 2019) as many of the proposed ocean-based solutions are still in their infancy.

Social challenges are involved in all ocean-based solutions (Gattuso et al. 2018, Mangan et al. 2016). An effective implementation of ocean-based solutions, the need to mitigate and adapt must be first acknowledges (Dannevig and Hovelsrud 2016). That would require increased ocean literacy and communication strategy for all stakeholders. Ocean literacy is the 'understanding of the ocean's influence on you and your influence on the ocean' (Cava et al. 2005). Being ocean literate implies being able to address marine issues in order to develop solutions and actions adapted to our culture and values (Dupont and Fauville 2017). Working closely with educators and communicators, scientists can play a key role in moving toward a more ocean literate society. Furthermore, it will also require insight and research into what hinders and drives collective action (Jagers et al. 2019). A collective action problem is normally described as a situation in which short-term self-interest conflicts with longer-term collective interests, generating a substantial risk that the collective benefit is not produced at all. This all to allow a balanced consideration of new ideas, possible avoiding social conflicts, and to provide decision making and policymakers with robust information.

6 OVERALL IMPACT ON NORWEIGIAN SOCIETY

Figure 16. Coastal community. Photo credit: Mark Berry

6.1 Methodology

As humans depend on ecosystem services, society is affected through the first- and second-order impacts of climate change. Climate sensitive sectors such as agriculture, forests, fishery and aquaculture, and hydro-electric power, are together with oil deposits, the basis of much of the industrial production and employment in Norway. Many research challenges remain to fully evaluate the effects of climate change and ocean acidification on people and society (Hovelsrud 2011). Two factors strongly limit our ability to make a proper assessment: societal adaptive capacity and uncertainties regarding future changes and impacts on climate, impacts and society (Hovelsrud 2011).

There is very limited knowledge on the impact of climate change on the Norwegian economy (CICERO/ Vestlandsforskning 2018). In this section we will therefore explore some general trends in how the impacts from climate change and ocean acidification on marine ecosystems and ocean-based industries can influence the Norwegian society. We will also briefly discuss how policy and society at local and global scales may influence ocean-based industries.

The impact on ocean-based industries and society are dependent on both mitigation efforts (scale of the future emissions) and by the ability for Norwegian society to adapt to present and future conditions.

6.2 Background

Most scientists and policy makers already recognize that climate change and ocean acidification is a complex social challenge and call for urgent action. Rogelj et al. (2016) describe efforts to limit warming to no more than 2°C relative to pre-industrial levels as a societal challenge, and they point out that 'preparing for a global transformation of development pathways is critical'.

As with other global challenges, such as biodiversity loss, tackling climate change and ocean acidification can be described as a wicked or persistent problem. It is characterized by a high degree of complexity and uncertainty; it persists over long time and involves a diverse range of actors with their respective interests and roles (Weseley et al. 2013). A wicked issue typically does not follow the existing organizational structures. Weseley et al. (2013) and Levin et al. (2007) emphasize that climate change and ocean acidification challenges even go beyond other policy problems, thus calling them "super-wicked". They point out that (1) time is running out to implement especially effective mitigation actions, as the natural environment cannot be negotiated with, (2) centralized governance is lacking and coordination across various scales is required, (3) actors aiming to end the problem are also its cause, and (4) decision makers and the public disregard even clear evidence on harmful consequences and instead focus on short term actions. AMAP (2019) found that climate change interacts with other environmental and health stressors together with a range of social, economic, and political factors that are fundamentally changing the nature of the Arctic, especially for the Indigenous cultures and economies.

Facing the severe consequences of inaction as well as the "super-wicked" nature of the challenge, several authors (e.g. Stern 2007, IPCC 2011) have stressed the need for approaches that enable transitions, shifting from currently dominant harmful regimes towards more sustainable forms. These radical changes towards new systems or system configurations carried out by multiple actors over long-time spans (usually 40-50 years) can encompass multiple changes in societal systems (Rotmans and Loorbach 2009). Norwegian society is closely linked to nature, and the Norwegian economy relies to a large extent on the country's natural conditions. This makes the Norwegian economy and society highly vulnerable to effects of climate change, but climate change can also open new opportunities (as discussed in chapters

Key findings:

- There is **limited knowledge** on direct and indirect consequences of climate change and ocean acidification impacts on society.
- Approaches that enable **transitions**, shifting from currently dominant harmful regimes towards more sustainable forms are needed. These include changes in technology, economy, institutions, behaviour, culture, ecology and belief systems.
- Impacts of ocean acidification and climate change on the ocean-based industries are uncertain but are **highly depend on emission scenarios** and then mitigation strategies.
- As ocean acidification and climate change impacts are already visible today, adaptation efforts to reduce the vulnerability of society to climate change impacts is essential. **Norway is perceived to be well prepared to adapt**. However, this capacity is not equally distributed in society and vulnerability to is highly differentiated between regions and sectors in Norway.
- It has been shown that well planned, early adaptation actions save money and reduce impact on society. At present, there is **no national strategy for ocean-based solutions in Norway**.

3-4). At the same time, the Norwegian economy is well integrated into the world economy making it vulnerable to climate change impacts in other countries but also provide additional adaptation opportunities.

6.3 Impact on society depending on mitigation

Impacts of ocean acidification and climate change on society is highly depending on the different CO_2 emission scenarios. Three Norwegian studies compare economic trends under "a business as usual" emission scenario vs. a more sustainable option (CICERO/ Vestlandsforskning 2018, Edvardsen and Almås 2017, Aaheim et al. 2017). Two studies focus on general costs for society (CICERO/ Vestlandsforskning 2018, Aaheim et al. 2017), while the one evaluates impacts on ocean-based industries (Edvardsen and Almås 2017).

CICERO (2019) conclude that socio-economic consequences of a temperature change up to 2.5°C by 2031-2060 may only have moderate impacts in Norway. However, following the same trend till 2100 would lead to a 4.5°C increase with dramatic consequences. Edvardsen and Almås (2017) confirm the "sustainable scenario" is the most favourable for Norwegian economic growth of the ocean-based industries towards 2030. A "sustainable scenario" would increase gross value added (GVA) by approximate 14% while a "business as usual" scenario would reduce GVA by approximately 25% by 2030. Aaheim et al. (2017) emphasize that it may be more profitable to implement major measures to reduce greenhouse gas emissions on the long term but with no positive economic gains at a global level over this century. The return on capital would also depends on type of development. Development with high emissions produce high returns in the first decades, but gradually reduce the return as a consequence of climate change. A low emission path leads an opposite trend. Initially, the return is low due to investment restrictions but limitation of the costly effects of climate change benefits on the long term. As expected, scenarios involving strong mitigation is detrimental for the fossil fuel extracting industries while all other sectors would be positively affected. These changes are associated with conflict between socioeconomic groups including conflicts of interest between generations. The transition to low-carbon economies may lead to negative economic consequences for the next generation, while further generations would benefit.

6.4 Impact on society depending on adaption

Implementation of adaptation solutions to reduce the vulnerability of society to climate change is unavoidable (Climate Policy Info Hub 2019). The urgency of adaptation measures increases dramatically if one fails in climate change mitigation (https://www.met.no/en/archive/climate-change-calls-for-verified-mitigation-and-adaptation-measures). Adaptation implies the reduction of the vulnerability to the harmful effects of ocean acidification and climate change but also taking advantage of potential beneficial opportunities (https://climate.nasa.gov/solutions/adaptation-mitigation/).

Norway is perceived as well prepared to adapt to both gradual and abrupt changes in climate, as it scores well on a number of factors associated with adaptive capacity, such as "wealth, technology, education, information, skills, infrastructure, access to resources, and management capabilities" (McCarthy et al. 2001). Sygna et al. (2004) suggest that while Norway has a high technical and financial capacity, the ability of communities to adapt is highly variable within Norway. Vulnerability is shaped not only by exposure, but also by underlying social and economic conditions that shape adaptive capacity. It depends on economic wealth, social structures, and previous experience with climate variability.

The impact of climate change and ocean acidification on sensitive sectors (ocean-based industries) are likely to be felt more severely in some regions than in others (Sygna et al. 2004).

While Norway is sometimes regarded as a potential winner from increased temperature, analysis of the social and economic context shows that there are important barriers to adaptation that may exacerbate negative impacts on certain sectors and regions (Sygna et al. 2004). For example, if accessible fish stocks get depleted, traditional inshore fisheries would be the first to be impacted as larger vessels have a better ability to adapt (e.g. travel farther, able to pursue different species).

As compared to small scale fisheries, the adaptive capacity of the Norwegian aquaculture industry is strong. The sector is innovative, financially strong and used to handle highly variable weather. However, they may underestimate the consequences of climate change, and may not be able to adapt fast enough to threads and potential benefits. Traditional environmental issues rather than ocean acidification or climate change is mainly driving current industry's innovations. A stronger focus on how to adapt to ocean acidification and climate change may strengthen the capacity of the industry to exploit the benefits climate change can offer (Hovelsrud 2016). On the other hand, ill-informed aquaculture choices increase the risk of maladaptation and further livelihood losses. For example, farm facilities not adapted to the range of variability expected in the near future may suffer higher cost of adaptation if maladaptation options are chosen first (Barange et al. 2018). Operational and breeding strategies could be implemented to reduce the impact of rises in ocean temperature and acidification. Stronger materials and better system designs (including mooring), coupled with the development and implementation of rigorous technical guidelines (Barange et al. 2018), play a role in reducing vulnerability to climate change in the marine aquaculture in Norway. Moving farming facilities further out offshore to cooler/deeper waters could free up coastal areas and reduce negative coastal environmental impact from fish farming activities (Verdiskapning i næringene 2019). Large offshore facilities would require large and powerful installations. Development of such expertise would offer significant opportunities nationally and internationally for the equipment industry. Moving water-based aquaculture (especially cages and pens for finfish) onto land and employing recirculating aquaculture system (RAS) technologies are also being proposed as a means of reducing exposure to climatic extremes (Barange et al. 2018). Rising ocean temperature open the possibility to exploit greater numbers of thermophilic species (Olafsen et al. 2012) increasing the potential adaptive capacity through economic diversification by providing the ability to shift from one species to another (Blanchet et al. 2019). Development of forecasting capabilities (e.g. early warning signal for extreme events) could assist marine resource users to plan their activities, minimise risks due to adverse conditions, and maximise opportunities (Spillman et al. 2014). This knowledge would also be of great benefit for marine managers and lead to science-based spatial planning and identification of new favourable and unfavourable areas and increase industry resilience to climate variability. A new Norwegian Research Centre on Sustainable Climate Change Adaptation (Noradapt) was established in 2019 and seeks to build knowledge on sustainable climate change adaptation. Noradapt holds that all adaptation efforts should be in accordance with the principles of sustainable development to avoid adding to the problem of climate change.

6.5 Policy and management

Coastal management is complex and will become increasingly complicated under climate change and ocean acidification (Wesely et al. 2013). Achieving "blue growth" is a current strategy of the Norwegian government. It will require a strengthening of the coastal zone management in order to maintain and further expand the capacity for increased activities (e.g. aquaculture, shellfish, kelp production, tourism), as well as ensuring that coastal ecosystems and services are resilient to the increasing environmental impacts (https://www.vestforsk.no/sites/default/files/migrate_files/acid-coast-finalposter-1-.pdf). For example, Dannevig et al. (2019) suggest that strategies to measure and prevent impacts of ocean acidification in Norway, are urgently needed to strengthen marine ecosystem resilience, adapt marine industries and coastal zone management. Adaptation measures include the reduction of other stressors (e.g. pollution and harvesting), protection of key ecosystems, management of land use that increases nutrient supply, and special planning of shellfish farming to avoid zones with local sources of acidification. This would require a national strategy that is not currently existing in Norway (Dannevig et al. 2019). The importance of adaptation has to a large extent been neglected within policy. Until now, climate policy has been equated with greenhouse gas mitigation policies and has not included measures aimed at reducing harmful effects or taking advantage of opportunities produced by climate change (Dannevig and Hovelsrud 2016.

The most important climate impacts may not be captured in studies focusing on a single system, sector or scale (Dannevig and Hovelsrud 2016). There is a need for adaptive co-management of the coastal zone (Dannevig et al. 2019). This requires greater interaction and participation across sectors and administrative level in coastal zone management. Coastal zone plans must also cover a wider geographical area. Multidisciplinary research approaches are needed to ensure better integration, sustainability, and synergies among activities in the coastal zone. Coastal areas are not just the literal boundary between fresh water, terrestrial and open sea ecosystems. They are also the practical interface whereby humans have been interacting with, and adapting to, their natural surroundings for thousands of years. A coupling between natural and social science studies is critical to assess ecosystem status and provides the foundation for understanding the future of the primary biological and socio-economic drivers of development in the northern regions (Jørgensen and Renaud 2015).

A better understanding of the threats and opportunities associated with climate change, ocean acidification and climate policy give us a better basis for making good decisions such as strategic investments in both the public and private sectors (NOU 2018). Furthermore, it can provide a faster and smoother transition to a low-emission society.

Global climate change will also increase the pressure on Norway's established foreign policy and its role in international institutions. Increasingly, climate change is perceived as a threat multiplier that can increase the risk of conflict in many ways (CICERO/Vestlandsforskning 2019). For example, movement of fish stocks (e.g. mackerel and NSS herring) due to global changes can lead to international disputes on harvest rights and quota sharing. Transnational expansion may lead to international (re-)negotiations on quotas and fishing rights.

7 OVERALL CONCLUSIONS

Ocean acidification and climate change are and will profoundly after marine environment, ecosystems and their associated services. Impacts on ocean-based industries is already visible and the extend of future impacts is highly dependent on what greenhouse gas emission scenarios will be followed. Impacts are projected to be more or less severe depending on human’s ability to apply mitigation (actions that are taken to reduce and curb greenhouse gas emissions) and adaption (actions that are based on reducing vulnerability to the effects of climate change). Several ocean-based solutions are available. Global mitigation solutions include the development of ocean based renewable energy, decarbonisation of ocean-based industry, CO_2 capture by the ocean and marine organisms and ecosystems. Local adaptation options involve the management of local stressors, limitation of the over-exploitation of resources, the protection of habitat and ecosystems and the exploration of genetic diversity.

Socio-economic consequences of climate change and ocean acidification will be dependent on the ability to quickly implement such mitigation and adaptation strategies. The understanding on the impacts on society is limited but it is clear that the more sustainable emission scenarios favour economic benefits on the long term. The implementation of adaptation solutions is critical to minimize the negative impacts and reduce the vulnerability of society. Norway is perceived to be well prepared to adapt. However, the adaptive capacity is not equally distributed and vulnerability to climate change and ocean acidification is highly differentiated between regions and sectors in Norway.

There are controversies and uncertainties around many of the current and new ocean-based solutions and ocean-based industries and their effects on the environment and society. Furthermore, climate change and ocean acidification have the potential to interact with these solutions. To be able to prioritize and successfully implement these solutions, there is an urgent need for the development of these solutions as well as a better scientific understanding of their costs, benefits and suitability at all levels from ecosystem to society.

References

Aaheim, A., Wei, T., Romstad, B., (2017). Conflicts of economic interests by limiting global warming to +3 °C, Mitig Adapt Strateg Glob Change (2017) 22: 1131. https://doi.org/10.1007/s11027-016-9718-8

Aksnes, D. L., Aure, J., Johansen, P.-O., et al. (2019). Multi-decadal warming of Atlantic water and associated decline of dissolved oxygen in a deep fjord. Estuarine, Coastal and Shelf Science, 228, 106392. doi:https://doi.org/10.1016/j.ecss.2019.106392

Albright, R., Anthony, K. R., Baird, M., et al. (2016). Ocean acidification: linking science to management solutions using the great barrier reef as a case study. J. Environ. Manage. 182, 641–650. doi: 10.1016/j.jenvman.2016.07.038

Almås, K.A. og Ratvik, I., (2017). «Sjøkart mot 2050,» SINTEF, Trondheim, 2017. https://www.sintef.no/contentassets/b26c5aed53be4385b4ab770c24761a95/sjokart--endelig-versjon-7.april-2017.pdf

AMAP (2019). Arctic Climate Change update 2019, AMAP. https://www.amap.no/documents/download/3298/inline

Anttila, K., Couturier, C., Øverli, Ø. et al. (2014). Atlantic salmon show capability for cardiac acclimation to warm temperatures. Nat Commun 5, 4252 doi:10.1038/ncomms5252

Araújo, R. M., Assis, J., Aguillar, R. et al. (2016). Status, trends and drivers of kelp forests in Europe: an expert assessment Biodivers Conserv. 25: 1319. https://doi.org/10.1007/s10531-016-1141-7

Arnberg, M., Calosi, P., Spicer, J. I., et al. (2018). Effects of oil and global environmental drivers on two keystone marine invertebrates, Scientific Reports (2018). DOI: 10.1038/s41598-018-35623-w

Arneberg, P. and Jelmert, A. (2017). Status for miljøet i Barentshavet - rapport fra Overvåkingsgruppen (Fisken og Havet). Havforskningsinstituttet.

Arneberg, P., van der Meeren, G. I. and Frantzen, S. (2018). Status for miljøet og ytre påvirkning i Nordsjøen og Skagerrak – rapport fra Overvåkingsgruppen 2018. Fisken og Havet, særnummer 3-2018, Havforskningsinstituttet.

Atkinson, A., Hill, S., Pakhomov, L. et al. (2019). Krill (*Euphausia superba*) distribution contracts southward during rapid regional warming. Nature Climate Change, 9(2), 142-147. doi:10.1038/s41558-018-0370-z

Baillon, S., Hamel, J.-F., Wareham, V. E., and Mercier, A. (2012). Deep cold-water corals as nurseries for fish larvae. Frontiers in Ecology and the Environment, 10(7), 351-356. doi:10.1890/120022

Barange, M., Bahri, T., Beveridge, M. C. M., eds. (2018). Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. FAO Fisheries and Aquaculture Technical Paper No. 627. Rome, FAO. 628 pp.

Barton, A., Waldbusser, R.A., Feely, S. B., et al. 2015. Impacts of coastal acidification on the Pacific Northwest shellfish industry and adaptation strategies implemented in response. Oceanography 28(2):146–159, https://doi.org/10.5670/oceanog.2015.38.

Baudron, A. R., Needle, C. L., Rijnsdorp, A. D., et al.. (2014), Warming temperatures and smaller body sizes: synchronous changes in growth of North Sea fishes. Glob Change Biol, 20: 1023-1031. doi:10.1111/gcb.12514

Beaugrand, G., Brander, K. M., Alistair Lindley, J. et al. (2003). Plankton effect on cod recruitment in the North Sea. Nature, 426(6967), 661-664. doi:10.1038/nature02164

Bergh, Ø., Asplin, L., Boxaspen, K. et al. (2007). KLIMAENDRINGER – konsekvenser for akvakultur i Norge. IMR 2–2007

Billé, R., Kelly, R., Biastoch, A. et al. (2013). Taking action against ocean acidification: a review of management and policy options. Environmental Management (2013) 52: 76-779. https://doi.org/10.1007/s00267-013-0132-7

BIOACID 2018: https://www.oceanacidification.de/category/news-en/?lang=en

BIOMAR (2017). Biomar først ute med mikroalger i fôret. https://goo.gl/6BH2cM

Bitner-Gregersen, E. (2016) Rethinking rouge waves. Towards better modelling, insight and action. DNV-GL. https://www.dnvgl.com/feature/rogue-waves.html

Blanchet, M.-A., Primicerio, R., Smalås, A., et al. (2019). How vulnerable is the European seafood production to climate warming? Fisheries Research, 209, 251-258. doi:https://doi.org/10.1016/j.fishres.2018.09.004

Blå muligheter (2019). Regjeringens oppdaterte havstrategi. Nærings- og fiskeridepartementet. https://www.regjeringen.no/globalassets/departementene/nfd/dokumenter/strategier/nfd_havstrategi_2019_norsk_uu.pdf

Bonanomi, S., Pellissier, L., Therkildsen, N. O., et al. (2015). Archived DNA reveals fisheries and climate induced collapse of a major fishery. Scientific Reports, 5, 15395. doi:10.1038/srep15395

Bopp, L., Resplandy, L., Orr, J. C., et al. (2013). Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. Biogeosciences, 10(10), 6225-6245. doi:10.5194/bg-10-6225-2013

Boyd, P. W., Collins, S, Dupont, S, et al. (2018). Experimental strategies to assess the biological ramifications of multiple drivers of global ocean change—A review. Glob Change Biol. 2018; 24: 2239– 2261. https://doi.org/10.1111/gcb.14102

Brander, K. M. (2007). Global fish production and climate change. Proceedings of the National Academy of Sciences, 104(50), 19709-19714. doi:10.1073/pnas.0702059104

Breimo, G., Leitet, M., Høyli, R., et al. (2018). Havnæringene i nord. Næringsutvikling og verdiskaping frem mot 2040. SINTEF report; 2018:01146. https://www.sintef.no/publikasjoner/publikasjon/?pubid=CRIStin+1704201

Breitburg, D., Levin, L. A., Oschlies, A., et al. (2018). Declining oxygen in the global ocean and coastal waters. Science, 359(6371), eaam7240. doi:10.1126/science.aam724010.1073/pnas.0702059104

Broch, O. J., Alver, M. O., Bekkby, T. et al. (2019). The Kelp Cultivation Potential in Coastal and Offshore Regions of Norway. Frontiers in Marine Science, 5(529). doi:10.3389/fmars.2018.00529

Broms, C., Strand, E., Rong Utne, R. et al (2016). Vitenskapelig bakgrunnsmateriale for forvaltningsplan for raudåte, Fisken og havet nr. 8/2016

Broström, G. (2008). On the influence of large wind farms on the upper ocean circulation. Journal of Marine Systems, 74(1), 585-591. doi:https://doi.org/10.1016/j.jmarsys.2008.05.001

Burkholder, J. M., and Shumway, S.E. (2011). Bivalve shellfish aquaculture and eutrophication, In: Shumway SE (ed) Shellfish and the environment. Wiley, New York, NY, p155–215

Burns, E. T., Flegal, J. A., Keith, D. W. et al. (2016). What do people think when they think about solar geoengineering? A review of empirical social science literature, and prospects for future research. Earth's Future, 4(11), 536-542. doi:10.1002/2016ef000461

Callaway, R., Shinn, A., Grenfell, S. E., et al. (2012). Review of climate change impacts on marine aquaculture in the UK and Ireland. Aquatic Conservation: Marine and Freshwater Ecosystems, 22 (3), pp. 389-421. https://doi.org/10.1002/aqc.2247

Cava F., Schoedinger, S., Strang, C. (2005) Science content and standards for ocean literacy: a report on ocean literacy. Available at http://www.coexploration.org/oceanliteracy/documents/ OLit2004-05_Final_Report.pdf.

Cheung, W. W. L., Reg, W., Telmo, M., et al. (2007). Intrinsic vulnerability in the global fish catch. Marine Ecology Progress Series, 333, 1-12. Retrieved from https://www.int-res.com/abstracts/meps/v333/p1-12/

Cheung, W. W. L., Sarmiento, J. L., Dunne, J. et al. (2012). Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. Nature Climate Change, 3, 254. doi:10.1038/nclimate1691 https://www.nature.com/articles/nclimate1691#supplementary-information

Cheung, W. W. L., Reygondeau, G., and Frölicher, T. L. (2017). Large benefits to marine fisheries of meeting the 1.5°C global warming target. Science, 354(6319), 1591-1594. doi:10.1126/science.aag2331

Cheung, W. W. L, Jones, M. C., Reygondeau, G., et al. (2018). Opportunities for climate-risk reduction through effective fisheries management. Glob Change Biol. 2018; 24: 5149– 5163. https://doi.org/10.1111/gcb.14390

Chierici, M., Vernet, M., Fransson, A., et al. (2019). Net community production and carbon exchange from winter to summer in the Atlantic water inflow to the Arctic Ocean. Frontiers in Marine Science, 6(528). doi:10.3389/fmars.2019.00528

Christiansen, J. S., Mecklenburg, C. W., Karamushko, O. V. (2014). Arctic marine fishes and their fisheries in light of global change. Global Change Biology, 20(2), 352-359. doi:10.1111/gcb.12395

Christiansen, J. and Olhoff, A. (2019) Lessons from a decade of emissions gap assessments. United Nations Environment Programme, Nairobi. https://wedocs.unep.org/bitstream/handle/20.500.11822/30022/EGR10.pdf?sequence=1&isAllowed=y

Christie, H., Norderhaug, K. M., Fredriksen, S. (2009). Macrophytes as habitat for fauna. Mar Ecol Prog Ser 396:221-233. https://doi.org/10.3354/meps08351

CICERO/ Vestlandsforskning (2018). Oppdatering av kunnskap om konsekvenser av klimaendringer i Norge. Oppdragsrapport, M-1209, 177 p. https://www.miljodirektoratet.no/publikasjoner/2019/januar-2019/oppdatering-av-kunnskap-om-konsekvenser-av-klimaendringer-i-norge/

Climate Policy Info Hub (2019). Mitigation: Co-Benefits and Interlinkages to Adaptation (https://climatepolicyinfohub.eu/mitigation-co-benefits-and-interlinkages-adaptation).

Colburn, L., Jepson, M., Weng, C. et al. (2016). Indicators of climate change and social vulnerability in fishing dependent communities along the eastern and gulf coasts of the U.S. Marine Policy. Biology and Environmental Science Faculty Publications. 55.

Collins, M., Knutti, R., Arblaster, J. et al. (2013). Long-term Climate Change: Projections, Commitments and Irreversibility. In T. F. Stocker, D. Qin, G-K. Plattner, M. M. B. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P. M. Midgley (Eds.), Climate Change 2013 - The Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 1029-1136). (Intergovernmental Panel on Climate Change). New York NY USA: Cambridge University Press.

Cushing, D. H. (1982) Climate and Fisheries. London: Academic Press.

Dahlke, F. T., Butzin, M., Nahrgang, J., et al. (2018). Northern cod species face spawning habitat losses if global warming exceeds 1.5°C. Science Advances, 4(11), eaas8821. doi:10.1126/sciadv.aas882

Dannevig, H., and Hovelsrud, G. K. (2016). Understanding the need for adaptation in a natural resource dependent community in Northern Norway: issue salience, knowledge and values. Climatic Change, 135(2), 261-275. doi:10.1007/s10584-015-1557-1

Dannevig, H., Mohus, T., Groven, K., (2019). Forslag til politikk for forvaltning av havforsuring i norske kystfarvann, 6-2019. Affiliation: Vestlandsforsking. https://www.vestforsk.no/sites/default/files/2019-07/Politikk%20for%20havforsuring_VF-rapport%206-2019.pdf

Deutsch, C., Ferrel, A., Seibel, B., et al. (2015). Climate change tightens a metabolic constraint on marine habitats. Science, 348(6239), 1132-1135. doi:10.1126/science.aaa1605

DeVries, A. L. and Cheng, C-H. C. (2005). Antifreeze proteins and organismal freezing avoidance in polar fishes. In: Farrell, A. P., Steffensen, J. F. (eds) Fish physiology, vol 22. Academic Press, San Diego, pp 155–20

DNV (2016). Charting a course for green coastal shipping. Input to the Norwegian government's commission on green competitiveness from the Green Coastal Shipping Programme. doi: 10.13140/RG.2.2.32516.94088

Duarte, C. M., Wu, J., Xiao, X., et al. (2017). Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation? Frontiers in Marine Science, 4(100). doi:10.3389/fmars.2017.00100

Dupont, S. and Fauville, G. (2017). "Ocean literacy as a key toward sustainable development and ocean governance," Chapters, in: Handbook on the Economics and Management of Sustainable Oceans, chapter 26, pages 519-537 Edward Elgar Publishing.

ECORYS and consortium partners (2014). Study in support of impact assessment work on blue biotechnology. https://ec.europa.eu/maritimeaffairs/publications/study-support-impact-assessment-work-blue-biotechnology_fr

Edvardsen, T. and Almås, K. A. (2017). Norsk havøkonomi mot 2050 – En videreføring av OECD’s rapport The Ocean Economy in 2030. SINTEF, Rapport nr. OC-2017 A-041

EIA (2019). International Energy Portal. Washington, D.C.: U.S. Energy Information Administration. https://www.eia.gov/

Eide, A., Ese, A., Hoel, A. (2014). Fisheries management and global warming effects of climate change on fisheries in the Arctic region of the Nordic countries. ISBN 978-92-893-2729-9. https://munin.uit.no/handle/10037/6780

Ellis, R. P., Urbina, M. A., Wilson, R. W. (2017). Lessons from two high CO_2 worlds – future oceans and intensive aquaculture. Glob Change Biol, 23: 2141-2148. doi:10.1111/gcb.13515

Eurasia, G., and Woodrow W. (2014). Opportunities and challenges for Arctic oil and gas development. Retrieved from http://www.deslibris.ca/ID/243976

EY (2019). Utredning om kunnskap og håndtering av grenseoverskridende klimarisiko i utvalgte land. M-1320, 88s.

Faber, D., Nelissen, G., Hon, H. et al. (2012). Tsimplis Regulated slow steaming in maritime transport: An assessment of options, costs and benefits CE Delft, Delft. https://theicct.org/sites/default/files/publications/CEDelft_slow_steaming_2012.pdf

Fagerli, C. W., Norderhaug, K. M., Christie, H. et al. (2014). Predators of the destructive sea urchin grazer *Stronglyocentrotus droebachiensis* on the Norwegian coast. Marine Ecology Progress Series 502: 207-218.

Field, C. B., and Mach, K. J. (2017). Rightsizing carbon dioxide removal. Science, 356(6339), 706-707. doi:10.1126/science.aam9726

Filbee-Dexter, K., and Wernberg, T. (2018). Rise of Turfs: A new battlefront for globally declining kelp forests. BioScience, 68(2), 64-76. doi:10.1093/biosci/bix147

Flæte, O., Bardalen, A., Dalen, L., et al. (2010). Adapting to a changing climate. Norway's vulnerability and the need to adapt to the impacts of climate change. - NOU. Norwegian Ministry of the Environment, Oslo, 296 s. https://www.regjeringen.no/contentassets/00f70698362f4f889cbe30c75bca4a48/pdfs/nou201020100010000en_pdfs.pdf

Forsgren, E., Aarrestad P. A, Gundersen, H. et al. (2015). Klimaendringenes påvirkning på naturmangfoldet i Norge - NINA Rapport 1210. 133 s. https://www.miljodirektoratet.no/globalassets/publikasjoner/M443/M443.pdf

Forster, J., and Hirst, A. G. (2012). The temperature-size rule emerges from ontogenetic differences between growth and development rates. Functional Ecology, 26(2), 483-492. doi:10.1111/j.1365-2435.2011.01958.x

Fossheim, M., Primicerio, R., Johannesen, E. et al. (2015). Recent warming leads to a rapid borealization of fish communities in the Arctic. Nature Climate Change, 5, 673. doi:10.1038/nclimate2647

Free, C. M., Thorson, J. T., Pinsky, M. L. et al. (2019). Impacts of historical warming on marine fisheries production. Science, 363(6430), 979-983. doi:10.1126/science.aau1758

Gattuso, J.-P., Magnan, A., Billé, R. et al. (2015). Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. Science, 349(6243), aac4722. doi:10.1126/science.aac472

Gattuso, J.-P., Magnan, A. K., Bopp, L. et al. (2018). Ocean Solutions to Address Climate Change and Its Effects on Marine Ecosystems. Frontiers in Marine Science, 5(337). doi:10.3389/fmars.2018.00337

Gobler, C. J., Doherty, O. M., Hattenrath-Lehmann, T. K., et al. (2017). Ocean warming since 1982 has expanded the niche of toxic algal blooms in the North Atlantic and North Pacific oceans Proc. Natl. Acad. Sci., 114 (2017), pp. 4975-4980, 10.1073/pnas.1619575114

Gourlie, D. (2017). Reeling in uncertainty: adapting marine fisheries management to cope with climate change effects on ocean ecosystems. Environmental Law, 47(1), 179-224. Retrieved from http://www.jstor.org/stable/44219040

Grasso, M. (2019). Oily politics: A critical assessment of the oil and gas industry's contribution to climate change. Energy Research & Social Science, 50, 106-115. doi:https://doi.org/10.1016/j.erss.2018.11.017

Greene, C. H., Huntley, M.E., Gerber, L.N., et al. (2016). Marine microalgae: Climate, energy, and food security from the sea. Oceanography 29(4):10–15, https://doi.org/10.5670/oceanog.2016.91.

Griffith, A. W., and Gobler, C. J. (2019). Harmful algal blooms: A climate change co-stressor in marine and freshwater ecosystems. Harmful Algae. doi:https://doi.org/10.1016/j.hal.2019.03.008

Griffith, A. W., Shumway, S. E., and Gobler, C. J. (2019). Differential mortality of north atlantic bivalve molluscs during harmful algal blooms caused by the dinoflagellate, *Cochlodinium (a.k.a. Margalefidinium) polykrikoides*. Estuaries and Coasts, 42(1), 190-203. doi:10.1007/s12237-018-0445-0

Gubbins, M. (2006). Impacts of Climate Change on Aquaculture in Marine Climate Change Impacts Annual Report Card 2006 (Eds. Buckley, P.J, Dye, S.R. and Baxter, J.M), Online Summary Reports, MCCIP, Lowestoft, www.mccip.org.uk

Gullestad, P., Abotnes, A. M., Bakke, G. et al. (2017). Towards ecosystem-based fisheries management in Norway – Practical tools for keeping track of relevant issues and prioritising management efforts. Marine Policy, 77, 104-110. doi:https://doi.org/10.1016/j.marpol.2016.11.032

Gundersen, H., Bryan, T., Chen, W. et al. (2017). Ecosystem Services: In the Coastal Zone of the Nordic Countries. Copenhagen: Nordisk Ministerråd. http://norden.diva-portal.org/smash/record.jsf?pid=diva2%3A1067839&dswid=-4231

Hancke, K., Bekkby, T., Gilstad, M. (2018). Taredyrking – mulige miljøeffekter, synergier og konflikter med andre interesser i kystsonen. NIVA-rapport 6423

Hanssen-Bauer, I., Førland, E. J., Haddeland, I. (2015). Klima i Norge 2100. NCCS report no 2/2015.https://cms.met.no/site/2/klimaservicesenteret/rapporter-og-publikasjoner/_attachment/6616?_ts=14ff3d4eeb8

Hanssen-Bauer, I., Førland, E. J., Haddeland, I. (2017). Climate in Norway 2100. NCCS report no. 1/2017. https://cms.met.no/site/2/klimaservicesenteret/klima-i-norge-2100/_attachment/11592?_ts=15c10419731

Hattenrath-Lehmann, T. K., Marcoval, M., Mittlesdorf, H. et al. (2015a). Nitrogenous nutrients promote the growth and toxicity of *Dinophysis acuminata* during estuarine bloom events PLoS One, 10, Article e0124148, 10.1371/journal.pone.0124148

Hattenrath-Lehmann, J. L., Smith, R. B., Wallace, L. R. (2015b). The effects of elevated CO_2 on the growth and toxicity of field populations and cultures of the saxitoxin-producing dinoflagellate, *Alexandrium fundyense*. Limnol. Oceanogr., 60, pp. 198-214, 10.1002/lno.10012

Henson, S. A., Cole, H. S., Hopkins, J. et al. (2017). Detection of climate change-driven trends in phytoplankton phenology. Global Change Biology, 24(1), e101-e111. doi:10.1111/gcb.13886

Hermansen, Ø. and Troell, M. (2012). Aquaculture in the Arctic – a review, 2012 Tromsø: Nofima AS 2012 (ISBN 978-82-8296-029-8) 32, p. Nofima rapportserie (36/2012)

Hevrøy, E.M., Hunskår, C., de Gelder, S. et al. (2013). GH–IGF system regulation of attenuated muscle growth and lipolysis in Atlantic salmon reared at elevated sea temperatures J Comp Physiol B (2013) 183: 243. https://doi.org/10.1007/s00360-012-0704-5

Hiddink, J. G., Burrows, M. T. and García Molinos, J. (2015). Temperature tracking by North Sea benthic invertebrates in response to climate change. Global Change Biology, 21(1), 117-129. doi:10.1111/gcb.12726

Hoegh-Guldberg, O., Cai, R., Brewer, P. et al. (2014). "The ocean," in Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, eds C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. F. Bilir et al. (New York, NY: Cambridge University Press), 1655–1731.

Hoegh-Guldberg, O., Caldeira, K., Chopin, K. et al. (2019). The Ocean as a Solution for Climate Change: Five Opportunities for Action. World Resources Institute. Report. Washington, D.C. Available at www.oceanpanel.org/climate.

Hollowed, A. B., Barange, M., Beamish, R. J. et al. (2013). Projected impacts of climate change on marine fish and fisheries. ICES Journal of Marine Science, 70(5), 1023-1037. doi:10.1093/icesjms/fst081

Holmyard, N. (2014) Climate change: implications for fisheries and aquaculture. University of Cambridge and Sustainable Fisheries Partnership, UK

Hovelsrud, G. (2011). Vær, vind og folk: klimaendringer og lokalsamfunn i nord. Ottar287: 34 – 39. Issn: 0030-6703. https://www.cicero.oslo.no/en/publications/external/484

Hovelsrud, G. (2016). Based on a presentation by Grete Hovelsrud (Nord University) at the 4th Nordic Conference on Climate Change Adaptation in Bergen, Norway, August 2016 https://www.google.no/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=2ahUKEwiQn4nvr7DlAhVxz6YKHaFDAuUQFjAAegQIABAB&url=http%3A%2F%2Fwww.climatechangepost.com%2Fnews%2F2016%2F9%2F21%2Fnorways-aquaculture-needs-more-focus-long-term-cli%2Fpdf%2F&usg=AOvVaw3fWtM5aKDtGQ8tGoA8QaaB

Huang, B., Banzon, V.F., Freeman, E. et al. (2015). Extended reconstructed sea surface temperature version 4 (ERSST. v4). Part I: Upgrades and intercomparisons. Journal of Climate, 28: 911–930. (also available at https://doi.org/10.1175/JCLI-D-14-00006.1).

IPBES (2019). Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. S. Díaz, J. Settele, E. S. Brondizio E.S., H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y. J. Shin, I. J. Visseren-Hamakers, K. J. Willis, and C. N. Zayas (eds.). IPBES secretariat, Bonn, Germany.

IPCC (2011): Summary for Policymakers. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

IPCC (2019). Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama, N. Weyer (eds.)]. In press.

Jagers, S. C., Harring, N., Löfgren, Å. et al. (2019). On the preconditions for large-scale collective action. Ambio. doi:10.1007/s13280-019-01284-w

Järnegren, J. and Kutti, T. (2014). Lophelia pertusa in Norwegian waters. What have we learned since 2008? – NINA Report 1028. 40 pp.

Jørgensen, L.L., and Renaud, P. (2015). Nordic Marine Fjords: Spatial Mapping and Ecosystem Understanding

http://www.ifram.no/db.343156.no.html?lid=308.a6943051592c55e0f0ea1c89499af9bc

Kartverket (2018). Temaside om vannstand og havnivå. Nettside oppdatert 27.2.2018. https://kartverket. https://www.kartverket.no/Kunnskap/vannstand-og-havniva/

Kielland, I. R. (2017). Natur og Ungdom: Aksjonene som endret norsk miljøkamp. 1st ed. Oslo: Cappelen Damm.

Krause-Jensen, D. and Duarte, C.M. 2014. Expansion of vegetated coastal ecosystems in the future Arctic. Frontiers in Marine Science 1: 77.

Krause-Jensen, D. and Duarte, C. M. (2016). Substantial role of macroalgae in marine carbon sequestration. Nature Geoscience, 9, 737. doi:10.1038/ngeo2790 https://www.nature.com/articles/ngeo2790#supplementary-information

Kristiansen, I., Gaard, E., Hátún, H. et al. (2015). Persistent shift of Calanus spp. in the southwestern Norwegian Sea since 2003, linked to ocean climate. ICES Journal of Marine Science, 73(5), 1319-1329. doi:10.1093/icesjms/fsv222

Kritzer, J. P., Costello, C., Mangin, T. et al. (2019). Responsive harvest control rules provide inherent resilience to adverse effects of climate change and scientific uncertainty. ICES Journal of Marine Science. doi:10.1093/icesjms/fsz038

Kroeker, K. J., Kordas, R. L., Harley, C. D. G. (2017). Embracing interactions in ocean acidification research: confronting multiple stressor scenarios and context dependence. Biology Letters, 13(3), 20160802. doi:doi:10.1098/rsbl.2016.0802

Lahn, B. (2019). Norwegian petroleum policy in a changing climate. CICERO Report. 2019:10

Lam, V. W. Y., Cheung, W. W. L., Sumaila, U. R. (2016). Marine capture fisheries in the Arctic: winners or losers under climate change and ocean acidification? Fish and Fisheries, 17(2), 335-357. doi:10.1111/faf.12106

Le Quéré, C., Andrew, R. M., Friedlingstein, P. et al. (2018). Global carbon budget 2017.Earth Syst. Sci. Data10, 405–448 doi:10.5194/essd-10-2141-2018

Levin, K., Cashore, B., Bernstein, S. et al. (2007). Playing it forward: Path dependency, progressive incrementalism, and the 'Super Wicked' problem of global climate change. International studies association 48th annual convention 28: 1-37.

Lind, S., Ingvaldsen, R. B., Furevik, T. (2018). Arctic warming hotspot in the northern Barents Sea linked to declining sea-ice import. Nature Climate Change, 8(7), 634-639. doi:10.1038/s41558-018-0205-y

Lorentzen, T. (2008), Modeling Climate change and the effect on the Norwegian salmon farming industry. Natural Resource Modeling, 21: 416-435. doi:10.1111/j.1939-7445.2008.00018.x

McCarthy, J. J., Canziani, O.F., Leary, N.N., et al. (2001). Climate Change 2001: Impacts, Adaptation and Vulnerability. Cambridge: Cambridge University Press; 2001.

Menon economics (2016). "Verdiskapingen til havnæringene». https://www.menon.no/publication/verdiskaping-havnaeringene-2016/

Miller, K. M., Teffer, A., Tucker, S. et al. (2014). Infectious disease, shifting climates, and opportunistic predators: cumulative factors potentially impacting wild salmon declines. Evolutionary applications, 7(7), 812-855. doi:10.1111/eva.12164

Miller, K., Thompson, K. F., Johnston, P. et al. (2017). An Overview of Seabed Mining Including the Current State of Development, Environmental Impacts, and Knowledge Gaps. Front. Mar. Sci, published online January 10, 2018; doi: 10.3389/fmars.2017.00418

Mills, K. E., Pershing, A. J., Brown, C. J. et al. (2013). Fisheries management in a changing climate lessons from the 2012 ocean heat wave in the Northwest Atlantic.Oceanography, 26(2), 191-195.

Montero-Serra, I., Edwards, M. and Genner, M. J. (2015). Warming shelf seas drive the subtropicalization of European pelagic fish communities. Global Change Biology, 21(1), 144-153. doi:10.1111/gcb.12747

Morrison (2018). Kelp harvesting (https://sp-bpr-en-prod-cdnep.azureedge.net/published/2018/11/12/Kelp-harvesting/SB%2018-75.pdf)

Munday, P. L., Warner, R. R., Monro, K., Pandolfi, J. M., & Marshall, D. J. (2013). Predicting evolutionary responses to climate change in the sea. Ecology Letters, 16(12), 1488-1500. doi:10.1111/ele.

Mydlarz, L. D., Jones, L. E. and Harvell, C. D. (2006). Innate Immunity, Environmental Drivers, and Disease Ecology of Marine and Freshwater Invertebrates. Annual Review of Ecology, Evolution, and Systematics, 37(1), 251-288. doi:10.1146/annurev.ecolsys.37.091305.110103

Nagelkerken, I. and Connell, S. D. (2015). Global alteration of ocean ecosystem functioning due to increasing human CO_2 emissions. Proceedings of the National Academy of Sciences, 112(43), 13272-13277. doi:10.1073/pnas.1510856112

Newell, P. and Simms, A. (2019). Towards a fossil fuel non-proliferation treaty, Climate Policy, DOI: 10.1080/14693062.2019.1636759

Nofima (2019), "Waste not, want not" – an analysis of the marine ingredients industry in Northern Norway". https://www.kbnn.no/en/article/waste-not-want-not-an-analysis-of-the-marine-ingredients-industry-in-northern-norway

Noone, K. J., Sumaila, U. R., Diaz, R. J. (2013). Managing Ocean Environments in a Changing Climate. Sustainability and economic perspective, Eliviser, London. p 359.

Norderhaug, K. M. and Christie, H. C. (2009). Sea urchin grazing and kelp re-vegetation in the NE Atlantic. Marine Biology Research, 5(6), 515-528. doi:10.1080/17451000902932985

Norsk klimastiftelse (2018). Hvordan møte klimarisiko? Råd og tips til selskaper og næringer som skal håndtere klimaendringer og strammere klimapolitikk. Report 6/2018 https://klimastiftelsen.no/publikasjoner/hvordan-mote-klimarisiko/

NORWEA (2017). Norsk Industri, Norges Rederiforbund, «Havvind - et nytt norsk industrieventyr»

NOU (2018). Climate risk and the Norwegian economy. https://www.regjeringen.no/en/dokumenter/nou-2018-17/id2622043/

NTNU (2013). Store mineralverdier på Norges havbunn. https://goo.gl/KxH44B

Olafsen, T., Winther, U., Olsen, Y. et al. (2012). Verdiskaping Basert På Produktive Hav I 2050. https://www.sintef.no/siste-nytt/verdiskaping-basert-pa-produktive-hav-i-2050/

Oliver, E. C. J., Donat, M. G., Burrows, M. T. et al. (2018). Longer and more frequent marine heatwaves over the past century. Nature Communications, 9(1), 1324. doi:10.1038/s41467-018-03732-9

Onarheim, I. H., and Årthun, M. (2017), Toward an ice-free Barents Sea, Geophys. Res. Lett., 44, 8387– 8395, doi:10.1002/2017GL074304.

Opdal, A. F., Lindemann, C. and Aksnes, D. L. (2019). Centennial decline in North Sea water clarity causes strong delay in phytoplankton bloom timing. Global Change Biology, 25(11), 3946-3953. doi:10.1111/gcb.14810

Orr, J. C., Fabry, V. J., Aumont, O. (2005). Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature, 437(7059), 681-686. doi:10.1038/nature04095

Ouellet, P., Chabot, D., Calosi, P. et al. (2017). Regional variations in early life stages response to a temperature gradient in the northern shrimp *Pandalus borealis* and vulnerability of the populations to ocean warming. Journal of Experimental Marine Biology and Ecology, 497, 50-60. doi:https://doi.org/10.1016/j.jembe.2017.09.007

Parkinson, C. L., Cavalieri, D. J., Gloersen, P. et al. (1999) Arctic sea ice extents, areas, and trends, 1978–1996. J Geophys Res-Oceans 104 (C9):20837–20856

Pauly, D. and Cheung, W. W. L. (2018). Sound physiological knowledge and principles in modeling shrinking of fishes under climate change. Global Change Biology, 24(1), e15-e26. doi:10.1111/gcb.13831

Pelc, R., and Fujita, R. M. (2002). Renewable energy from the ocean. Mar. Policy 26, 471–479. doi: 10.1016/S0308-597X(02)00045-3

Pecl, G. T., Araújo, M. B., Bell, J. D. et al. (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. Science, 355(6332), eaai9214. doi:10.1126/science.aai9214

Perry, A. L., Low, P. J., Ellis, J. R. et al. (2005). Climate change and distribution shifts in marine fishes. Science, 308(5730), 1912-1915. doi:10.1126/science.1111322

Porteus, C. S., Hubbard, P. C., Uren Webster, T. M. et al. (2018). Near-future CO_2 levels impair the olfactory system of a marine fish. Nature Climate Change, 8(8), 737-743. doi:10.1038/s41558-018-0224-8

Post, E., Bhatt, U.S., Bitz, C.M. et al. (2013). Ecological consequences of sea-ice decline. Science. 2013;341:519–524.

Preston, C. J. (2013). Ethics and geoengineering: reviewing the moral issues raised by solar radiation management and carbon dioxide removal. Wiley Interdisciplinary Reviews: Climate Change, 4(1), 23-37. doi:10.1002/wcc.198

Pörtner H.-O., Karl D., Boyd, P. et al. (2014). "Ocean systems," in Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, eds C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. F. Bilir et al. (New York, NY: Cambridge University Press), 411–484.

Qiu, Z., Coleman, M. A., Provost, E. et al. (2019). Future climate change is predicted to affect the microbiome and condition of habitat-forming kelp. Proceedings of the Royal Society B: Biological Sciences, 286(1896), 20181887. doi:10.1098/rspb.2018.1887

Rau, G. H. (2011). CO_2 Mitigation via Capture and Chemical Conversion in Seawater. Environmental Science & Technology, 45(3), 1088-1092. doi:10.1021/es102671x

Rau, G. H. (2014). "Enhancing the ocean's role in CO_2 mitigation in global environmental change," in Handbook of Global Environmental Pollution, Vol. 1, ed. B. Freedman (Dordrecht: Springer), 817–824.

Rinde, E., Christie, H., Fagerli, C.W. (2014) The influence of physical factors on kelp and sea urchin distribution in previously and still grazed areas in the NE Atlantic. PLOS ONE 9(6): e100222. https://doi.org/10.1371/journal.pone.0100222

Rogelj, J., den Elzen, M., Höhne, N., et al. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature, 534, 631. doi:10.1038/nature18307https://www.nature.com/articles/nature18307#supplementary-information

Rotmans, J. and Loorbach, D. (2009), Complexity and transition management. Journal of Industrial Ecology, 13: 184-196. doi:10.1111/j.1530-9290.2009.00116.x

Russell, L. M., Rasch, P. J., Mace, G. M., et al. (2012). Ecosystem impacts of geoengineering: a review for developing a science plan. Ambio, 41(4), 350-369. doi:10.1007/s13280-012-0258-5

SAM (2017). Food from the Oceans - How can more food and biomass be obtained from the oceans in a way that does not deprive future generations of their benefits? High Level Group of Scientific Advisors Scientific Opinion No. 3/2017. https://ec.europa.eu/research/sam/pdf/sam_food-from-oceans_report.pdf

Sanford, E., Sones, J. L., García-Reyes, M., et al. (2019). Widespread shifts in the coastal biota of northern California during the 2014–2016 marine heatwaves. Scientific Reports, 9(1), 4216. doi:10.1038/s41598-019-40784-3

SAPEA (2017). Food from the oceans: how can more food and biomass be obtained from the oceans in a way that does not deprive future generations of their benefits?, in Evidence Review Report No. 1. 2017, Science Advice for Policy by European Academies: Berlin. p. 99.

Schmidtko, S., Stramma, L. and Visbeck, M. (2017). Decline in global oceanic oxygen content during the past five decades. Nature, 542, 335. doi:10.1038/nature21399

Skjelvan, I., Jansson, E. Chierici, M. (2014). Havforsuring og opptak av antropogent karbon i de Nordiske hav, 1981-2013, Rapport, Miljødirektoratet, M244-2014.

Smale, D. A., Wernberg, T., Oliver, E. C. J. et al. (2019). Marine heatwaves threaten global biodiversity and the provision of ecosystem services. Nature Climate Change, 9(4), 306-312. doi:10.1038/s41558-019-0412-1

Smith, L. C. and Stephenson, S. R. (2013). New Trans-Arctic shipping routes navigable by midcentury. Proceedings of the National Academy of Sciences, 110(13), E1191-E1195. doi:10.1073/pnas.1214212110

SPC (2013). Deep Sea Minerals: Deep Sea Minereals and the Green Economy.Baker, E., and Beaudoin, Y (Eds.) Vol. 2. Secretariat of the Pacific Community.

Spijkers, J. and Boonstra, W.J. (2017). Environmental change and social conflict: The northeast Atlantic mackerel dispute. Reg Environ Change, doi:10.1007/s10113-017-1150-4

Spillman, C. M. and Hobday, A. J. (2014). Dynamical seasonal ocean forecasts to aid salmon farm management in a climate hotspot. Climate Risk Management, 1, 25-38. doi:https://doi.org/10.1016/j.crm.2013.12.001

Stendardo, I. and Gruber, N. (2012). Oxygen trends over five decades in the North Atlantic. Journal of Geophysical Research: Oceans, 117(C11). doi:10.1029/2012jc007909

Stern, N. (2007) The Economics of Climate Change: The Stern Review. Cambridge: Cambridge University Press.

Stocker, T.F., Qin, D., Plattner, M. et al. (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. - Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Sumaila, U. R., Cheung, W. W. L., Lam, V. W. Y. et al. (2011). Climate change impacts on the biophysics and economics of world fisheries. Nature Climate Change, 1(9), 449-456. doi:10.1038/nclimate1301

Sundby, S. and Nakken, O. (2008). Spatial shifts in spawning habitats of Arcto-Norwegian cod related to multidecadal climate oscillations and climate change, ICES Journal of Marine Science, Volume 65, Issue 6, Pages 953–962, https://doi.org/10.1093/icesjms/fsn085

Sygna, L., Eriksen, S., O'Brien, K., et al. (2004). Climate change in Norway: Analysis of economic and social impacts and adaptations. CICERO Report 2004:12

Sweetman, A. K., Smith, C.R., Shulse, C.N.,et al (2018). Key role of bacteria in the short-term cycling of carbon at the abyssal seafloor in a low particulate organic carbon flux region of the eastern Pacific Ocean. Limnology and Oceanography. DOI: 10.1002/lno.11069

Sæther, A. K. (2017). De beste intensjoner: Oljelandet i klimakampen. Oslo: Cappelen Damm.

Teagle, H. and Smale, D.A. (2018). Climate-driven substitution of habitat-forming species leads to reduced biodiversity within a temperate marine community. Diversity and Distributions, 24(10), 1367-1380. doi:10.1111/ddi.12775

Teagle, H., Hawkins, S. J., Moore, P.J., and Smale, D. A. (2017). The role of kelp species as biogenic habitat formers in coastal marine ecosystems. Journal of Experimental Marine Biology and Ecology, 492, 81-98. doi:https://doi.org/10.1016/j.jembe.2017.01.017

The Global Climate Action Summit (2018). https://selectra.co.uk/energy/news/world/global-climate-action-summit-2019

The Norwegian Directorate of Fisheries (2016). The Directorate of Fisheries' statistics bank. https://www.barentswatch.no/en/articles/Fisheries-statistics/

Thyholdt, S. B. (2014). The importance of temperature in farmed salmon growth: regional growth functions for Norwegian farmed salmon. Aquaculture Economics & Management, 18(2), 189-204.

Toft, J. D., Munsch, S. H., Cordell, J. R. et al. (2018). Impact of multiple stressors on juvenile fish in estuaries of the northeast Pacific. Glob Change Biol. 2018; 24: 2008– 2020. https://doi.org/10.1111/gcb.14055

Torrissen, O., Norberg, B., Viswanath, K. et al. (2018) Framtidsrettet matproduksjon i kyst og fjord – En vurdering av muligheter for økt sjømatproduksjon i Norge (Rapport fra Havforskningen nr. 23–2018)1893-4536

Toresen, R., Skjoldal, H. R., Vikebø, F., and Martinussen, M. B. (2019). Sudden change in long-term ocean climate fluctuations corresponds with ecosystem alterations and reduced recruitment in Norwegian spring-spawning herring (*Clupea harengus, Clupeidae*). Fish and Fisheries, 20(4), 686-696. doi:10.1111/faf.12369

Townhill, B.L., Pinnegar, J.K., Righton, D.A., et al. (2017), Fisheries, low oxygen and climate change: how much do we really know?. J Fish Biol, 90: 723-750. doi:10.1111/jfb.13203

Tveterås, R. and Almaas, H. (1999). "Patterns of Productivity Growth in the Norwegian Salmon Farming Industry," SSE/EFI Working Paper Series in Economics and Finance 301, Stockholm School of Economics.

United Nations Global Compact (2019). Global Goals, Ocean Opportunities https://www.regjeringen.no/contentassets/68d58632424b4ea7ba6a571fcb7bbd09/global-goals-ocean-opportunities-ungc.pdf

Van Dover, C. L., Ardron, J. A., Escobar, E. et al. (2017). Biodiversity loss from deep-sea mining. Nature Geoscience, 10, 464. doi:10.1038/ngeo2983

Verdiskaping i næringene (2019). Faggrunnlag for oppdatering av forvaltningsplan for Norskehavet og for Nordsjøen-Skagerrak M-1408 | 2019

Vikeså, V., Nankervis, L., and Hevrøy, E. M. (2017). Appetite, metabolism and growth regulation in Atlantic salmon (*Salmo salar L.*) exposed to hypoxia at elevated seawater temperature. Aquaculture Research, 48(8), 4086-4101. doi:10.1111/are.13229

Weatherdon, L. V., Magnan, A. K., Rogers, A. D. et al. (2016). Observed and Projected Impacts of Climate Change on Marine Fisheries, Aquaculture, Coastal Tourism, and Human Health: An Update. Frontiers in Marine Science, 3(48). doi:10.3389/fmars.2016.00048

Wesely, J., Feiner, G., Omann, I. et al. (2013). Transition management as an approach to deal with climate change. https://www.researchgate.net/profile/Niko_Schaepke/publication/262379517_Transition_management_as_an_approach_to_deal_with_climate_change/links/0c9605378f8496bb29000000/Transition-management-as-an-approach-to-deal-with-climate-change.pdf

Williamson, K., Satre-Meloy, A., Velasco, K. (2018). Climate change needs behavior change: Making the case for behavioral solutions to reduce global warming. Arlington, VA: Rare.

Williamson, P., and Bodle, R. (2016). Update on climate geoengineering in relation to the convention on biological diversity: potential impacts and regulatory framework, CBD Technical Series No. 84. Montreal: Secretariat of the Convention on Biological Diversity, 158.

Wiltshire, K. H., Malzahn, A.M., Wirtz, K. et al. (2008). Resilience of North Sea phytoplankton spring bloom dynamics: an analysis of long-term data at Helgoland Roads. Limnol Oceanogr 53:1294–1302

Winther, U. Sandberg, M. G., Henriksen, K. T. et al. (2013). Sunnanå, «Sektoranalyse for de marine næringene i Nord-Norge; Statusbeskrivelser og fremtidsutsikter,» SINTEF, Trondheim, 2013.

Østhagen, A., and Raspotnik, A. (2019). Why Is the European Union Challenging Norway Over Snow Crab? Svalbard, Special Interests, and Arctic Governance. Ocean Development & International Law, 50(2-3), 190-208. doi:10.1080/00908320.2019.1582606

Appendices

R&D institutions survey.

The project was to set out to summarize the 20 most important publication/reports and projects on the theme, however the projects group found this was an impossible task. This because the research area is large, and several excellent reports and projects are important depending on what exactly you want to investigate. Therefore, a slightly different approach was used. We instead identified the most relevant knowledge gaps to be able to fully answer how climate change and ocean acidification can impact ocean-based industries and society in Norway. Thereafter we have identified projects that can help get further understanding regarding the knowledge gaps. Findings in the report are based on both the literature study (in main report) and the answer from the R&D institutions survey (described below). Findings of knowledge gaps from the report is described very broadly, while knowledge gaps from the R&D institutions survey are described more in detail below.

A survey that was sent to R&D institutions working on the theme's climate effects and ocean acidification. The purpose of the survey was to ensure good Norwegian anchoring in the knowledge acquisition for the project. Since the questionnaire was only sent to a select few working on this topic in each R&D institution, the feedback may be a bit more biased than generalized for the whole research community.

In the survey we asked the following questions.

1. Does your institution work on projects with focus on studies of the effects of climate change and / or ocean acidification on marine ecosystems, ocean-based industry and society?

2. In that case, which are the most important projects that the institution participates in that focus on climate change and / or ocean acidification on marine ecosystems, marine industry and society? What is the time perspective / project period on these?

3. Please list the most relevant publications (max 20) with contributions from your institution focusing on the effects of climate change and / or ocean acidification on marine ecosystems, ocean-based industries and society

4. What do you consider to be the largest knowledge gaps in Norway and internationally with regard to the effects of climate change and ocean acidification on marine ecosystems, ocean-based industries and society?

5. Do you work on projects focusing on how ocean-based actions or measures can help mitigate and reduce the magnitude of climate effects, ocean acidification and environmental problems, including potential trade-offs in the potential. We would like to have the institution's views / thoughts on this topic.

Some knowledge gaps identified by R&D institutions

There are uncertainties in fish migration and stock size and how this would affect fisheries on the Norwegian coast. Nor is there very clear answers how so-called marine death zones and what effects these could have on coastal populations. Furthermore, no good estimates have been made of the social and economic consequences this may have for Norway, and the Norwegian industries, and what kind of response one should have related to this. How will industries be affected by these changes in ecosystems, and what measures should be implemented in management and business? How will coastal communities, including industries, be affected by the changes and how will they adapt to the changes? Understand the importance of total impacts at multiple complexity levels in the ocean.

There are many knowledge gaps still to fill regarding the impact of climate change on marine ecosystems, not least foundation level information on the impacts of OA, salinity fluctuation, temperature and oxygen levels on long established marine communities. There is very little targeted research on ocean acidification and its variability in Norway as it is for example in the US. Variation in the effects of ocean acidification and climate change throughout the year (which season and life stages are most exposed?) and across geographical areas. Related to point above, good time series on pH throughout the year and in different places are needed. How does OA affect coastal systems and communities? How is the best way to involve communities and municipalities is the research and ensure that the management authorities are aware of the coastal variation of climate change and develop monitoring to that effect. Research on cost-effective methodology for climate and environmental monitoring is needed.

There is little research on how climate change will affect coastal areas. How will these changes interact / combine with other stressors in coastal zones (such as nutrient discharge, runoff of organic matter from land)? How will climate change affect marine ecosystems, not just individual species? How will land changes change supply (of nutrients, particles, carbon, environmental toxins) from land to sea and how will this affect ecosystems? There is a research need for combined effects in nature (e.g. acidification, heating, phenology). There is furthermore research need for the potential for evolutionary adaptations of species

There is little research on glacier-ocean interactions and their impact on Arctic marine ecosystems. Furthermore, how fast will sea ice melt and how will this affect Arctic ecosystems? In general, there is little research on Arctic species, given that climate change and ocean acidification should have the strongest impact in Arctic regions.

There is also little research on system-wide impacts (feedbacks across scales) and incentives for behavioural change, conflicts and interdependencies between individual sustainable development goals. No bridge between knowledge and policy / industry. No National Climate Adaptation Plan that would prepare the industry e.g. fisheries and aquaculture to take measures to adapt to climate change. There is very limited knowledge and research on direct and indirect consequences of climate change and ocean acidification for society. The research community further request funding to initiate sector specific climate adaptation plans that may feed into National Multiannual Climate Adaptation Plans are welcomed.

Some relevant projects. (this is information from R&D institutions and was not translated due to maintain the clarity of the statements, since this information is for The Norwegian Environment Agency).

Spatial shifts of marine stocks and the resilience of polar resource management (https://www.fni.no/projects/spatial-shifts-of-marine-stocks-and-the-resilience-of-polar-resource-management-stockshift-article1151-277.html)

ClimeFish: The overall goal of ClimeFish is to help ensure that the increase in seafood production comes in areas and for species where there is a potential for sustainable growth, given the expected developments in climate, thus contributing to robust employment and sustainable development of rural and coastal communities. (https://climefish.eu/aims-and-goals/)

NFR BIOTEK project from the Digital Life program NFR 248840 “dCod 1.0: decoding systems toxicology of cod (*Gadus morhua*) - environmental genomics for ecosystem quality monitoring and risk assessment”, which will run from 01.04.2016 to 31.03.2020. This is a relevant project for the topic of ocean acidification which has had endeavours to include it as a stress-parameter in their experimental design, as soon as capacity and resources allow.

Langvarig forskning på hvordan fisk påvirkes av høyt CO_2 (kontaktperson Sveinung Fivelstad). Sveinung.Fivelstad@hvl.no

Biological Impacts of Ocean ACIDification: Effects of acidification are investigated through experimental studies of broodstock and offspring of Atlantic cod. Studies have been conducted at Kraknes and AMSE is responsible for analyses of histological effects in cod larvae organs. Inger-Britt Falk-Petersen

Viral diversity and interactions in a changing environment on kelp (prosjektsøknad HAVBRUK 2). Her undersøkes bl.a. pH og temperatur som klimaparametre (kontaktperson Ingunn Alne Hoell).

AquaVitae Horisont2020: EU har valgt Nofima til å lede et omfattende prosjekt for å utvikle nye produkter og metoder for miljøvennlig oppdrett av lavtrofiske marine arter, som alger og kråkeboller. De neste fire årene skal det forskes på kryss og tvers av Atlanterhavet.

Offshore wind development (kontaktperson Valeria Jana Schwanitz).

System-wide impacts with respect to environmental, economic and social impacts, e.g. hydropower <-> Fjord landscape (kontaktperson Valeria Jana Schwanitz).

Climate change impact (using SSP scenarios and linking with regions/local data) (kontaktperson Valeria Jana Schwanitz).

H2020 COMETS - Collective Action Models for Energy Transition and Social Innovation (05/2019-04/2022), time perspective: this century/human planning horizon (kontaktperson Valeria Jana Schwanitz).

CONNECT: The International Context for Norway's Transition to a Low Emissions Economy. How will shifts in international climate policy change the conditions for Norway's transition to a low emissions economy? The project is financed by the Norwegian Research Council.

Arven etter Nansen: The Nansen Legacy is the collective answer of the Norwegian research community to the outstanding changes witnessed in the Barents Sea and the Arctic as a whole. The Nansen Legacy constitutes a joint Norwegian research platform to address the following over-arching objectives: Improve the scientific basis for sustainable management of natural resources beyond the present ice edge, Characterize the main human impacts, physical drivers, and intrinsic operation of the changing Barents Sea ecosystems – past, present, and future. https://arvenetternansen.com/

Climate Change and Sea Level Rise in the Anthropocene: Challenges for International Law in the 21st Century (https://www.fni.no/projects/climate-change-and-sea-level-rise-in-the-anthropocene-challenges-for-international-law-in-the-21st-century-article285-277.html), 2014-2019

“Coastal water darkening”. https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.14810 This was also commented upon on «Forskning»: https://forskning.no/havet-partner-plankton/morkere-vann-forsinker-algenes-arlige-varfest-i-nordsjoen/1560756 The study refers to previous published studies on the “coastal darkening” phenomenon and its climate link. BIO was awarded a new NFR project on this topic this year (NFR 287490 “A green-blue link made browner: how terrestrial climate change affects marine Ecology" which will run from 01.08.2019 to 31.12.2022.

Ocean warming and deoxygenation of fjord basins. http://bio.uib.no/te/news/index.php#190919 This project is not supported by NFR or other external bodies.

BarEcoRe: The objective of the BarEcoRe project is to evaluate the effects of global environmental change on the future structure and resilience of the Barents Sea ecosystem. http://www.imr.no/forskning/prosjekter/barecore/en

Coreplan: Integrert kystsoneforvaltning og planlegging – Økosystemtjenester og kystforvaltning Konkurransen om kystarealene og -ressursene øker, og forvaltningen må ta hensyn til mange ulike interesser. I dette prosjektet studerer vi løsninger for en mer helhetlig og bærekraftig forvaltning av arealene i kystsonen (2016-2020, Norges forskningsråd).

Barents-RISK (Assessing risks of cumulative impacts on the Barents Sea ecosystem and its services; Research Council of Norway, 20 million NOK 2018-2022)

CECO Cells in the cold (CECO)

ABC: Arctic Ocean ecosystems – Applied Technology, Biological interactions and Consequences in an era of abrupt climate change (Arctic ABC).

EU H2020: JERICO-NEXT and JERICO-S3 Joint European Research Infrastructure network for Coastal Observatory – Novel European eXpertise for coastal observaTories 2015-

ARCTIC 2030: Modelling changes in flux of DOC, methane, and CO2 to the ocean as a consequence of erosion and melting of permafrost in the Arctic ecosystem – PERMAFLUX

EU H2020: INTAROS Integrated Arctic Observation System 2016-2021

SCAR Integrated climate and ecosystem dynamics (ICED) 2009-present

SCAR Action Group on ocean acidification 2010-present

AMAP Working Group on ocean acidification 2010-present

IMBeR/Future Earth Coasts Continental Margins Working Group 2017-present

Monitoring Ocean Acidification in Norwegian Seas 2017-2020, Norwegian Environment Agency

Monitoring Ocean Acidification in the Coastal Zone 2019-2020, Norwegian Environment Agency

Marin restaurering, med fokus på Blå Skog (se prosjekter på https://www.niva.no/forskning/marin-biologi).

Naturlig blå skog kan avbøte gjennom lagring/binding av CO2, lokale reduksjoner i OA, og samtidig ivareta høstbare ressurser (Norwegian Blue Forest Network, se http://nbfn.no/, også http://www.merces-project.eu/, https://sciencenordic.com/climate-change-climate-solutions-denmark/how-nordic-marine-forests-can-help-fight-climate-change/1458309).

Taredyrking (prosjekter på https://www.niva.no/forskning/marin-biologi) kan også avbøte, med potensielle avveininger (f. eks. påvirkninger på kystøkosystemer, http://kelppro.net/).

Grønnskift innenfor maritim næring (f. eks. rensing av ballastvann, https://ballasttech-niva.com/).

Anvendelse av mikroalgteknologi og utvikling av bioprodukter (se https://www.niva.no/forskning/Mikroalger). Alger er kjent som fornybare, bærekraftige og økonomiske kilder til forskjellige bioprodukter, med eksempelvis store miljøgevinster for rensing av avløpsvann og for reduksjon av karbonutslipp.

Utvikling av mer bærekraftige tilnærminger i fiskeoppdrett (f. eks. landbasert, Aquaponics, semi-lukkede systemer, se prosjekter på https://www.niva.no/forskning/akvakultur, også https://www.niva.no/nyheter/sirkulaer-okonomi-i-sanntid-pa-akvariet-i-bergen)

Utvikling av et kunnskapsgrunnlag for å hjelpe kystkommuner og virksomheter til å ta bærekraftige beslutninger (se prosjekter på https://www.niva.no/tjenester/samfunnsperspektiv-pa-vann, https://www.niva.no/forskning/oseanografi).