Marine heatwaves in Northen Sea areas

Occurrence, effects, and expected frequencies

Borgman , Elvira ; Pedersen, Morten Foldager; Upadhyay Stæhr , Peter Anton ; Fischer-Bogason , Rikke

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MARINE HEATWAVES IN NORTHERN SEA AREAS

Occurrence, effects, and expected frequencies

PlanMiljø

This report was written by PlanMiljø on behalf of the Norwegian Environment Agency, 2021.

Authors:

Elvira Borgman, PlanMiljø
Morten Foldager Pedersen, Professor at the Department of Science and Environment, Roskilde University
Peter Anton Upadhyay Stæhr, Professor at the Institute for Ecoscience, Aarhus University
Project Management by Rikke Fischer-Bogason, PlanMiljø

A special thanks for the contributions from:

Geir Ottersen, Researcher at the Norwegian Institute of Marine Research
Léon Chafik, Researcher at the Meteorological Institute, Stockholm University
Mads Solgaard Thomsen, Associate professor at the Centre of Integrative Ecology, University of Canterbury
Mark Payne, Researcher, Danish Meteorological Institute
Thomas Wernberg, Professor at the School of Biological Sciences and the University of Wester Australia's Oceans Institute

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LIST OF TERMS AND ABBREVIATIONS

AMO	Atlantic Multidecal Oscillation
CMIP	Coupled Model Intercomparison Project
ENSO	El Niño-Southern Oscillation
GHRSST	Group for High Resolution Sea Surface Temperature
IPCC	The Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
NAO	North Atlantic Oscillation
OISST	Optimum Interpolation Sea Surface Temperature
RCP	Representative Concentration Pathway
SST	Sea Surface Temperature

1. EXECUTIVE SUMMARY

Marine heatwaves (MHW) are extended periods of anomalously warm ocean temperatures. It is a growing phenomenon globally and in Northern sea areas, but little is known of the extent of the problem and the derived effects on marine organisms, ecosystems, and ecosystem services. This report has been commissioned by the Norwegian Environment Agency with the aim to address this knowledge gap and increase the understanding of MHWs in Northern seas. The long term aim is to use the knowledge acquired through the report as a basis for sustainable marine management in the future.

Through a literature study, a webinar and a gap analysis this report has studied the climatic functions, geographically specific effects, anthropogenic drivers, biological effects, identification and monitoring, and future prognosis of MHWs in Northern sea areas. The main results are that on a global scale, evidence indicates that a majority of all MHWs can be attributed to anthropogenic warming. It seems evident, also in the Northern sea areas, that the frequency, intensity and duration will continue to increase with further temperature increases. According to our results, some areas and ecosystems are more susceptible to MHWs. This includes the Arctic Ocean where the relative temperature changes may have larger effects, and coastal areas where kelp ecosystems are particularly vulnerable. Considering the wider biological effect of MHWs in Northern sea areas, they are not well studied, and there are many uncertainties regarding impacts of MHWs on species and ecosystems. In order to achieve a clearer understanding of these impacts, more extensive biological monitoring is needed. Although our study found few examples of current monitoring directly aimed at MHWs, there are ongoing monitoring efforts of SST, both satellite derived measurements and in situ measurements. These can be used to provide the information needed to map the extent of MHW in Northern sea areas.

Based on the findings of the literature study, webinar and gap analysis, we propose the following recommendations

RECOMMENDATIONS

- Historical and current changes in the occurrence of MHWs should be documented
- Adequate MHW monitoring should be in place to inform proper marine management
- Biological monitoring is recommended for temperature sensitive species and their relative communities
- Temperature data should be gathered to develop appropriate baseline conditions
- The overall resilience of marine systems should be strengthened to increase their ability to withstand stress induced by MHWs
- Human induced marine pressures should be reduced and protection of marine areas should be enhanced

2. INTRODUCTION

Marine heat waves (MWH) are a growing phenomenon which already today has many measurable negative effects on marine habitats. Visible impacts include bleached coral reefs, harmful algae blooms, mass deaths among seabirds, and fish species found hundreds of miles from their traditional habitats (Smale et al., 2019). The full range of consequences is not yet understood, nor are the complex interaction of MHWs and other human pressures. Future MWHs are expected by The Intergovernmental Panel on Climate Change (IPCC) to occur 20 to 50 times as often as in preindustrial times, depending on developments in greenhouse gas emissions (Collins et al., 2019). According to the IUCN it is likely that there will be an increase in mean global ocean temperature of 1-4º C by 2100 (with the greatest ocean warming occurring in the Southern Hemisphere) (IUCN, 2017). On top of this gradual temperature increase, the frequency of extreme temperature events are expected to increase further. Although MWHs are getting increasing attention, the phenomenon was not mentioned at all in the IPCC's report from 2014, while there was an entire subchapter on this important subject in their Special Report on the Ocean and Cryosphere in a Changing Climate from 2019 (IPCC, 2014; Collins et al., 2019).

The scientific understanding of MWHs and their consequences is far greater for the Pacific than for European waters. Especially in the Nordic seas there is little knowledge of the extent of the problem and the derived effects on marine organisms, marine ecosystems, and ecosystem services. It is therefore a highly relevant study that is commissioned by the Norwegian Environment Agency. By studying existing literature and identifying knowledge gaps this study will provide recommendations for future monitoring and assessment of MHWs and highlight the known and expected impacts on biological conditions in Nordic seas. This will enable the Norwegian administration to implement appropriate management of their sea areas. Also, this study can provide relevant knowledge for future research required to fill important identified knowledge gaps within the field of MHWs in Nordic seas.

2.1. Scope of the study

This study examines different aspects of MHWs in Nordic sea areas with the aim to increase knowledge and provide recommendations for monitoring and management of MHWs. The studied topics encompass climatic functions, geographically specific effects, anthropogenic drivers, biological effects, identification and monitoring and future prognosis of MHWs.

2.1.1. Definition of Marine Heatwaves

The most commonly used definition for MHW has been developed by Hobday et al. (2016), who describes a MHW as *"a discrete prolonged anomalously warm water event"*. Hobday et al. developed this definition influenced by the existing definitions for atmospheric heatwave definitions, especially by Perkins & Alexander (2013).

In the Hobday et al. definition "*Anomalously warm*" refers to temperature relative to a baseline for the long-term mean seasonal cycle. The "mean seasonal cycle" is defined on the basis of data for a 30-year historical time series. A 30-year period was selected based on the availability of sea surface temperature measured via satellite and as an appropriate baseline from a period which was not severely affected by climate change (Hobday et al., 2016).

By definition, a MHW occurs when the temperature for a calendar day exceeds the threshold of the 90th percentile value for temperature determined from the 30-year baseline period (Figure 1).

"*Prolonged*" refers to a time period that is unusually long relative to ecological processes and thresholds. Based on a review of global mean times for MHWs, Hobday et al. proposed a standard duration of five days or longer for the definition of MHW.

According to the Hobday et al. definition, a MHW is also a "*discrete*" event, meaning that the start and end are clearly defined. If there are gaps of less than two days between identified MHWs that each last for five days or longer, the period is seen as a continuous MHW event.

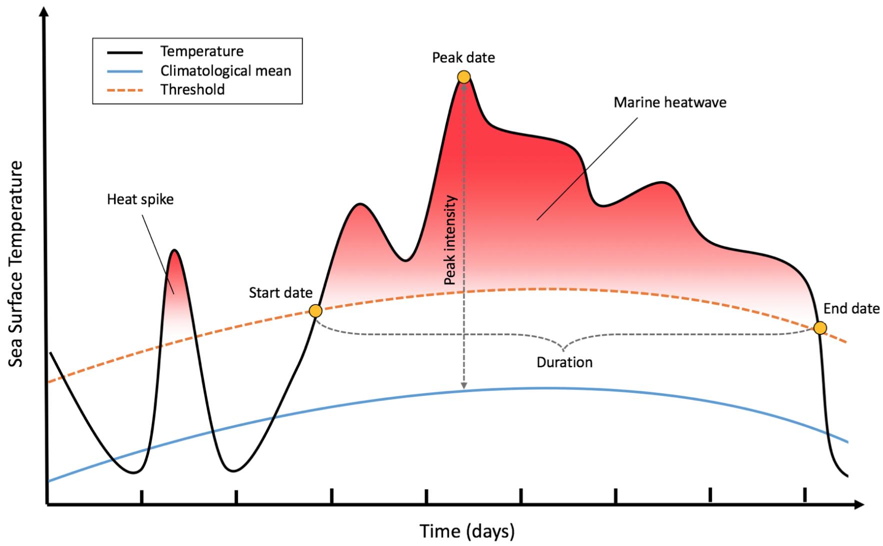

Figure 1. Two anomalously high temperature events, one heat spike (duration <5 days) and one MHW (duration >5 days). Adapted from Hobday et al. (2016).

While the report mainly applies the MHW definition by Hobday et al. (2016) for the litterature review, it also includes literature that uses other definitions of MHWs. When other definitions are used this will be stated in the text.

2.1.2. Geographical scope

The geographical scope of the study is the Northern sea areas. In this context, the northern sea areas were defined to include the North Sea (including Skagerrak and Kattegat), the North Atlantic Ocean, the Norwegian Sea, the Arctic Ocean, Barents Sea and the Baltic Sea. These are sea areas that lie in proximity to Norway and the other Nordic countries, and that have a great ecological, economic and cultural importance for the Nordic countries.

2.2. Research questions

The study investigates five research questions:

- What are the drivers for MHWs in Northern oceans and seas, and do these differ from drivers in other parts of the world?
- Will the Northern seas and oceans be exposed to a particularly large increase in frequency and duration of MHWs, compared to other sea areas?
- Does the literature identify ecosystems or geographical areas in the northern seas which are particularly exposed to marine heat waves? Which areas, and why are they particularly exposed?
- How do MHWs affect the biology of marine systems in northern, especially Norwegian, sea areas?
- What are the methods and requirements for monitoring and forecasting MHWs?

3. METHODOLOGY

3.1. Literature review

The study consisted of a systematic literature review divided into three phases. The first phase consisted of a literature search and the making of a long list of articles and reports. The literature search applied predefined search words (Annex A) and themes defined from the study questions. In the second phase, the abstracts of the long list were studied in order to select which literature to include in the analysis. The selection was based on predefined prioritization criteria which helped reduce the literature to the most relevant for the theme of the analysis. Finally, the selected literature was systematically analyzed to for information relevant to the defined research questions.

3.1.1. Literature selection criteria

Literature included in the study should fulfil some defined literature selection criteria:

A. **Geographical scope**

Selected literature should be relevant to a Nordic context, meaning that it is applicable to conditions in the northern sea areas off the Norwegian coast (the North Sea, the North Atlantic Ocean, the Norwegian Sea, the Arctic Ocean and the Barents Sea)

B. **Publishing date**

Selected literature should have a publishing date after 2010. Few key articles with a publishing date before 2010 may be included.

C. **Robustness**

The selected academic articles should preferably be peer-reviewed. Other types of literature included (typically reports) should be published by well-known institutions in the field.

After literature is selected according to the above criteria, the literature which is to be included in the study is prioritized on the basis of prioritization criteria:

A. **Relevance**

Articles, studies and papers with higher relevance to the research questions should be prioritized. This criterion is applied on the title in the first stage, and in the second stage on the abstract, to make the final selection of studies that are included in the analysis.

B. **Number of citations**

Articles with many citations are prioritized.

C. **Broad scope of literature**

Include key reports from multilateral organisations, academic studies and national studies.

D. **Topicality**

To include the newest insights of e.g. research and technology development.

Of 154 studies found in the first phase, 41 went to the second phase, and finally 20 articles were compiled in a short list and analyzed according to a literature analyzation framework.

3.2. Webinar

A webinar was held on the topic of Marine Heatwaves – occurrence, effects and expected frequencies in October 2021. There was attendance of 82 international participants, many of them representing academic or policy institutions that work within the field of climate change effects on oceans. Presentations on the topics of trends and frequencies, impacts and consequences and monitoring and forecasting of marine heatwaves were made by researchers Thomas Wernberg, Mads Thomsen and Mark Payne respectively. Researchers Peter Upadhyay Stæhr and Morten Foldager Pedersen presented findings of development and impacts of MHWs in Nordic sea areas, and facilitated discussions on future scenarios in Nordic sea areas and criteria for a Nordic monitoring system. Information from the presentations and discussions of the webinar was compiled in a written summary, which was analyzed for relevant additions that were then added to the study.

3.3. Gap analysis and assessments

A gap analysis was performed to assess the status on the knowledge on MHW and derived effects in the northern sea areas. The gap analysis builds on the knowledge attained through the literature study and on expert input gathered from the webinar. It aims to assess the following questions:

- What are the most important knowledge gaps in the field of marine heat waves in Nordic, especially Norwegian, sea areas?
- What is the expected future occurrence of marine heat waves in the northern sea areas?
- What are the expected consequences of marine heat waves in northern sea areas? And how does this differ from long-term gradual warming related to climate change?
- What monitoring of MHWs and their effects are currently available in northern sea areas and how suitable are these for assessment of the Norwegian seas?

Findings from the gap analysis are accounted for in Chapter 4.

4. LITERATURE REVIEW

4.1. Climatic functions

Climate change has increased the temperature of the atmosphere, causing the oceans to gradually absorb more heat from the atmosphere than it releases back. As a results sea surface temperatures (SST) have gradually increased over the last three decades and along with this, the likelihood for extreme events such as MHWs (Oliver et al., 2020).

MHW events can differ vastly in their properties and vary significantly in intensity, duration and frequency. The intensity of an MHW event describes the temperature anomaly, which is the deviation from the upper 90-percentile for that season. The duration of an MHW event is the temporal extent from the beginning to the end of the heat wave, usually counted in days. The cumulative intensity is the integral of temperature over time, adding up the temperature exceeding the mean during the full extent of the MHW. Other properties that describe the development of marine heatwaves, but that are not related to individual events, include the annual frequency, which describes the number of events in a specific year, and annual marine heatwave days, which describes the number of days in a year that were included in a marine heat wave. These MHW properties are determined by a number of climatic factors which will be described in the following sections.

Climatic functions that stimulate the occurrence of MHWs are a relatively new research field, and therefore not yet well understood. The drivers of MHWs are better understood in some areas of the world, such as in Australian waters where more research has been conducted on the topic, than in others. In the Southern Pacific Ocean part of Australian waters, specific climatic events, such as the El Niño Southern Oscillation (ENSO) seems to drive the development, intensity, and duration of MHWs (Gupta et al., 2020). However, how these phenomena arise is not yet well understood for northern sea areas. Processes that drive the occurrence, persistence, and decay of MHWs are complex and can be affected by multiple causal factors. Holbrook et al. (2019) have studied MHW drivers at a global scale. A “driver” has - in this context - been defined as a “set of causative mechanisms that combine to produce a MHW event”. A visual representation of different types of MHW drivers can be seen in Figure 2.

Climate modes of variability

Climate modes of variability are large-scale climate oscillation phenomena that extend over a large time and space scale. Examples include ENSO and the North Atlantic Oscillation (NAO).

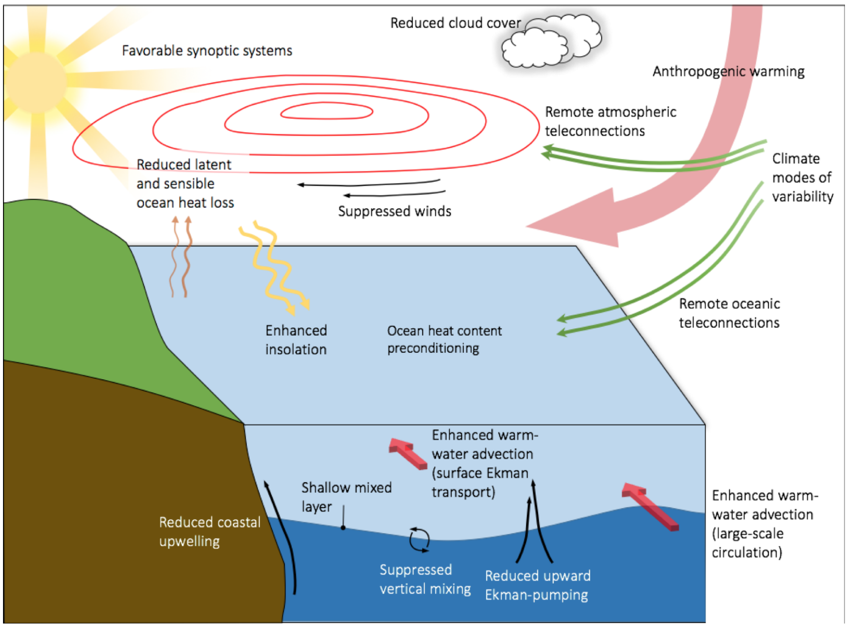

Figure 2. Graphical representation of MHW drivers. Adapted from Holbrook et al. (2020).

Holbrook et al. divided drivers into three categories:

1) Local processes

Local processes encompass processes such as horizontal and vertical mixing, horizontal advection, heat fluxes and vertical entrainment. These processes have direct effect on the ocean temperature

2) Climate forcings

Climate forcings describe large-scale climate modes such as ENSO or the North Atlantic Oscillation (NAO) that drive climate conditions at a larger scale.

3) Teleconnection processes.

Teleconnection processes include processes such as atmospheric bridges or planetary waves that make up the physical connection between remote forcing of climate modes and the local temperature influencing processes.

The spatial and temporal scale for the three different types of MHW drivers are shown in Figure 3.

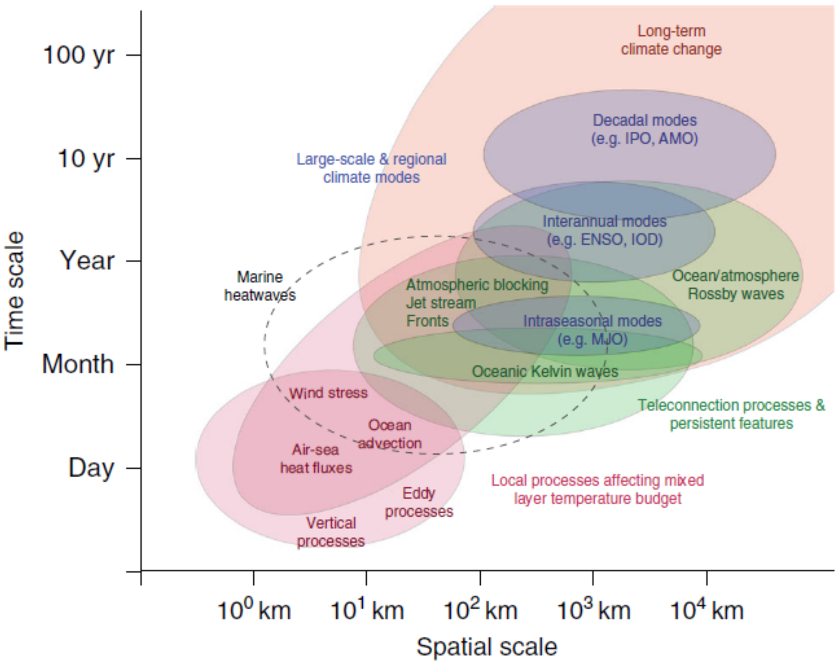

Figure 3. Figure by Holbrook et al. (2019). Spatial and temporal scale of drivers that contribute to local MHW events. Local processes are depicted in red, climate forcings in blue and teleconnection processes in green.

At the global scale, long-term increases in SST, small-scale and large-scale oceanic forcing and atmospheric forcing all contribute to the build-up of MHWs. Gupta et al. (2020) found that the occurrence of MHWs probably is a consequence of three types of climatic causes: persistent large-scale synoptic systems, changes in ocean heat transport, and coupled air-sea feedback processes. They found that the most extreme MHW events were often associated to large, persistent high-pressure systems prior to and during the MHW.

Oliver et al. (2019) studied MHW trends in relation to longer-term trends in SST. They found that global changes in mean SST seem to be the main driver of the increase in the number of MHW days and they estimated that the increase in mean SST is the reason behind the increase in MHW days in two thirds of the ocean globally, meaning that rising sea temperatures is the main driver for the increase in MHW exposure. The remaining one third of the increase in MHWs is driven by changes in the SST variability. Oliver et al. (2019) found no correlation between the mean increase in SST, changes in SST variability and the intensity of MHWs, and they concluded that the mechanisms driving MHW intensity remain unknown at the moment.

Both global and regional climate modes can influence the occurrence of MHWs. For the global climate modes, Scannell et al. (2016) found that the size-frequency distribution of positive SST anomalies is related to oscillation patterns in the Atlantic Ocean. Two oscillation patterns are especially important in this context: The Atlantic Multidecadal Oscillation (AMO) and the North Atlantic Oscillation (NAO). The AMO is a SST fluctuation in the North Atlantic Ocean related to the thermohaline circulation (Christensen et al., 2013). SST variations related to AMO run over several decades, however they are not temporarily regular as the name oscillation may imply. NAO describes the irregular phenomena of varying air pressure over the North Atlantic Ocean. This phenomenon is made up by variations in strength and size of a low pressure system over Iceland and a high pressure system over the Azores. These systems control the westerly winds across the North Atlantic. Both AMO and NAO influence SST anomalies, however AMO has the strongest influence on the positive SST trends. Scannell et al. (2016) suggest that both phenomena contribute to influence the probability of MHW events. The NAO brings atmospheric forcing through air-sea heat fluxes and wind-driven Ekman transport, which contributes to weak positive fluctuations in the SST. When there is a negative NAO phase, the likelihood of MHW occurrence increases with over 40% in the North Atlantic Ocean according to Holbrook et al. (2019).

Concerning a regional climate mode, ENSO events are found to influence MHW patterns in the Atlantic. Although ENSO events are created by the atmospheric and SST variations in the Pacific Ocean, it has global effects. Teleconnections from ENSO events can thus favor sustained warm weather in the Atlantic basin, thereby affecting the likelihood for ocean warming events (Holbrook et al., 2019). Atmospheric processes such as the jet stream work as teleconnection processes and also influence conditions in the North Atlantic Ocean. When there is a northward movement of the Atlantic jet stream there is a higher risk of buildup of stable high-pressure areas that increase surface air temperatures, reduce winds and inhibit ocean mixing, thereby promoting MHW events (Holbrook et al., 2019).

Previous observations indicate that MHWs in Northern sea areas typically are driven by atmospheric forcing rather than ocean circulation driven forcing (M. Payne, personal communication, 28 October 2021; L. Chafik, personal communication, 12 November 2021). This is particularly evident in more enclosed sea areas such as Kattegat, Skagerrak and the Baltic Sea (M. Payne, personal communication, 28 October 2021). For example, observations of MHWs in the Northern Baltic Sea, the Southern Baltic Sea and the North Sea from the summer of 2018 were co-occuring with strong high-pressure atmospheric weather systems characterized by warm and calm weather (L. Chafik, personal communication, 12 November 2021). Atmospheric extreme temperature events such as terrestrial heatwaves are therefore thought to have a larger impact on MHWs in Northern sea areas. In the future, terrestrial heatwaves are expected to increase substantially, however the spatial patterns of this increase are not yet well known (Seneviratne et al., 2021). It is therefore difficult to project the future importance of these types of drivers on MHWs in the Nordic region. The drivers behind a MHW event can also influence the MHW properties. Typically, set up time and duration of MHWs is longer for ocean current driven MHWs than for MHWs driven by atmospheric forcings (T. Wernberg, personal communication, 28 October 2021).

4.2. Geographically specific effects

Evidence from modelling point towards large temperature changes in the Arctic Ocean compared to other oceans. According to Frölicher et al. (2018) there is a large increase in the probability for MHWs to occur in the Arctic Ocean. These findings are derived from future climate scenarios based on Earth system modelling and analysis of satellite observations of SST. In the Arctic Ocean there are normally very small seasonal and interannual variations in SST, since the area is surrounded by an ice pack that keep the temperature relatively constant. Since the temperature is usually quite stable, small variations in SST can have bigger impacts on the ecosystem in the Arctic Ocean than in other oceans. The study was based on a MHW definition as an event where the daily SST exceeds the 99th percentile, corresponding to a one-in-a-hundred-days event. This percentile threshold is higher than that used by the Hobday et al. definition, meaning that the number of heatwave days are fewer than they would be if this study would have made use of the Hobday et al. 90th percentile definition. This is despite the fact that Hobday et al. include a duration threshold of five days, which Frölicher et al. do not use in their study. Frölicher et al. found that when studying annual mean SST variations of the same magnitude on a global scale, the SST variations resulted in much larger changes in the probability of exceeding the 99th percentile in the Arctic than in other oceans. Given that the approach applied by Frölicher et al. is more conservative than the one by Hobday et al., this supports the conclusion that the Arctic is strongly affected by MHW's.

Hu et al. (2020) found that the frequency of MHWs in the Arctic currently ranges from one to four events annually. The duration of MHWs varies between 9 and 25 days, while the intensity is highly variable depending on the exact geographical area. Hu et al. showed further that the areas that have been affected by severe MHW events have extended northward during the latest decade. When comparing Arctic Sea areas that have multiple year ice, first year ice and open water, they found that in areas with multiple year ice cover, the MHW generally had the highest frequency, longest duration and lowest intensity. In areas with first year ice, MHW had high frequency, medium duration and high intensity. In open Arctic waters, the MHWs were characterized by medium frequency, short duration and high intensity.

Oliver et al. (2020) studied the increase in MHW frequency globally by analyzing ocean temperature data between 1925 and 2016. They studied in situ measurements and gridded monthly in situ-based data sets and found that there has been an increase in the frequency of MHWs corresponding to 2-6 additional annual events in the North Atlantic Ocean (north of 50° North), which is the highest increase in MHW frequency globally in this time period.

Our literature review indicates that MHW impact temperatures in regional seas and local waters to a different extent depending on the physical conditions of the system. In a study performed in British Columbia, Canada, that examined temperature conditions in fjords after a large heat wave in the North Pacific, it was found that warm conditions in the fjords persisted for two years after the MHW disappeared (Jackson et al., 2018). In general, evidence from other parts of the world shows that sheltered environments have been more affected than open waters, and that shallow areas with low water exchange are more sensitive than open waters (T. Wernberg, personal communication, 28 October 2021). It should be noted that physical conditions may vary between individual fjords in Nordic sea areas, which will affect their susceptibility for MHWs. Although we found no literature on the specific effects of MHW on conditions in different habitats such as coastal areas, reefs and fjords in northern sea areas, evidence from other parts of the world suggest that the development and extent of MHWs vary geographically, highlighting the relevance of studying specific habitat types in northern sea areas.

4.3. Anthropogenic drivers

It is clear that the probability for MHW events to occur have increased substantially over the last three to four decades in parallel with the average increase in SST, which is caused primarily by anthropogenic forcing (Frölicher et al., 2018). Therefore, it also seems evident that the frequency, intensity and duration of MHW events will continue to increase with further temperature increases. The frequency, intensity and duration of MHWs are accordingly expected to surpass those caused by natural climate variability by the beginning or middle of the twenty first century (Oliver et al., 2019).

Individual MHW events have been explicitly attributed to anthropogenic global warming, including events in the Tasman Sea, California current, the Bering Sea and in Australian waters (Oliver et al., 2020). Frölicher et al. (2018) simulated future climate scenarios using Earth system modelling and found that at present day warming (i.e. about 1°C), 87% of all MHW can be attributed to anthropogenic warming. At a scenario of 2°C increase in mean temperature, essentially all MHWs can be attributed to anthropogenic impacts. Their modelling attempts suggest that pre-industrial MHW events lasted for 11 days on average, with an intensity of 0.4°C and cumulative mean intensity of 3 °C d, while the spatial extent averaged around 0.4 million km^2 globally (Table 1). When using a 1 °C warming scenario, equivalent to the current situation (2021), and simulations predict an average duration of 25 days, intensity of 0.8°C and cumulative mean intensity of 13 °C d.

Table 1. MHW properties for three different climate scenarios (pre-industrial times, 1 °C warming and 3.5 °C warming) simulated through Earth system modelling. Data adapted from Frölicher et al. (2018).

	Pre-industrial times	1 °C warming scenario	3.5 °C warming scenario
Occurrence probability (relative to pre-industrial times)	1	9 (6-12)	41 (36-45)
Mean duration (days)	11	25 (15-33)	112 (92-129)
Mean spatial extent (mio. km$^{2)}$	0.4	1.3 (0.4-1.3)	8.8 (6.3-12.2)
Cumulative mean intensity (°C d)	3	13 (8-18)	164 (126-214)

The models predict further a 6-12 time-fold increase in the probability of MHW events, and a three-fold increase in their spatial extent. These predicted changes of frequency, duration, cumulative mean intensity and spatial extent of MHWs are in scale with the climate change progression, including the cumulative greenhouse gas concentrations and the global mean temperature and Frölicher et al. conclude that there is a direct link between human actions and the simulated increase in MHWs.

Laufkötter et al. (2020) used an attribution framework with preindustrial and present-day model simulations to quantify the contribution of anthropogenic climate change to MHW events. The authors focused on seven recent, large MHWs that have had an extent of more than one million km^2. Six of these seven events have been the longest and most intense since the start of satellite SST measurements in 1981. According to their study, the intensity, cumulative intensity and duration probabilities have increased by more than a factor of 20 due to anthropogenic climate change and they concluded that “it is very unlikely that the MHWs could have reached the high temperatures that were measured without the influence of climate change”.

Laufkötter et al. (2020) also studied how the so-called return periods for MHW events would change at different global warming scenarios. These model predictions showed that MHWs with the same level of intensity, duration and cumulative intensity as those presently observed in the North Atlantic used to have return periods of hundreds to thousands of years, while global warming will decrease these return times substantially. With an average global warming of two degrees or more, the return periods are thus expected to be less than ten years for events with the magnitude of previously observed extreme events in the North Atlantic occurring every hundred years or longer. At the same time the confidence intervals decrease, meaning that a warming scenario above two degrees is more likely to reduce the return periods than warming scenarios below two degrees. Warming of less than two degrees will, however, still have impacts: for example, a 1.5-degree increase in temperature is expected to reduce return times to between 10 and 100 years for MHWs in the North Atlantic.

4.4. Biological effects

Of the multiple facets of climate change, warming is the most pervasive transformation of the Earth, as temperature influences biological processes across scales from genes to ecosystems (Kordas et al., 2011). Globally, surface waters have warmed at a rate of 0.1°C per decade over the last century (Burrows et al., 2011), but even small increases in temperature lead to a substantial increase in the frequency and severity of MHWs, as natural variation superimpose onto the climbing trend (Oliver et al., 2018). All species are characterized by survival within a range of temperatures set by lower and upper lethal limits and by optimum temperatures where their performance is at maximum. Although organisms can acclimate to tolerate slightly warmer conditions (e.g. Staehr & Borum, 2011), temperatures above that optimum will affect performance negatively for example through reduced growth and reproduction, while exposure to temperatures near to the upper level of tolerance lead to enhanced mortality. Severe heat stress may thus lead to reduced fitness, local extinctions and, eventually, to large-scale changes in range distribution (Pecl et al., 2017).

The latitudinal range distribution of most marine species is largely determined by water temperature and their range distribution does thus reflect the temperature interval within which they thrive (Lüning, 1990). Experimentally determined temperature responses are only available for few marine species and mainly so, for ecologically important species such as habitat forming species (i.e. “foundation” species), or species of commercial interest such as some invertebrates and fishes, which makes it difficult to predict exactly which species are threatened by MHW events. Even less is known about the effects of heat stress on whole communities or ecosystems. Studies have however shown systematic patterns in the metabolic temperature sensitivity among aquatic ecosystem (Yvon-Durocher et al., 2012) and for a number of aquatic species (Watson et al., 2021; Deutsch et al., 2020) which generally show that warming will increase respiratory oxygen demand more than primary production. In organically enriched coastal systems, elevated summer temperatures can lead to an unfavorable metabolic balance, eventually causing large scale ecosystem anoxia (Staehr et al., 2021).

It may be useful to distinguish between effects caused by the slow but significant increase in average sea water temperature that occurs over decades to centuries and the effects of MHW events. Ongoing increases in average SST do usually not pose a direct threat of enhanced mortality, because this slow climb allows mobile organisms to migrate towards latitudes with more appropriate temperature regimes. Even non-mobile populations such as seagrasses, attached seaweeds and sessile invertebrates may be able to change their range distribution through dispersal of seeds, spores and pelagic larvae, and thus, keep pace with changes in temperature although their spread will appear more slowly than for the truly mobile species. Slow increases in average SST may also leave room for adaptation to higher temperature and thus, reduced sensitivity to heat stress. Little is presently known about the adaptation potential of most marine species, but the potential will likely vary substantially among species depending on the amount of genetic diversity within populations and their generation time, since selection and adaptation requires sufficient time. MHWs represent, in contrast, a more acute and dramatic exposure to elevated temperatures that may approach or exceed the upper lethal level of many species in an area. Rapid exposure to such temperatures does neither allow time for substantial changes in range distribution for sessile or slow-moving species, nor for selection and adaptation to take place. MHWs occurring in summer and/or near the equatorial (i.e. warm) edge of a species range distribution may therefore pose a significant risk of increased mortality and local or regional extinctions, which may be exacerbated in areas affected by non-climatic anthropogenic stressors such as eutrophication, pollution and over-fishing (Smale et al., 2019).

4.4.1. Overall ecosystem effects

Little is presently known about the effects of MHWs at the community and ecosystem levels although some patterns have started to emerge. Smale et al. (2019) published a comprehensive review on the ecological consequences of eight major and sufficiently studied MHW events occurring between 1992 and 2011 including three from the Mediterranean Sea, four El Niño events and one from Western Australia. They found that these events were associated with negative ecological effects, but across all ecological indices they were unable to find a relationship between overall effect size and MHW intensity or duration. Major taxonomic groups differed substantially in their response to the MHWs; drifting (i.e. plankton) and mobile (mobile invertebrates, fishes, mammals) taxa remained generally unaffected (or even positively affected in the case of fishes) by the MHWs, while sessile organisms (corals and other immobile invertebrates, kelps and seagrasses) and sea-birds were negatively impacted by the events. The MHWs also had varying effects on ecological processes; growth and primary production were only affected marginally, while reproduction, abundance, survival and especially bleaching among tropical corals were severely impacted by the MHW events when assessed across all taxonomic groups involved in the analysis. The analysis showed that populations appearing close to the warm-water edge of their range distribution were affected much more by MHWs than populations appearing in the center or near the cold edge of their range distribution (> 80% affected near the warm edge versus 55% affected near the cold edge), indicating that populations residing near the warm edge of their range distribution are much more vulnerable to acute warming events (Figure 4).

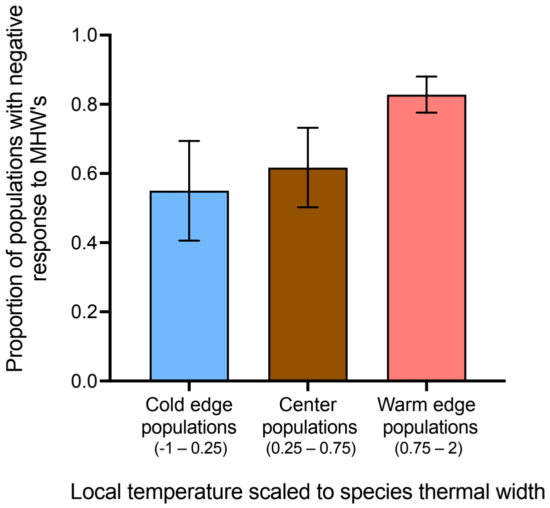

Figure 4. Populations located towards the warm-water edge of their species distribution tend to respond more negatively to MHWs than those located in the center or along the cold edge of their species distribution. The relative position of each population within its species range was calculated by scaling the local average SST as a proportion of the difference between the 10th and 90th percentile temperatures experienced through the species geographical range. The figure was re-drawn based on information contained in Smale et al. (2019).

An increasing number of studies have documented large-scale changes in the range distribution of marine species globally. A common feature of these changes is that species tend to undergo a pole-ward change in their range distribution as average SST and the frequency of MHWs increase. Such changes may - or may not - have serious consequences for ecosystem structure and functioning. Some ecosystems may thus lose species while, at the same time, they receive new ones that are functionally redundant in which case ecosystem function may remain largely unaltered. In contrast, losses of ecologically “unique” species such as “foundation” or “keystone” species may lead to substantial changes in ecosystem structure and function (i.e. “regime shifts”) that may persist beyond the duration of the MHW and so, have serious consequences for the ecosystem services provided. Only few studies have looked specifically on the potential effects of MHWs in the northern sea areas and predictions at this point must therefore be based on these few studies and on studies from other areas with similar populations and/or ecosystem structure. While these studies are relevant, it should be kept in mind that all ecosystems have individual traits that must be considered, and that results from other areas can not necessarily be directly translated to a Nordic context.

4.4.2. Open ocean effects

Extraordinary strong phytoplankton blooms including those of many harmful algae (HABs) have often been attributed to especially warm periods with strong insolation and calm weather conditions. Smale et al. (2019) found however no significant coupling between MHWs and plankton in their review of the effects eight prominent MHW events (effect size not different from zero). The findings from this study have been supported by two recent and more comprehensive studies on the potential correlation between MHW events and phytoplankton biomass in the oceans.
Hayashida et al. (2020) studied the effects of MHW events in 23 tropical and temperate oceanic regions between 1992 and 2014, and they found that these events were correlated with significant reductions in the mixed layer depth and in nitrate concentrations within the upper layer of the water column. Reduced mixing layers should improve light conditions for phytoplankton, thereby stimulating phytoplankton blooms, while reduced nitrate levels should have the opposite effect. The response of the phytoplankton communities was mixed - blooms during MHWs were weak in areas with low back-ground nitrate concentrations and stronger in areas with high back-ground nitrate concentrations where nutrient concentrations would remain high even after the MHW-mediated reductions. Gupta et al. (2020) made a similar evaluation covering more oceanic areas and reach-

Foundation species

A species that creates or maintains the habitat of the ecosystem, and thereby makes up the physical ”foundation”. They are typically among the most abundant species in the ecosystem

Keystone species

A species that has a disproportionally large impact on the ecosystem compared to its occurrence. Keystone species have traits that are essential for the functioning of the ecosystem.

ing the same overall conclusion, but were also able to show that MHWs generally led to reduced phytoplankton biomass at low and mid altitudes (i.e. nutrient poor waters) while MHW events lead to phytoplankton blooms at higher altitudes (i.e. higher than 40°N or 40°S; i.e. in more nutrient rich areas). Both these studies show that the effect of MHWs on phytoplankton blooms can be mixed and depends on the nutrient status of the ocean area in question. Since phytoplankton is a controlling factor in oceanic marine biogeochemical cycles (food webs), MHW effects on algal blooms are likely to multiply to system-wide effects in these systems.

Little is known about MHW effects on zooplankton and higher trophic levels. Suryan et al. (2021) evaluated the community and ecosystem effects of a multi-year warming event that hit the Gulf of Alaska (GOA) between 2014 and 2016. They used long-term monitoring data for a great variety of major taxonomic groups ranging from phytoplankton to whales, but also included commercial harvest of fishes in their analysis. The authors found that the GOA heat wave had an overall negative impact on coastal seaweeds and phytoplankton biomass, but little effect on zooplankton abundance; cool-water zooplankton species remained largely unaffected by the MHW, while the abundance of warm-water species increased (Figure 5). The abundance of planktivorous fishes such as capelin, herring and sand lance was nevertheless affected negatively by the MHW and so were stocks of many larger "ground" fishes such as cod, sable fish, flounder and pollock. The significant decline in fish stocks were mirrored in comparable declines in population size among piscivorous sea birds (as also found by Smale et al. 2019) and marine piscivorous mammals (e.g. otters and pinnipeds). The decline in ground-fish populations during the MHW was followed by reduced commercial harvest of these species with serious consequences for the communities.

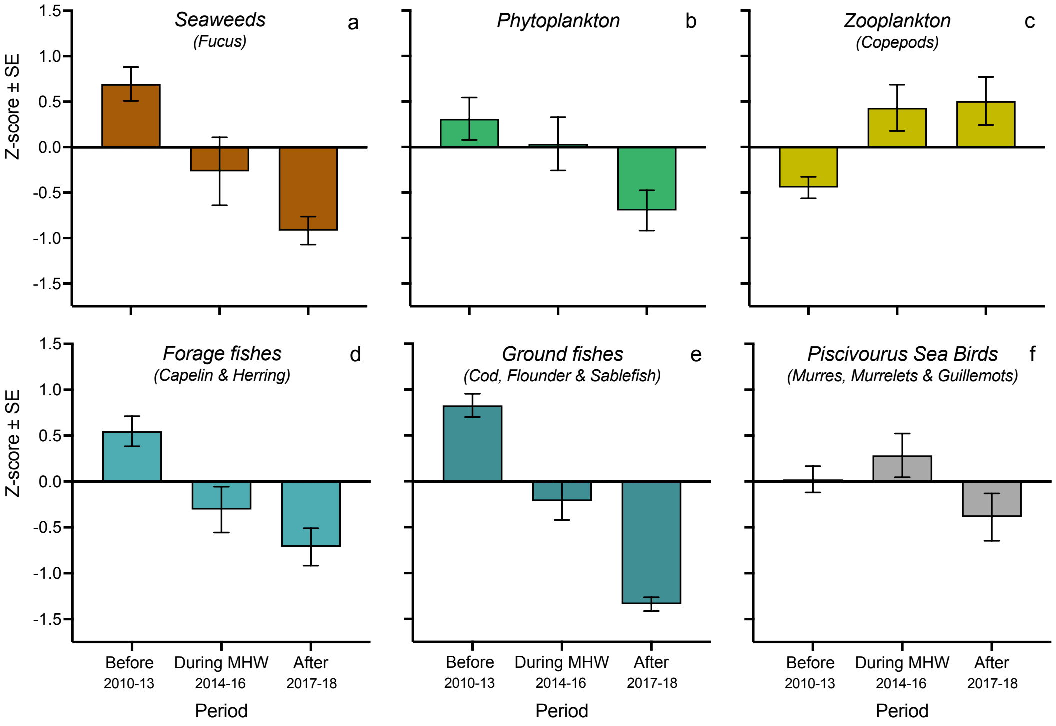

Figure 5. Average response of various trophic level species or groups in the Gulf of Alaska before, during and after the 2014–2016 northeast Pacific marine heatwave. (a) Intertidal algae (*Fucus*), (b) phytoplankton indexed by satellite-derived chlorophyll biomass, (c) Zooplankton (copepod) abundance, (d) abundance of forage fishes (capelin and herring), (e) adult female spawning biomass of Pacific cod, arrowtooth flounder and sablefish, (f) abundance of marine piscivore birds (murres, murrelets and pigeon guillemots). Values are z-score standardizations, so the y-axes are unitless. The figure was re-drawn based on information contained in Suryan et al., 2021.

4.4.3. Coastal effects

Potential MHW impacts on coastal ecosystems may best be evaluated through an assessment of the effects on the major habitat-forming (i.e. foundation) species of the systems in question (Thomson et al., 2015). Kelp forests constitute the most wide-spread and important coastal ecosystem type in the Nordic Seas (Gundersen et al., 2016). Kelps are large, slow-growing, but highly productive (per unit area and time) brown algae that function as “foundation” species in most cold-temperate and Arctic coastal areas where they provide habitat and food for many ecologically and commercially important species (Wernberg et al., 2019). Kelp forest ecosystems are found from the Skagerrak-Kattegat area (between Sweden, Denmark and Norway) in the South, along the Norwegian west-coast and into the Barents Sea, and into the Arctic (Svalbard, Iceland and Greenland) in the north (Lüning, 1990). Only one kelp species is endemic to the Arctic (*Laminaria soludungula*) while all other kelp species found in the Nordic seas are cold-temperate species that have their southern distribution edge in mid-northern Europe (Lüning, 1990). All these kelp species may therefore be susceptible to further elevations in SST and especially so to MHW events occurring in summer.

Loss of kelp forests may have severe ecosystem consequences, because the “removal” of a foundation species may lead to cascading effects that will impact ecosystem structure, function and services. Kelp forests have disappeared globally over the last 50-60 years due to overgrazing from sea-urchins (stimulated by overfishing of top-predators), coastal eutrophication and lately, due to ocean warming and MHW events (Wernberg et al., 2019).

Well-described examples of kelp losses related directly to MHWs can be found from Australia, North America and northern Europe. The 2011 “Ningaloo Niño” MHW off Western Australia lasted for almost 100 days with temperatures exceeding the climatic average by 7°C. This MHW resulted in a substantial die-back among the dominant kelp *Ecklonia radiata* and other habitat forming seaweeds along the northern (warm) edge of their range distribution and a subsequent range contraction of ca. 100 km (Smale & Wernberg, 2013). The direct warming effect on kelp was exacerbated by increased herbivory on kelps by tropical and subtropical herbivorous fishes (e.g. rabbit fish) that expanded their range distribution southward in response to elevated ocean temperatures (Wernberg et al., 2013). The lost kelp forests along the northern warm edge of their distribution range were replaced by communities of fast-growing turf-algae with significant changes in the community structure of higher trophic levels as a consequence (Wernberg et al., 2013). These changes have persisted beyond the extent of the MHW itself and the turf dominated systems have sustained for at least eight years after the warming event (Straub et al., 2019).

The coastline of California has suffered several MHW events over the period 1984 - 2011 and Smale et al. (2019) found a moderately strong, negative correlation between the biomass of Giant kelp (*Macrocystis pyrifera*) and the number of MHW days per year along the coastline of California. The northern coastline of California was hit by a severe multi-year MHW lasting from 2014 to 2016 that resulted in a unprecedented loss (ca. 90%) of bull kelp (*Nereocystis luetkeana*) along 350 km of coastline and a subsequent regime shift from kelp forest dominated systems to sea urchin barrens (McPherson et al., 2021). The massive decline in bull kelp resulted from the combined effect of several stressors triggered by the warming event. The warming event had a direct negative effect on the performance of bull kelp, but it also triggered other changes that indirectly affected the kelp populations. The anomaly warm waters appearing during this period had lower than normal nitrate concentrations, which left bull kelp N-limited and, therefore, more susceptible to heat stress. Bull kelp came finally under increased pressure from intensified grazing; sea stars (the major predator on sea urchins in this area) suffered from the epidemic “sea star wasting syndrome”, which was likely stimulated by the warming event and reduced predation on sea urchins by sea stars allowed sea urchin populations to increase dramatically in numbers and increase their grazing pressure on bull kelp. The combination of factors driven by anomaly high SST during the multi-year MHW in this area resulted in the observed regime shift. The broader ecological consequences of this shift remain unknow but is thought to have had severe consequences for local communities, economies and fisheries (McPherson et al., 2021).

Norwegian kelp forests have experienced large changes over the last 40-50 years. Kelp forests dominated by *Laminaria hyperborea* have been lost from large areas along the west and north-west coast of Norway since the 1970's due to massive out-breaks of the green sea urchin (*Strongylocentrotus droebachiensis*) that have transformed vast areas of healthy kelp forest into sea urchin barrens (Norderhaug & Christie, 2009). This regime shift has without any doubt had substantial consequences for ecosystem structure, function and services provided by these systems, although detailed analyses are lacking. The demise of the central-northern Norwegian kelp forests was not triggered by increasing SST and/or a higher frequency of MHWs, but rather by overfishing and removal of large apex predators such like coastal cod, wolf-fish and edible crab, which are among the main predators on sea urchins in this area (Norderhaug & Christie, 2009). Increasing SST combined with MHW events seem nevertheless to have had a positive impact on these coastal systems because the recruitment of green sea urchin has been negatively affected by higher temperatures in the southernmost part of the impacted area (Fagerli et al., 2013, Gundersen et al., 2016). The southern range distribution of green sea urchins is therefore moving north, which has reduced the grazing pressure in the more southernly parts of the coast substantially. Kelp forest of *L. hyperborea* have now started to re-establish along the coast of the Norwegian Sea, where ca. 50% of the previously lost kelp forests have recovered over the last 1 - 2 decades. The situation in the Barents Sea region in northern-most Norway is, in contrast, still critical since only 20% of the original kelp forests remain today and there has been no recovery recorded recently (Verbeek et al., 2021).

Sugar kelp (*Saccharina latissima*) is the dominant kelp species in southern Norway including the Skagerrak area. Sugar kelp has declined substantially in this area over the last 20 years and has - in most cases - been replaced by dominance of fast-growing filamentous turf-algae (Moy & Christie, 2012). The demise of sugar kelp in southern Norway was originally explained by a combination of factors such as coastal eutrophication, increased turbidity in the water column, increased sedimentation and increasing SST. While this may be true, a recent paper by Filbee-Dexter et al. (2020) was able to associate recent kelp losses in southern Norway directly to an increasing frequency of longer and more intensive MHW events in the Skagerrak area between 1990 and 2018. Filbee-Dexter et al. (2020) did further experimantelly demonstrate that sugar kelp suffered enhanced mortality in the field during a MHW event occurring in the summer of 2018, which is consistent with the effects of heat exposure found in manipulative experiments with sugar kelp (e.g. Nepper-Davidsen et al., 2019) and from aquaculture mortality observations during a MHW in the Kattegat region in 2018 (Pers. Obs).

4.5. Identification and monitoring

Monitoring MHWs can provide crucial information for understanding and predicting the phenomenon. Increased amounts of data will both provide relevant local insights, the possibility of working with preventive measures, and an overall statistical robustness for assessments and modelling purposes.

Monitoring of MHWs and related proxy indicators for heatwaves is not a common activity or a highly prioritized field of research worldwide, but registering sea surface temperature in situ or remote is widespread, and numerous databases covering this indicator exists.

Analyses of MHWs via remote sensing has become increasingly possible through numerous satellite measurements. One example of a high-resolution daily dataset at a 0.01 x 0.01° grid of over 18 years is the Group for High Resolution Sea Surface Temperature (GHRSST) Level 4 MUR Global Foundation SST analysis, which uses a combination of scanning microwave scanning radiometers, spectroradiometers, WindSat radiometers, the advanced very high-resolution radiometer , and in situ SST observations (PODIAAC, 2021). Some of these individual datasets extend back to 1981, and they all be used individually to measure MHWs. It is also relevant to examine anomalous subsurface ocean temperatures and whether coherent temporal and spatial patterns can be detected in these. This type of data serves as a complement for SST data, and can be collected from Argo profiling floats which provide measurements at 10-day resolution, or through data assimilation methods using relationships with data variables such as salinity, sea surface height and temperatures collected through remote sensing (MDPI, 2021).

Examples of monitoring data are gathered as part of an Ocean Monitoring Indicators program; a part of the EU Copernicus Program (Copernicus, 2021a). Through the program, online ocean monitoring indicators (OMIs) are free to download in terms of trends and data sets covering the recent 25 years. It can be used to track the vital health signs of the ocean and climate related changes such as heatwaves. Temperature data are available for the Atlantic-European North West Shelf Ocean, the Atlantic Iberian Biscay Irish Ocean, the Baltic Sea, Black Sea, and the Mediterranean Sea.

T-MEDNet[1] has developed a marine heatwave tracker that monitors Mediterranean MHW events in near real time at 4 km resolution. The monitoring setup uses satellite-derived sea surface temperature information from the Copernicus Marine Service, and the tracker provides a day-to-day description of the magnitude and spatial extent of MHWs over the entire Mediterranean Sea and coastal zone (Copernicus, 2021b).

Another MHW tracker is a global tracker developed by the MHWs International Working Group (Schegel, 2020). This tracker is built on Optimum Interpolation Sea Surface Temperature (OISST) data from the National Oceanic and Atmospheric Administration (NOAA) (Reynolds et al., 2007). The OISST data is a long term climate data record which combines data observations from for example satellites, buoys and ships. The tracker built on this data displays MHW status on a global scale near real time, defined by four heatwave categories as described by Hobday et al. (2018).

Oceanographers from NOAA Fisheries' Southwest Fisheries Science Center have developed an experimental tool; the California Current MHW Tracker for natural resource managers. It is a program designed to understand, describe, and provide a historical context for 'the 2014-16 blob' by providing delayed-time tracking of MHW conditions off western North America. It also produces a range of indices that could help forecast or predict future MHWs. The system automatically analyzes sea surface temperature anomalies (SSTa) from 1984- present, with a particular focus on detecting the presence of significant ”blob-class” events. Sea surface temperature (SST) data have been obtained from a variety of different platforms (satellites, ships, buoys) on a regular global grid at a resolution of 1/4° (NOAA, 2021).

Another example of a monitoring setup for MHWs is given by the Danish Fish Forward project based at DTU Aqua, through which five marine areas were monitored specifically for heatwaves (Payne, 2020):

- Baltic Sea
- North Sea
- Danish archipelago
- European North-west Shelf
- Hoiho breeding areas in New Zealand

The monitoring of these five areas is based on SST observations based on Reynolds SST[2] (Reynolds et al., 2007). In this method, the tracking is based on 5 km resolution which allows monitoring of smaller areas including fjords. Monitoring with this tool detected a MHW in Danish waters in the summer of 2018 which

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[1] T-MEDNet initiative is devoted to develop an observation network on climate change effects in marine coastal ecosystems by spreading the acquisition of standard monitoring protocols on seawater temperature and biological indicators.

[2] For example https://fishforecasts.dtu.dk/Heatwaves/Baltic [Accessed 5. October, 2021]

brought temperature anomalies up to 8°C above mean temperature (M. Payne, personal communication, October 28, 2021).

In terms of developing a relevant and applicable monitoring setup, a number of factors have to be considered; including:

- Availability of data
- Quality of data
- Future data collection processes – what are the options

In terms of quality, Hobday et al. (2016) have stated that high quality data, referred to here as "optimal," used for the detection of MHWs should meet the following criteria:

1. A time series length of at least 30 years.
2. Quality controlled
3. Spatially and temporally consistent
4. Be of the highest spatial and temporal resolution possible/available
5. In situ data should be used to compliment remotely sensed data where possible

Schlegel et al. (2019) have shown that there is no need to avoid using sub-optimal time series, such as might be the best available for coastal research or sub-surface analyses. MHW results are dependent on the time series length, and there may be unforeseeable effects of shorter time series on the data. These effects can however be corrected, and even shorter time series such as those of ten years length can be useful in research. When detecting MHWs, missing data has larger impact on the detection results. Up to 50% of missing data can however be compensated for using linear interpolation (Schlegel et al., 2019).

4.5.1. Forecasting

As described above, there are a number of tools that track the current and past MHW situation at global and local scales. To include a future dimension and create opportunities to foresee MHW events there is a need for forecasting products which are currently not well developed in this field. Forecasting products are in demand in order to mitigate the consequences of MHWs in the Nordics, both at short and long-time scales.

There are examples of marine seasonal forecasts for certain types of ecosystems, for example the NOAA Coral Reef Watch. This application provides forecasts for coral stress levels four months ahead based on expected SST temperatures. It is used by reef managers to foresee coming ocean conditions in their local area, and in some cases, it has provided managers with data that has motivated them to close access to reefs to reduce cumulative stress on corals (M. Payne, personal communication, October 28, 2021).

Another forecasting tool for seasonal temperature anomalies is an SST outlook from the Australian Bureau of Meteorology's climate forecast system, ACCESS-S. This tool displays a map that provides up to six months forecast of SST in Australian regions. The product is built on OISST v2 climatology data and ACCESS-S model data and it operates at approximately 25 km resolution (Australian Government, 2021). This tool also forecasts coral bleaching risk.

On a longer time-scale there are products that provide forecasts for ocean conditions several years ahead. One example is the Global annual to decadal climate update which is published every five years (WMO, 2021). It does not predict future MHW properties specifically, however it includes SST predictions and probabilities of above average SST. These data can be used to determine the risk for MHWs also in the Norwegian seas. Nino 3.4 indices which build on SST data also provide global forecasts on a decadal timescale, including the probability of above average SST. Long-term forecasts provide an opportunity to take impacts over larger temporal scale into account, and there are expectations that these models will improve in the coming years.

Based on the findings of our study there are no existing products that provide forecasting of MHWs for Northern sea areas. Temperature data is currently included in fish stock modelling, and it has been suggested that these models can be developed to include more specific data on MHWs.

4.6. Future prognosis

According to the IPCC, there is very high confidence that the duration, frequency, spatial extent and intensity of MHWs will increase in all ocean basins with future climate change (Collins et al., 2019). There is consensus in the scientific community that the increase in different MHW properties will be stronger as global warming progresses. Oppositely, if warming is kept below 2°C, or below 1,5 °C, the risk of large increases in MHW occurrence, spatial extent and maximum intensity will be substantially reduced. There is 60% less probability of MHW occurrence in a 1,5°C climate change scenario compared to a 3,5°C scenario (Frölicher et al. 2018). But forthcoming developments in MHWs will differ between geographical areas, and there is little research on what the projected changes will look like under local conditions, including the conditions in northern sea areas. Studies that have been carried out mostly build on global climate projections, where northern sea areas are one part of the analysis, but few studies focus directly on the specific conditions around the Nordic countries. Findings that are relevant to the future prognosis of MHWs in northern sea areas are presented in this section, mostly focused on the North Atlantic Ocean as this was the area most frequently studied in the literature analyzed.

Oliver et al. (2019) have used CMIP5 global climate projections to predict the frequency and intensity of MHWs in the future. They considered two greenhouse gas emission pathways as defined by the IPCC, Representative Concentration Pathways (RCP) 4,5 and 8,5. Models based on both of these pathways predict "permanent MHW states" in the coming century, meaning that the temperatures will constantly be above the MHW threshold. This state is predicted to take effect in at the end of the 21st century in the North Atlantic. In tropical areas of the Pacific and the Atlantic this state is already expected at the end of 2020, while it is predicted to happen in most tropical and subtropical areas between 2020 and 2040. This development can be predicted both in a RCP4,5 scenario and in a RCP8,5 scenario, however the development is much more progressive in the RCP8,5 scenario. These results indicate that the North Atlantic will be among the last ocean areas to be affected by a permanent MHW state compared to other ocean areas that lie closer to the equator.

Plecha et al. (2021) studied projections of MHWs in the North Atlantic Ocean by analyzing SST data from observations and from CMIP5 global climate models. They included two RCPs in their analysis, RCP 4,5 and RCP8,5, and examined future MHWs for the time periods 2041-2070 and 2071-2100. For the projections they used a stationary SST threshold obtained from a historical reference period (1971-2000) and classified MHWs according to Hobday et al. (2016). Their projections from all CMIP5 models showed that the duration and intensity of MHWs will increase substantially, while some models projected an increase in frequency and others projected a decrease. The results showed that RCP8,5 projections for the period 2041-2070 were similar to RCP4,5 projections for the period 2071-2100, indicating that increases in MHW properties will arrive sooner in a RCP8,5 scenario. Using the MHW threshold based on historical values, they found that the mean duration of MHWs is projected to over 2-6 consecutive years in the period 2041-2070, and more than 6-16 years in the 2071-2100, for respectively RCP4,5 and RCP 8,5. These results highlight the long periods of elevated SST that can be expected in the North Atlantic Ocean.

Alexander et al. (2018) analyzed changes in mean temperature in the North Atlantic using CIMP5 models and their results indicated that, in a RCP 8,5 scenario (also called "business as usual"), the Norwegian Sea and the Barents Sea will experience the strongest warming (in terms of rising mean SST) during the period 1979-2099 compared to other oceans. Generally, the trend will be stronger during summer than in winter, especially for higher latitudes. As an increase in mean SST seems to be the main driver of an increase in

MHW days (Oliver, 2019), it can be assumed that the warming can lead to more MHW days in the Barents and Norwegian seas.

According to models by Frölicher et al. (2018), the probability of MHW days in Northern sea areas increases with global warming. They define a MHW event as when the temperature exceeds it local 99th percentile on the basis of model and or satellite data from preindustrial times. At a 1 °C warming scenario, which is the approximate warming level in the current situation (2021) the probability increases around 2-4 times compared to preindustrial levels (Table 2). In a 2 °C warming scenario, the probability increases 8-15 times in in the North Sea and Norwegian Sea, while it increases up to 40 times in the Arctic sea areas. At a 3,5 °C warming pathway, probability of MHW days increases between 20-30 times in the North Sea and Norwegian Sea, and between 30-70 times in the Arctic Ocean.

Table 2. Probabilities of MHW occurrence relative to pre-industrial times in the North Sea and Norwegian Sea, and Arctic Sea. Probabilities for three different global warming scenarios, 1°C, 2°C and 3.5°C are included. Based on data from Frölicher et al. (2018)

	North Sea and Norwegian Sea	Arctic Sea
Pre-industrial times	1	1
1 °C warming scenario	2-4	2-4
2 °C warming scenario	8-15	40
3.5 °C warming scenario	20-30	30-70

Several sources have expressed the need for refined climate models to make better projections of MHWs. Plecha et al. (2021) found a number of biases when comparing Global Climate Models (GCMs) with SST observations. According to their study, the model underestimated the MHW intensity, but overestimated the frequency and duration of MHW events. They suggest using for example higher resolution GCMs or coupled regional models to increase the accuracy of the projections.

5. GAP ANALYSIS: DISCUSSION AND ASSESSMENTS

This report is the result of a thorough literature review using a combination of a systematic search strategy and back tracking of literature identified in key studies. All the studies referred to in this section have been published in highly esteemed, international peer-reviewed journals. Furthermore we were in dialogue with experts within the field of MHW monitoring, forecasting and assessment of biological effects. To our knowledge, we have found all relevant studies to address the questions and aims of this report. In addition to this, we base our findings on a well prepared webinar with inputs from three highly recognized scientists working with MHWs. The findings from this webinar were summarized and provided very useful inputs for the report. All in all we find that the information on which this report relies, is complete, of high consistency and validity, providing sufficient background for the conclusions and recommendations drawn.

5.1. Consequences of MHWs on the Nordic seas

Ongoing, global increases in SST go hand in hand with an increasing frequency and intensity of MHWs making it difficult to separate the biological effects caused specifically by MHW’s. Slow long-term increases in SST will lead to large-scale changes in the range distribution among many marine species. Some of these changes may appear fast (e.g. for mobile fauna) while other organisms may change their range distribution more slowly (e.g. sessile plants, seaweeds and invertebrates). Substantial changes in range distributions have already been reported for a broad range of marine plants, seaweeds and animals related to long-term increases in SST.

MHWs may, in contrast, impose acute stress, reduced performance and in extreme cases, elevated mortality that affect populations, communities and ecosystems more locally. The number of studies that aim to review the ecological effects of MHWs is low but increasing and the picture that emerges is generally that the overall effect at the species, community and ecosystems levels are negative and that at least some of these negative effects persist for long after the MHW event. MHWs may thus advance the processes driven by slow increases in SST.

Most studies on the biological effects of MHWs stem from tropical (e.g. El Niño events in the eastern Pacific Ocean) and warm temperate areas (e.g. the Mediterranean Sea and Western Australia) and the question is of course whether the findings from these studies can be used to evaluate the risk in Northern Seas. One comprehensive study from a cold, temperate/Arctic area (Gulf of Alaska) may be more comparable to the situation in the Nordic Seas. The results of this study were comparable to those from the above-mentioned studies from warmer latitudes. The conclusion is that the existing knowledge on the biological effects of MHWs can be used to assess the possible risk in Nordic Seas.

A full and comprehensive assessment of the ecological risk related to MHWs in Nordic Seas requires, however, that the thermal response of many species is known, which is presently not the case. Ecological risk assessment can alternatively be based upon an assessment of various foundation species because it is expected that removal of such species will cause cascading effects that may alter ecosystem structure and function.

Table 3 shows the optimum temperature for growth, the upper lethal temperature and the southern European range (= warm edge) of several important foundation species from the Nordic seas. The level of risk has been set by comparing the upper lethal temperature of each species with its the southern (warm) distributional edge.

For example - *Laminaria solidungula*, which is the only true arctic kelp species , has an upper lethal temperature limit of 16 °C. However, in Nordic seas *L. solidungula* is only found along the coast-lines of Greenland and Svalbard and in the White sea (Mikhaylova 2021) where maximum summer SST averages around 5 °C and rarely exceeds 8-9 °C during the warmest years, why this species is at low risk even during intensive

MHW events. In contrast - species with upper lethal temperatures of 17 - 23 °C (such as *Laminaria hyberporea*, *L. digitata* and *Saccharina latissima*) that also occur on southern Scandinavian waters (i.e. the North sea, Skagerak and Kattegat) may be at high risk during warm summers and especially so with additional MHW events. The comparison in Table 3 shows that some of these species have upper lethal temperatures that are encountered in warm summers and during MHWs in southern Scandinavia (including southern Norway). It is expected that some of these species will suffer more often as the frequency and intensity of MHWs will increase in the near future.

Table 3. Optimum temperatures for growth, upper lethal thermal limits, southern European range limits and presumed risk of a negative impact (increased mortality) in Nordic Seas for a number of important Nordic kelps, fucoids and seagrasses that function as foundation species.

Species	Optimum temperature	Upper lethal temperature	Southern European range limit	Risk in Nordic seas
Kelps:				
Laminaria solidungula	5 - 10 °C	16 °C	65°N (Greenland, Svalbard, White sea)	Low
Saccorhiza dermatodea	5 - 10 °C	~17 °C	65°N (N. Norway)	Rel. Low
Laminaria digitata	~10 °C	20 - 23 °C	43°N (N. Spain)	Rel. High in S. Scandinavia
Laminaria hyperborea	10 - 17 °C	20 - 23 °C	45°N (N. France)	Rel. High in S. Scandinavia
Saccharina latissima	10 - 15 °C	17 - 23 °C	45°N (N. France)	Rel. High in S. Scandinavia
Fucoids:				
Fucus serratus	10 °C	20 - 25 °C	41°N (N. Portugal) 28°N (Canary Islands)	Rel. High in S. Scandinavia
Fucus vesiculosus	15°C	30 °C	35°N (N. Morocco) 28°N (Canary Islands)	Low
Seagrass:				
Zostera marina	ca. 20 °C	30 - 35 °C	35°N (N. Med)	Rel. Low

5.2. Future occurrence of MHWs

The future occurrence of MHW in the Northern Sea areas are expected to increase several fold with global warming. At a 1 °C warming scenario, similar to the current situation (2021), the probability of MHW days increases around 2-4 times compared to preindustrial levels (Table 2). This occurrence corresponds well with current observations of increased MHW as documented in eg. Nepper-Davidsen et al., (2019). In a 2 °C warming scenario, which according to the latest assessments (IPCC, 2014; Collins et al., 2019) seems inevitable, the probability increases 8-15 times in the North Sea and Norwegian Sea. At the extreme 3.5 °C warming scenario, the probability of MHW days increases between 20-30 times in the North Sea and Norwegian Sea. Regardless of the effectiveness of measures to mitigate release of greenhouse gas emissions, the current, and near future occurrence of MHWs for the Northern Sea areas are highly concerning.

5.3. Monitoring systems

5.3.1. Existing monitoring efforts

In Norway, there are several types of ongoing in situ monitoring of sea temperature. The Norwegian Institute of Marine Research (IMR) is responsible for monitoring the conditions for fish stocks, and this makes up the basis for several types of sea temperature monitoring. The temperature monitoring is thereby not directly adapted to MHWs, however it may still be useful in this context.

Since 1936, IMR has had a number of measuring stations along the Norwegian coast that have contributed to the build-up of a long-term data series of sea temperature (G. Ottersen, personal communication, 18 November 2021). Measurements have generally been performed around two times per month. Currently (2021) there are 8-10 hydrological measuring points where temperature data is collected along a vertical gradient down to 300 m (The Norwegian Institute of Marine Research, 2021).

IMR also monitors the temperature conditions in offshore areas. A few times yearly, research ships collect temperature data in transects of the largest ocean currents on Norwegian waters (The Norwegian Institute of Marine Research, 2021). These measurements are made along a vertical gradient between one to six times per year, depending on the location (G. Ottersen, personal communication, 18 November 2021). The ships typically depart from the coast and cover coastal waters as well as open ocean areas, including the Arctic ocean. Since 1984 there are yearly research trips in certain areas that monitor fish stocks, and data on sea temperature is also collected during these trips. In addition, IMR gathers temperature data from passenger and cargo ships, so called “ships of opportunity”. These ships log temperature data at 4 m depth which is reported to IMR, an initiative which has been ongoing since the 1930s (Norwegian Marine Data Centre, 2021).

In addition to these datasets, data is gathered through different research projects organized by universities and other research institutions (G. Ottersen, personal communication, 18 November 2021). Data collected through these projects is typically more detailed than other available temperature monitoring data, but covers a shorter time span as research projects rarely include long term monitoring.

5.3.2. Suitability assessment

Long-term data series of sea temperatures are important to determine the relevant baseline from which to compare and assess MHW. Here ship based in situ data are valuable. Even though they don’t measure very frequently. Reviewing the historical and existing in situ monitoring efforts, it seems likely that it should be possible to acquire high quality data from both open and coastal waters around Norway, suitable for deriving baseline data sets covering a 30 years of data as recommended by Hobday et al., (2016). Efforts are however, needed to make these data easily accessible for relevant geographical areas in the Norwegian Seas.

To determine if a MHW is occurring, daily temperature measurements are necessary. While these can be obtained via satellites in the more open waters during most parts of the year, interference with land near the coastline makes them less suitable here. Also, while satellites provide important information on large-scale SST conditions, other types of measurements are required to obtain information below the upper mixed zone of the water column. Thus, in order for adequately monitor temperature changes along the coastline, where most of the vulnerable benthic habitats are located, and to determine the vertical distribution of MHWs, daily in situ measurements are required. Also, the quality of satellite derived SST data is highly dependent on quality assurance and calibration against in situ measurements, which accordingly are needed at a range of spatial scales (nearshore, offshore, different depths). Although several types of monitoring effort are currently taken place, the extent to which current monitoring provides such essential data remains uncertain.

5.4. Knowledge gaps

Biological consequences of MHWs:

- We have very limited knowledge on the exact temperature response of most marine species. This is a critical knowledge gap if we want to provide more exact predictions on the biological effects of MHW's
- Another major knowledge gap concerns the adaptation potential of species to warming which we currently have limited knowledge. Future studies combining traditional population and physiological studies with new molecular methods are seriously needed to evaluate the potential for thermal adaptation for most marine organisms
- We found very few studies which document impacts of MHWs on biological systems within the Norwegian seas. Most importantly there are very few studies which provide regionally relevant information on expected future impacts of MHWs on biological systems (ie. species composition, distribution, ecosystem productivity, water quality.
- As MHW's may significantly affect the performance of species, their distribution as well as water quality conditions (e.g. anoxia), lack ofknowledge on the extent of MHW's and monitoring on their direct effects, reduces to the ability to understand and manage other environmental pressures such as eutrophication. Accordingly, there is risk that effects that are assigned to certain marine pressures (e.g. eutrophication, pollution) in reality are consequences of MHWs. Furthermore, it remains highly unknown how MHWs interact with other climate related changes (acidification, general warming, stratification, precipitation and related runoff) and other human related pressures such as eutrophication, overexploitation of fisheries, hazardous substances, marine litter and introduction of non-indigenous species

Future occurrence of MHWs:

- More work on regional climate models are required to accurately project expected changes in water temperatures and their extremes in the Norwegian part of the NE Atlantic. This will help provide needed knowledge on the natural variability of water temperatures and its connection to large-scale patterns of climate variability
- While the occurrence of MHWs is projected to increase, in the Norwegian seas, evidence of historical changes in their occurrence in marine ecosystems within this region are not well documented

MHW occurrence:

- Availability and quality of data collected though historical and contemporary in situ temperature monitoring needs to be clarified
- Availability of human and financial resources to implement an operational monitoring of SST with satellite data is not clear

6. CONCLUSION

Biological consequences of MHWs

There is increasing evidence of large biological impacts of MHWs in many parts of the world's oceans. Effects span large-scale changes in the geographical distribution of marine species, species extinctions and impacts on ecosystem productivity, trophic interactions, water quality, and ecological status, with implication on the functions and services the ocean and coastal waters provide.

While the regional knowledge of MHWs on the biological conditions remains limited, there is reason to expect that MHWs pose a greater threat to the marine systems than the gradual temperature increase associated with global warming. Ongoing, global increases in SST go hand in hand with an increasing frequency and intensity of MHWs and it is difficult to separate the biological effects caused by one or the other process. Slow long-term increases in SST will lead to large-scale changes in the range distribution among many marine species, some of which may appear fast (e.g. for mobile fauna) while others may change their range distribution more slowly (e.g. sessile plants, seaweeds and invertebrates). MHWs may, in contrast, impose acute stress, reduced performance and in extreme cases, elevated mortality and may thus push the processes driven by slow increases in SST forward.

Recent studies have shown that Marine heat waves - eventually in combination with ongoing increases in SST - have an overall negative effect on costal ecosystem structure and function. Ecosystems effects is mainly expected to occur through a direct negative effect on important foundation species (such as kelp and seagrass species). Extensive losses of kelp forests or seagrass meadows over large areas represents a regime shift with negative effects cascading up through the food-web.

Species and populations near the warm edge of their range distribution are more susceptible to both increasing SST and MHW events than more central populations and those near their cold edge. Species and ecosystems based on species appearing near the warm edge of their latitudinal range distribution must therefore be considered at higher risk than those appearing in the center or near the cold edge of their distributional range.

It should be kept in mind that the overall effect of MHWs is context dependent as exemplified by the response of oceanic phytoplankton biomass to MHW's, where back-ground nitrate-levels dictate whether the MHW response is negative or positive. Another good example is the indirect "positive" effect of increasing SST and MHWs on kelp seen below 65 °N along the Norwegian west-coast, which is caused by a direct negative effect of increasing SST on sea-urchins that pose a recent and more substantial threat to kelp at the moment.

MHWs are known to interact with other climate change related effects (run-off, acidification) with amplified effects in systems that are already under pressure from other human activities such as eutrophication, overfishing, introduction of invasive species and pollution with hazardous substances.

MHW occurrence

MHWs are an important attribute of the gradual warming of our seas all around the globe. The climatic and oceanic drivers vary between regions, and are currently not well described and parameterized for the Norwegian Seas.

The large-scale information on MHW occurrence available for the Northern Seas, indicate that their occurrence have grown rapidly within the recent decades, with expectations of an 8-15 times increase in the North Sea and Norwegian Sea under a 2 ^{o}C temperature increase scenario, compared to historical conditions.

Experiences from southern latitudes, show that it is possible to parameterize and make predictive models to enable useful forecasts of MHWs. Besides locally adapted hydrodynamic models, this requires access to high quality measurements of daily sea temperatures to ensure adequate calibration and validation of model products. A combination of satellite derived SST products and in situ sampling via existing monitoring can facilitate this.

MHW monitoring

There are several types of ongoing in situ monitoring of sea temperature which in combination with satellite derived SST can provide most of the required information needed to map the extent of MHW in the Norwegian Seas. Gaps in temperature monitoring can easily be covered using low cost reliable temperature loggers. Coordination of monitoring efforts, efficient sharing and quality assessment of monitoring data, is essential along with efforts to develop forecast models in relevant geographical regions of the Norwegian Seas.

7. RECOMMENDATIONS

- To document the historical and current changes in the occurrence of MHWs and improve our understanding of MHW impacts on species distribution, ecosystem functioning, quality and status, dedicated MHW monitoring is required. Otherwise, it is very likely that sudden changes in biological systems constituting the Norwegian waters, can occur without a proper understanding of the underlying causes.
- Given the identified rate of change and concern associated with MHWs in Norwegian Seas, adequate MHW monitoring is essential to inform proper management of our natural environment and resources. While satellites can provide frequent and large scale coverage of SST, they are less appropriate to monitor development of MHW's in nearshore regions where many important coastal habitats occur (eg. Kelp forests). Monitoring in these coatal regions should therefore be supplemented with continuous in situ observations. To ensure that gradients with depth are properly recorded, in situ measurements should both be made in surface waters and with increasing depth. Observations deeper in the water column are especially important in coastal areas and fjords since these are more temperature sensitive systems. Incorporating data from temperature bouys and aquaculture should be considered as part of an extensive monitoring program.
- Biological monitoring of MHW is recommended to focus on the distribution and health of temperature sensitive species and their related communities. Monitoring on the distribution and health of foundation species (see Table 3) seem particular relevant.
- Efforts should be made to gather all existing temperature data to develop appropriate baseline conditions needed to evaluate MHW events from. A repository of available in situ and satellite data should be established, quality checked and used for calibration of satellite derived SST products. Given the large interest and exposure of fish farms along the Norwegian coastline, efforts should be made to develop regional models which can forecast MHW events.

  While reductions in greenhouse gas emissions will hopefully counter and slow down the gradual increase in biosphere temperatures there is no doubt that climate changes will continue, and with these the extreme weather conditions leading to more MHW events. In view of this, climate change mitigation / adaptation seems the only way to counteract the negative biological effects. Here, the best adaptation response available is to strengthen the resilience of marine systems overall through reduction of other pressures. Beyond climate change, most marine systems are facing multiple pressures of which most have a human origin. Reducing these pressures will overall strengthen resilience of the marine habitats and their species.

- Furthermore, it is recommended to enhance protection of marine areas. Especially those where the temperature increases are expected to be lower as these can function as so-called climate refuges (Giraldo-Ospina 2020). These could become a last outpost for species affected by climate change and help ensure reestablishment of lost habitats and species through donation of spores and larvae.

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ANNEX A – SEARCH STRINGS

Search string	Query	Results	Targeted research question(s)
String 1	Marine* OR Ocean* AND Heatwave OR “Heat wave” OR MHW OR Warm-spell OR “Warm spell” AND Nordic OR “North Sea” OR “North Atlantic*” OR Norwegian* OR Norway OR Barents*	154	What are the drivers for MHWs in Northern oceans and seas, and do these differ from drivers in other parts of the world? Will the Northern seas and oceans be exposed to a particularly large increase in frequency and duration of MHWs, compared to other sea areas?
String 2 Biological effects	Adding to string 1: Ecosystem* OR biological* AND effect* OR response To the above	84	Does the literature identify ecosystems or geographical areas in the northern seas which are particularly exposed to marine heat waves? Which areas, and why are they particularly exposed? How do MHWs affect the biology of marine systems in northern, especially Norwegian, sea areas?
String 3 Identification and monitoring	Adding to string 1: Monitoring OR identification OR indicator	60	What are the methods and requirements for monitoring and forecasting MHWs?

String 4 Anthropogenic impacts	Adding to string 1: human* OR anthropogenic* OR “man-made” AND impact OR * warming OR “climate change” OR driver	92	What are the drivers for MHWs in Northern oceans and seas, and do these differ from drivers in other parts of the world?