Surface and bottom ~~M~~marine heatwave characteristics in the Barents Sea: ~~impact of changing baselines~~a model study

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Abstract. Anomalously warm oceanic events, often termed marine heatwaves, can potentially impact the ecosystem in the affected region and has therefore become a hot topic for research in recent years. Determining the ~~amplitudes~~ intensity and spatial extent of marine heatwaves, however, depends on the definition and climatological ~~baseline~~ average used. Moreover, the stress applied by the heatwave to the marine ecosystem will depend on which component of the ecosystem is considered. Here, we utilize a model reanalysis (1991-202~~1~~2) to explore the frequency, ~~intensity~~intensity, and duration of marine heatwaves in the Barents Sea, as well as ~~their~~ regional ~~expression~~~~occurrence of MHWs~~heterogeneities. We find that major marine heatwaves are rather coherent throughout the region, but surface marine heatwaves occur more frequent while heatwaves on the ocean floor have longer duration. ~~and have comparable characteristics near the sea surface and the bottom~~sea ~~floor~~ ~~expressions.~~ Moreover, we investigate the sensitivity to the choice of ~~utilize a 60-year regional model hindcast to show the impact of changing~~climatological average length when calculating marine heatwave statistics ~~baselines on marine heatwave statistics~~. Our results indicate that severe marine heatwaves ~~are likely~~may becom~~ing~~e more frequent in a future Barents Sea due to ongoing climate change.

1 Introduction

A ~~M~~marine heatwave~~s~~ (MHW) ~~are~~is a period~~s~~ of a warm spell~~s~~ in an ocean region and ~~are~~is usually defined as a period~~s~~ when the temperature exceeds a given threshold ~~based on~~relative to a climat~~ic~~ological ~~baseline~~average (e.g., Marbá et al., 2015; Hobday et al., 2016; Scannell et al., 2016; Hu et al., 2020; Huang et al., 2021). Due to the potential profound impact on marine life (e.g., Smale et al., 2019; Husson et al., 2022) and, hence, also socioeconomic impacts (Smith et al., 2021), MHWs have received increasing attention in recent years, see Oliver et al. (2021) for a comprehensive review of recent literature. While the criteria to define MHWs seem to converge to those proposed by Hobday et al. (2016), i.e., the temperature~~s~~ ~~above~~exceeding the 90^{th} percentile ~~based~~ o~~n~~f ~~a~~the moving ~~fixed baseline~~climatological average, little attention has been given to the impact of the choice of ~~baseline period, or~~ climat~~e~~ological average ~~normal,~~ on the MHW characteristics and statistics such as frequency, intensity and duration (Chiswell, 2022). The underlying trends of global ocean warming (e.g., Cheng et al., 2022) and regional

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climate variability (e.g., Smedsrud et al., 2022) both impact the MHW statistics, and some regions may eventually enter a state of permanent MHW, depending on the climatological average chosen~~ when compared with fixed baseline periods~~. As an example, while Fröhlicher et al. (2018) found a doubling of MHW days between 1982 and 2016 globally, Chiswell (2022) showed that accounting for climate change by removing the linear trend resulted in weaker MHWs in the tropics and stronger MHWs in the northern Pacific and Atlantic Oceans.

When MHWs are calculated as a timeseries for a whole region, possible regional heterogeneities ~~will~~ may be masked~~lacking, and,~~ thereby reducing the applicability of ~~such~~ using the timeseries as an MHW index. The Barents Sea is a complex shelf sea that mainly consists of a relatively warm and ice-free Atlantic Water dominated part in the south, and a cold, seasonally ice-covered Arctic Water dominated part in the north. The southern part is kept ice free by relatively warm and saline Atlantic Water entering to the southwest. The Atlantic Water gives up most of its heat (relative to the average temperature of the Polar Basin) to the atmosphere while en route (e.g., Gammelsrød et al., 2009; Smedsrud et al., 2013). Moreover, the inflow of Atlantic Water has been shown to be a precursor for interannual variability in the Barents Sea sea-ice cover (Onarheim et al., 2015; Schlichtholz, 2019) as well as the ocean heat content further downstream in the Barents Sea (Lien et al., 2017). ~~Moreover, b~~Both the southern and northern Barents Sea~~ regions~~ have varying seasonal stratification, mainly from melting of sea ice in the north and solar insolation causing thermal stratification in the south (e.g., Smedsrud et al., 2013; Lind et al., 2018). The marine ecosystem is~~ therefore also~~ differing between the two main regions, with further diversification within each region. ~~(see, e.g., Jakobsen and Ozhigin (2011) for a comprehensive overview).~~ However, the extension of the two regimes is changing due to ongoing climate change, with the boreal, southern part expanding at the expense of the northern, Arctic part (e.g., Fossheim et al., 2015; Oziel et al., 2020). The Barents Sea is home to several important, commercial fish stocks, both pelagic (e.g., capelin (*Mallotus villosus*) and Norwegian spring spawning herring (*Clupea harengus*)) and demersal (e.g., northeast Arctic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*)), in addition to a diverse marine ecosystem including large groups of marine mammals and sea birds as well as unique benthos communities (see Jakobsen and Ozhigin (2011) for a more comprehensive overview). Hence, MHWs may have profound impacts on marine living resources, ~~especially~~ but with different species exhibiting differences in resilience to MHW events (e.g., Husson et al., 2022). Recent studies on MHWs in the Barents Sea, however, have focused on the surface or the upper parts of the water column (Mohamed et al., 2022; Husson et al., 2022).

Here, we investigate the occurrences of both surface and bottom MHWs in four contrasting environments in the Barents Sea. Moreover, we explore the differences in frequency, intensity and duration~~ and intensity~~ ~~based on~~using varying ~~methodology~~ climatological ~~baseline~~average lengths for estimating MHWs. We also focus on the ~~most severe~~highest-intensity MHW event in terms of cumulative degree-days and investigate its oceanic and atmospheric preconditioning and ~~decay~~decline.

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2 Data & Methods

2.1 Model data

We base<u>d</u> our analysis on ~~modeled~~<u>modelled</u> daily averages from ~~two different models;~~ the EU Copernicus Marine Service ocean reanalysis for the Arctic region based on the TOPAZ model system<u> for the period 1991-2022</u> (Sakov et al., 2012; Xie et al., 2016;<u> Lien et al., 2016</u> product ref 1, Table 1), hereinafter termed *TOPAZ reanalysis*. ~~In addition, we have used a regional model hindcast utilizing the ROMS model (Regional Ocean Modeling System; Shchepetkin and McWilliams, 2005) configured for the Nordic and Barents Seas region (Lien et al., 2013, 2014, 2016; product ref 2, Table 1), hereinafter termed~~ ~~*ROMS regional hindcast*.~~

Table 1: Products used and their documentation.

Product ref. no.	Product ID & type	Data access	Documentation
1	ARCTIC_MULTIYEAR_PHY_002_003; Numerical models	EU Copernicus Marine Service Product (2022)	Quality Information Document (QUID): Xie & Bertino (2022) Product User Manual (PUM): Hackett et al. (2022)
~~2~~	~~NordicSeas_4km, Numerical models~~	~~MET Norway Thredds Service~~	~~Lien et al. (2013, 2014)~~
<u>2</u>~~3~~	Conductivity-Temperature-Depth data obtained in the Barents Sea	IMR database TINDOR (data accessible upon request)	
<u>3</u>~~4~~	ERA5 Gridded Reanalysis (0.25 * 0.25 deg); monthly average on single level	EU Copernicus Climate Service Product (2023)	Hersbach et al., 2023

2.2 Ocean observation data

We have used available CTD (*Conductivity-Temperature-Depth*) casts (product ref. ~~3~~<u>2</u>, Table 1)<u>, covering the period 1986 to 2020,</u> for assessing the ~~performance~~ <u>quality</u> of the ~~two~~ model dataset~~s~~ with regard to bottom temperatures in four regions of the Barents Sea (Fig. 1)<u> before we use the models results to calculate MHW statistics</u>. The CTD data were obtained from the Institute of Marine Research database TINDOR (The Integrated Database for Ocean Research).

2.3 Atmospheric data

Monthly averages of turbulent heatfluxes and outgoing longwave radiation for the period 1993 to 2021 were downloaded from the EU Copernicus Climate Service website (product ref. 3~~4~~, Table 1).

2.4 Marine heatwave estimation method

We have adopted the definition of MHWs proposed by Hobday et al. (2016), where an MHW~~s~~ ~~are~~ is defined as a period of more than five days where the temperature is above the 90th percentile of the ~~seasonally~~ daily varying ~~90th percentile threshold relative to a predefined baseline~~ climatolog~~y~~y averaged o~~f~~ver a period ~~at~~of at least 30 years. Moreover, two consecutive events divided by a gap of two days or less is~~are~~ considered a single event.

The TOPAZ reanalysis covers the time period 1991-202~~1~~2. In compliance with common standards by the World Meteorological Organization (WMO 2007; WMO 2015), we have chosen the period 1991-2020 as the climatological ~~normal~~ average period. To study the effect of changing the climatological average period, we have calculated the MHW statistics using also the 25-year period 1996-2020 and the 20-year period 2001-2020 as the climatological average periods.~~For the ROMS regional hindcast, which covers the period 1960-2020, we have used two 30-year periods, 1961-1990 and 1991-2020. These periods correspond to the previous and most recent, respectively, widely adopted climate normal periods. We choose these periods to examine the effect on MHW statistics of using different baseline periods. The first period, 1961-1990, was a relatively cold period in the Barents Sea region, whereas the period 1991-2020 has been relatively warm (e.g., González-Pola et al., 2020).~~

We have chosen four sub-regions where we compute the daily spatially averaged surface and bottom temperatures representing contrasting marine environments: the Bear Island Trough in the south-western Atlantic Water inflow area to the Barents Sea; the adjacent Spitsbergen Bank which represents a productive, shallow bank with an Arctic marine environment; the ~~n~~North~~-~~east~~ern~~ Basin in the north-eastern Barents Sea which represents the outflow region where strongly modified Atlantic-derived water masses leave the Barents Sea; the Pechora Sea to the south-east which represents a shallow and coastal water influenced area (see map, Fig. 1). Our Bear Island Trough region ~~falls~~ is pushed towards the southern slope of the trough ~~outside the full Barents Sea region, due to a compromise because of the orientation of the grid, but it~~to cover~~s~~ the area around 72°30'N ~~where the topography is less complex than further east and~~which is where the core of the main inflow branch carrying Atlantic Water to the Barents Sea is located (e.g., Skagseth et al., 2008).

For estimating MHW statistics we have used the python package provided by Eric C. J. Oliver: https://github.com/ecjoliver/marineHeatWaves and using the default settings.~~.~~ ~~Note, that the MHW detection algorithm counts every single MHW during a year as a separate event, meaning that a single MHW event that extends over two or more calendar years can be counted several times. This will impact the calculation of frequency and the associated trend in occurrences.~~

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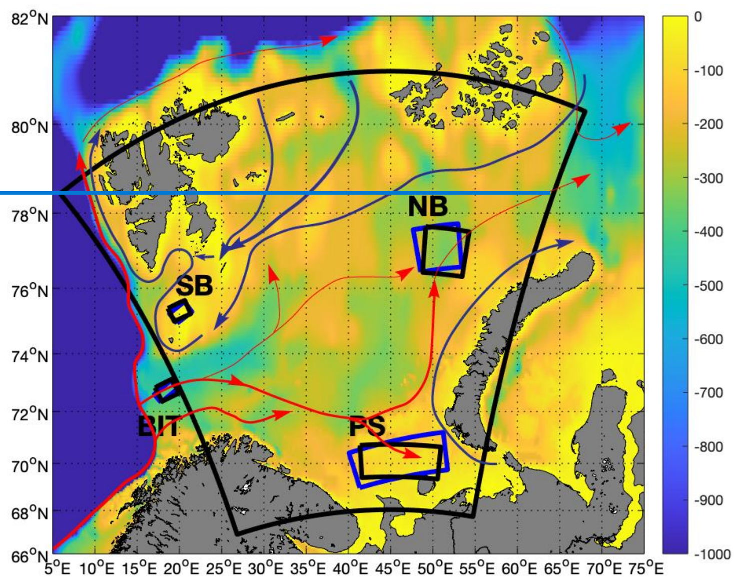
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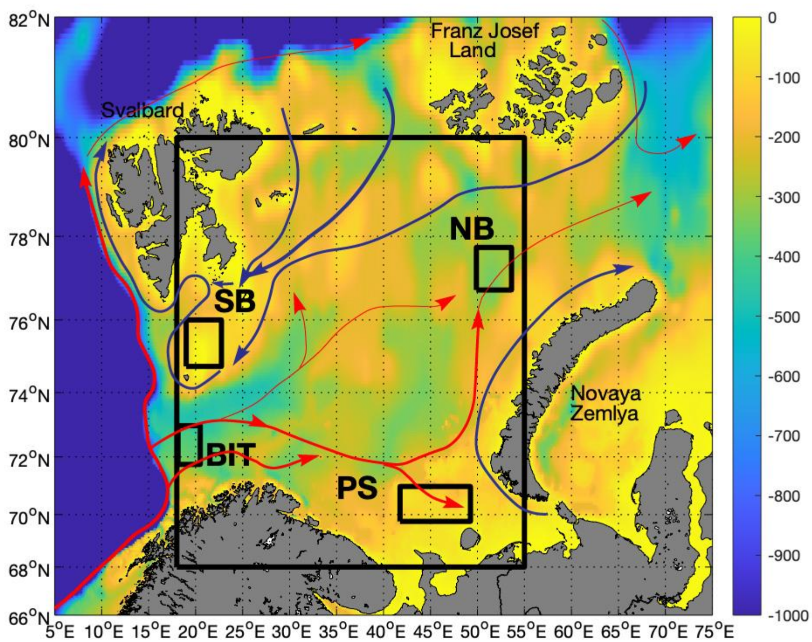

Figure 1:Update regions! Map of the Barents Sea. Colors show the bathymetry (in meters). Arrows show the main current patterns for Atlantic Water (red) and Arctic Water (blue). Boxes show regions for estimating marine heatwaves statistics from the TOPAZ reanalysis (black) and ROMS regional hindcast (blue). BIT: Bear Island Trough; NB: ~~n~~North~~-~~east~~ern~~ Ba~~rents~~sin~~ Sea~~; SB: Spitsbergen Bank; PS: Pechora Sea.

2.4 Model evaluation

~~Even though b~~T~~oth t~~he model product~~s~~ used in this study ha~~ve~~s previously been evaluated ~~in previous studies~~against a suite of ocean observations (~~for TOPAZ reanalysis, see:~~e.g., Lien et al. (2016); Xie et al. (2019, 2023)~~; for ROMS regional hindcast see: Lien et al. (2013, 2014, 2016)~~)~~.~~, However, because we also used the model for analysis of MHWs near the ocean floor, we here provide an assessment of the quality of the model by direct comparison with observations of near-bottom temperature from CTD casts where available in the four sub-regions. The motivation for comparing only bottom temperatures ~~-~~ is that

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satellite sea surface temperature observations are assimilated into the TOPAZ reanalysis. Moreover, the sea surface temperature is also constrained by ocean-atmosphere bulk fluxes. ~~Furthermore, the novelty of our study is the analysis of MHW events near the ocean bottom, in comparison to previous studies in the Barents Sea focusing mostonly on MHW events at the sea surface or in the upper 50 m of the water column (e.g., Mohamed et al., 2022; Husson et al., 2022).~~

~~Here~~In this model quality assessment, we compared modelled and observed near-bottom temperatures averaged in time (monthly) and space (see sub-regions, Fig. 1). The modelled seasonal signal was removed from both model and observation timeseries before the correlation was calculated. The comparison~~s~~ ~~are~~is summarized in Table 2~~1~~ and Supplementary Figure S1.

Table 2: Statistics summarizing the comparison between the models and observations at *N* CTD locations. Correlations are shown in boldface when *p* < 0.05 and underlined boldface when *p* < 0.01. BIT: Bear Island Trough; SB: Spitsbergen Bank; PS: Pechora Sea; N~~E~~B~~S~~: North ~~E~~east~~ern~~ Ba~~rents~~sin ~~Sea~~.

Model	**Statistic**	**BIT**	**SB**	**PS**	**N~~E~~B~~S~~**
TOPAZ	*N*	202	49	34	11
	Bias [°C]	1.9	-2.1	-0.8	-0.6
	RMSd [°C]	2.0	2.4	1.0	0.7
	Correlation [*r*]	<u>**0.55**</u>	<u>**0.39**</u>	<u>**0.78**</u>	**0.66**

3 Results

We first ~~estimate~~ calculated the MHW statistics based on the TOPAZ reanalysis for the full Barents Sea region for the period 1991-2022 (see Fig. 1 for area definition), which ~~. Among the MHWs identified, T~~two ~~distinct MHW events are identified distinguished both in terms of intensity and duration in both the surface and bottom temperature time series. While the strongest MHW, in terms of cumulative effect (degree days), appeared in 2016 both near the surface and near the bottom, the second strongest MHW appeared in 2013 near the surface and in 2012 near the bottom (see Supplementary Figures S2 and S3 for the full timeseries). When applying the MHW definition provided by Hobday et al. (2016), we computed t~~The following ~~computed MHW statistics (~~are summarized in figure 2 and Tables 3-5~~)~~. A total of 29 MHWs were identified at the surface compared to 5 MHWs near the bottom, equating to a frequency of 0.90 year^{-1} at the surface and 0.16 year^{-1} near the bottom. The average maximum intensity was 1.41 °C and 1.07 °C at the surface and near the bottom, respectively. The duration was, on average,

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longer near the bottom (214 days) than at the surface (33 days). Moreover, we found a positive, decadal trend in the MHW frequency at the surface of 0.82 year^{-1} ($p < 0.05$), while for all the other metrics mentioned above, the decadal trends were non-significant.

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Two periods are distinguished in terms of MHW cumulative intensity (°C days), both at the surface and near the bottom. The strongest MHW in the Barents Sea as a whole, in terms of cumulative intensity, occurred in 2016 both at the surface and near the bottom (Fig. 3a,f). At the surface, the 2016 MHW had an average intensity of 1.29 °C (maximum of 3.41 °C) and a total duration of 480 days (from December 19, 2015, to April 11, 2017). Near the bottom, the 2016 MHW had an average intensity of 1.10 °C (maximum of 1.28 °C) and a total duration of 479 days (February 28, 2016, to June 20, 2017). The second strongest MHW in terms of cumulative intensity in the Barents Sea as a whole, occurred in 2013 at the surface and in 2012 near the bottom (see Supplementary Figure S2). While an investigation on possible mechanisms for the decoupling between the surface and the bottom is beyond the scope of this work, we note that the 2012/13 MHW event was preceded by an extraordinarily large temperature anomaly but close to average volume transport in the Atlantic Water entering the Barents Sea to the southwest (e.g., ICES, 2022), as opposed to extraordinarily large volume transports preceding the 2016 MHW event (see below for more details). Moreover, previous studies have suggested that temperature anomalies that are advected into the Barents Sea at depth during the stratified summer season, can reemerge at the surface further downstream through vertical mixing during the following winter (e.g., Schlichtholz, 2019).

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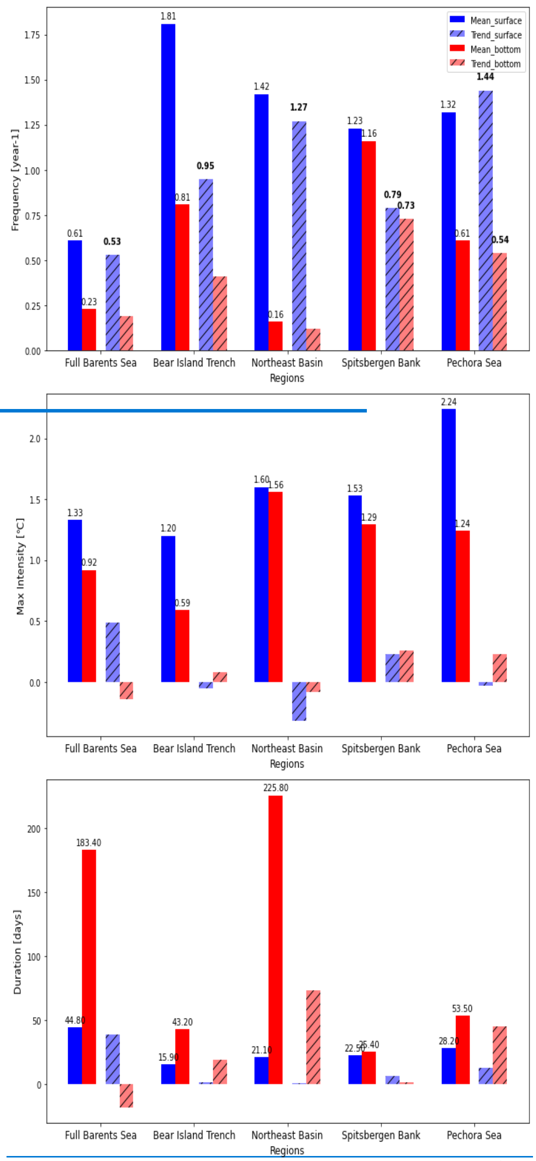
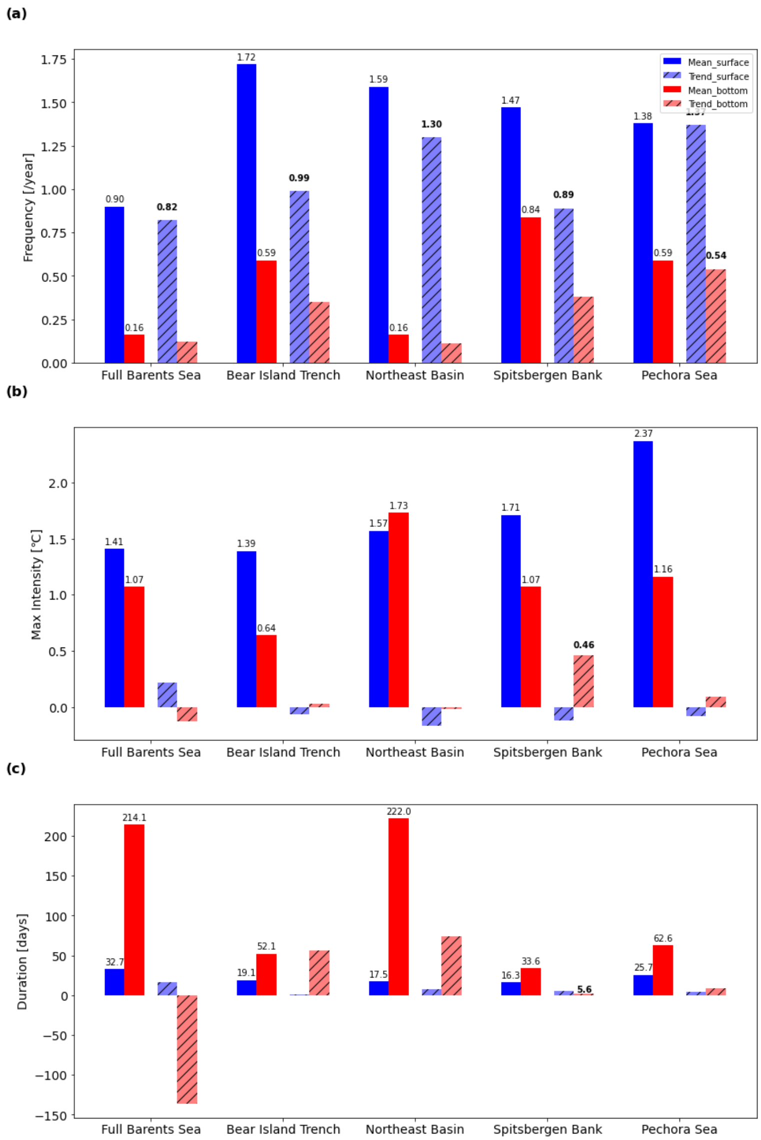
Near the surface, the 2016 MHW had an average intensity of 1.25 °C above the climatological temperature average temperature and a total duration of 512 days (from November 18, 2015, to April 12, 2017). The nNear- the bottom, the MHW expression had an average intensity of 1.02 °C above the climatological temperature and a total duration of 587 days (December 30, 2015, to August 7, 2017). However, while the MHW statistics at the surface and near the bottom expression ofwere comparable in the 2016 MHW event are comparable, we find some differences between the surface and the bottom when comparing the MHW statistics between the average surface and bottom expressions of MHW in the Barents Sea in general. The frequency of MHWs for the 1991-20212 period was found to be 0.61 year^{-1} near the surface and 0.23 year^{-1} near the bottom, while the average maximum intensity was found to be 1.33 °C and 0.92 °C near the surface and bottom, respectively. The duration was, on average, longer near the bottom (183 days) compared with near the surface (45 days). The frequency and maximum intensity had positive trends both near the surface and near the bottom, while the duration had a positive trend near the surface and a negative trend near the bottom. However, these statistics need to be interpreted with care. For example, while we identified two main MHW events, several shorter periods were also classified as MHWs, especially within the near-bottom (Supplementary Figures S4a, S5a). Some of these events were related to the same warm period but with intermittent periods with temperatures below the 90th percentile in between. These shorter periods affected the calculation of the duration trend. Thus, although all the near-bottom MHW events detected occurred within the last 18 years of the 1991-2021 period, no significant trends were detected in the average duration appeared with a negative trend in the calculations.


Mean_surface
Trend_surface
Mean_bottom
Trend_bottom
Frequency [year-1]
1.81
1.42
1.27
1.23
1.16
1.32
1.44
0.95
0.81
0.79
0.73
0.61
0.53
0.23
0.16
0.61
0.54
Full Barents Sea
Bear Island Trench
Northeast Basin
Spitsbergen Bank
Pechora Sea
Regions
Max Intensity [°C]
2.24
1.33
0.92
1.20
0.59
1.60
1.56
1.53
1.29
1.24
Full Barents Sea
Bear Island Trench
Northeast Basin
Spitsbergen Bank
Pechora Sea
Regions
Duration [days]
225.80
183.40
44.80
15.90
43.20
21.10
26.40
28.20
53.50
Full Barents Sea
Bear Island Trench
Northeast Basin
Spitsbergen Bank
Pechora Sea
Regions



(a)
Mean_surface
Trend_surface
Mean_bottom
Trend_bottom
Frequency [/year]
0.90
0.16
0.82
1.72
0.59
0.99
1.59
0.16
1.30
1.47
0.84
0.89
1.38
0.59
0.54
Full Barents Sea
Bear Island Trench
Northeast Basin
Spitsbergen Bank
Pechora Sea
(b)
Max Intensity [°C]
1.41
1.07
1.39
0.64
1.57
1.73
1.71
1.07
0.46
2.37
1.16
Full Barents Sea
Bear Island Trench
Northeast Basin
Spitsbergen Bank
Pechora Sea
(c)
Duration [days]
32.7
214.1
19.1
52.1
17.5
222.0
16.3
33.6
5.6
25.7
62.6
Full Barents Sea
Bear Island Trench
Northeast Basin
Spitsbergen Bank
Pechora Sea

Figure 2: Marine heatwave statistics for the full Barents Sea for the period 1991-2022, using 1991-2020 as the climate average period. a) Number of marine heatwave events per year ~~(top),~~; b) maximum intensity of the heatwave events ~~(middle)~~; c) ~~and~~ average marine heatwave duration ~~(bottom) for the full Barents Sea and four sub-regions during the period 1991-2021~~. The associated decadal trends are shown in hatched colors. The trend is provided in boldface if significant to 95% (p < 0.05). Surface values are shown by blue bars and bottom values are shown by red bars. Based on data from the TOPAZ reanalysis.

To ~~look for~~investigate possible regional ~~differences~~heterogeneity in MHWs within the Barents Sea, we ~~chose to investigate~~calculated ~~the 2016~~ MHW statistics~~event, which was the most severe MHW event detected in the Barents Sea as a whole,~~ in the four sub-regions depicted in figure 1. The results are summarized in Table 3, 4, and 5. In all regions, we found a higher frequency of MHW events than for the Barents Sea as a whole (except for near the bottom in the Northeast Basin). Moreover, all regions showed a larger, positive decadal trend in the frequency compared with the Barents Sea as a whole, although near the bottom only the trend in the Pechora Sea was found to be statistically significant (p < 0.05; Table 3). For the average maximum intensity, at the surface, we found that the Bear Island Trough, which is the upstream inflow region, had similar statistics as for the Barents Sea as a whole, while for the other three regions the intensity was generally larger (Table 4). Near the bottom, the intensity in the Bear Island Trough was less than that of the Barents Sea as a whole, while in the downstream Northeast Basin the intensity was larger on average. In the two other regions the differences were smaller. In terms of duration, all the regions experienced shorter MWHs on average compared to the Barents Sea as a whole, and especially so near the bottom. The exception was the Northeast Basin, where the average duration of near-bottom MHWs was found to be comparable to that of the Barents Sea as a whole (Table 5).

To investigate further regional heterogeneity, we considered the MHW event in 2016 in each of the regions. At the surface, ~~In the TOPAZ reanalysis, t~~the 2016 MHW event was the most severe MHW event in terms of cumulative intensity ~~during the full 1991-2021 period~~ in t~~three~~hree out of the four sub-regions investigated. The exception was the Bear Island Trough, where the 2012 MHW event was more severe (not shown).~~: the Northeast Basin, the Spitsbergen Bank, and the Pechora Sea.~~ Near the bottom, ~~In~~the 2016 MHW event was the most severe MHW event in all four regions~~ the Bear Island Trough, the temperature anomaly classified as an MHW intermittently throughout 2016 and while the cumulative impact intensity in terms of degree days was largest in 2016~~ (~~at the surface; Supp.~~ Fig. ~~S4b~~3)~~, 2012 experienced the most severe continuous MHW (Fig. 3, 4)~~. The progression of the 2016 MHW event was comparable in all regions, except for the Spitsbergen Bank where the onset of the MHW occurred later, near mid-summer, compared to the other regions where the onset occurred during late winter. However, on the Spitsbergen Bank the 2016 MHW was preceded by several but less intense and intermittent MHWs. It is also worth noting that the onset in the other three regions, as well as the Barents Sea as a whole, occurred in late February/early March, except for in the upstream Bear Island Trough where the onset occurred in the beginning of April. Moreover, both the average and maximum MHW intensity was less in the Bear Island Trough compared to the other regions. ~~Other regional~~

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differences include that in the downstream north-eastern Barents Sea, the surface expression of the 2016 MHW was most severe in the first half of 2016, while on the Spitsbergen Bank it was most pronounced in the second half of 2016 (Fig. 4). In the Pechora Sea, the 2016 MHW persisted throughout the whole year. Moreover, the intensity of the MHW increased downstream in the Barents Sea, from an average 1.21 °C and 0.60 °C above the climatology near the surface and bottom, respectively, during the most severe part of the 2016 MHW event in the Bear Island Trough, to 1.54 °C and 1.68 °C, respectively, in the north-eastern Barents Sea and 2.45 °C and 1.51 °C, respectively, in the Pechora Sea. On the Spitsbergen Bank, the average intensity was 2.28 °C near the surface and 2.25 °C near the bottom.

In all the sub-regions, except for the Spitsbergen Bank where the water column is well-mixed due to tidal mixing, the frequency of MHWs frequency is was larger near the surface than near the bottom (Fig. 2a). In the Bear Island Trench and the Pechora Sea, the maximum intensities of the MHWs near the surface awere approximately about twice as large as the maximum intensities near the bottom, whereas in the north-eastern Barents Sea and on the Spitsbergen Bank the intensities are similar near the surface and bottom (Fig. 2b). However, the MHWs near the bottom tend to be more persistent, as seen from the longer average duration (again, the Spitsbergen Bank is an exception; Fig. 2c).

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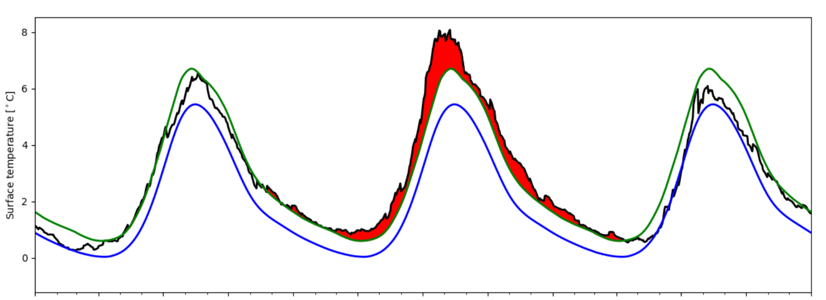

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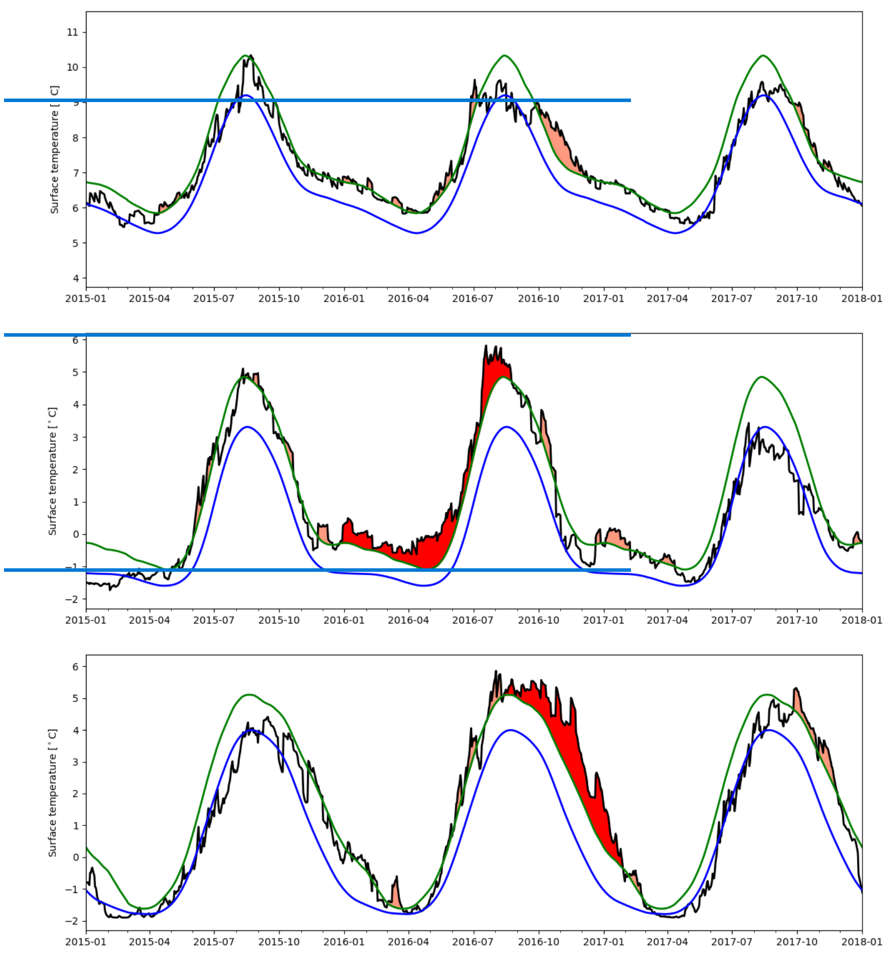

Surface temperature [°C]
2015-01
2015-04
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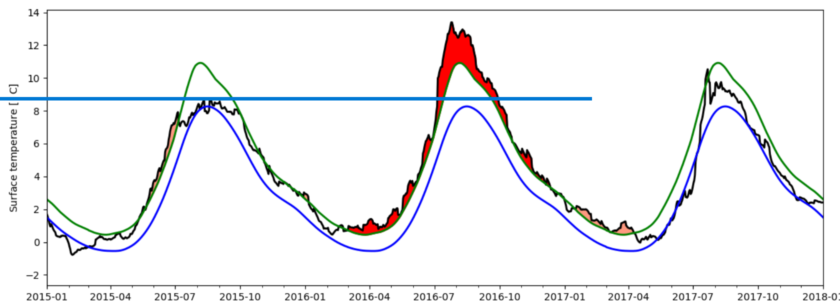
2017-10
2018-01


Surface temperature [C]
14
12
10
8
6
4
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0
−2
2015-01
2015-04
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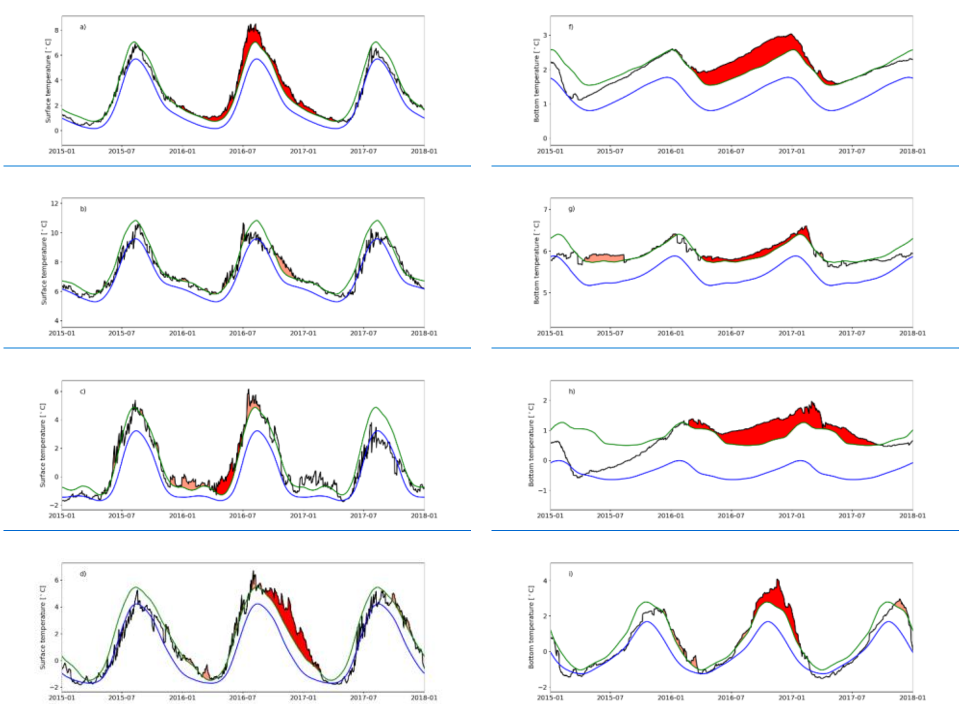
2017-10
2018-01


a)
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Surface temperature [°C]
Bottom temperature [°C]
2015-01
2015-07
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2017-01
2017-07
2018-01

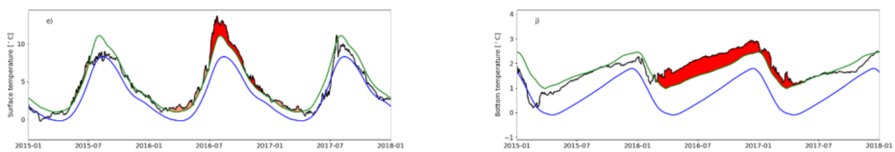
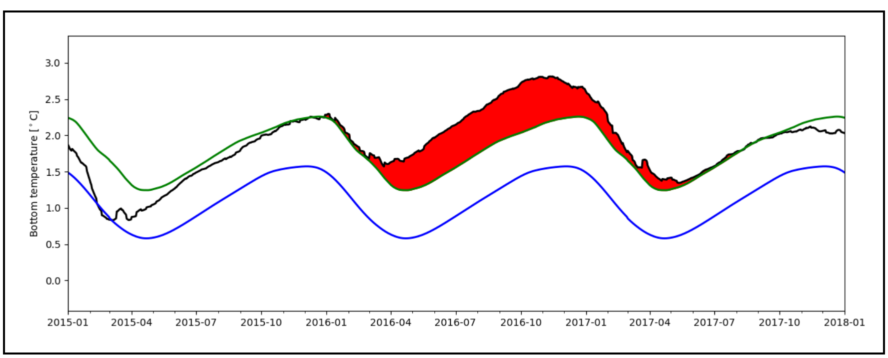
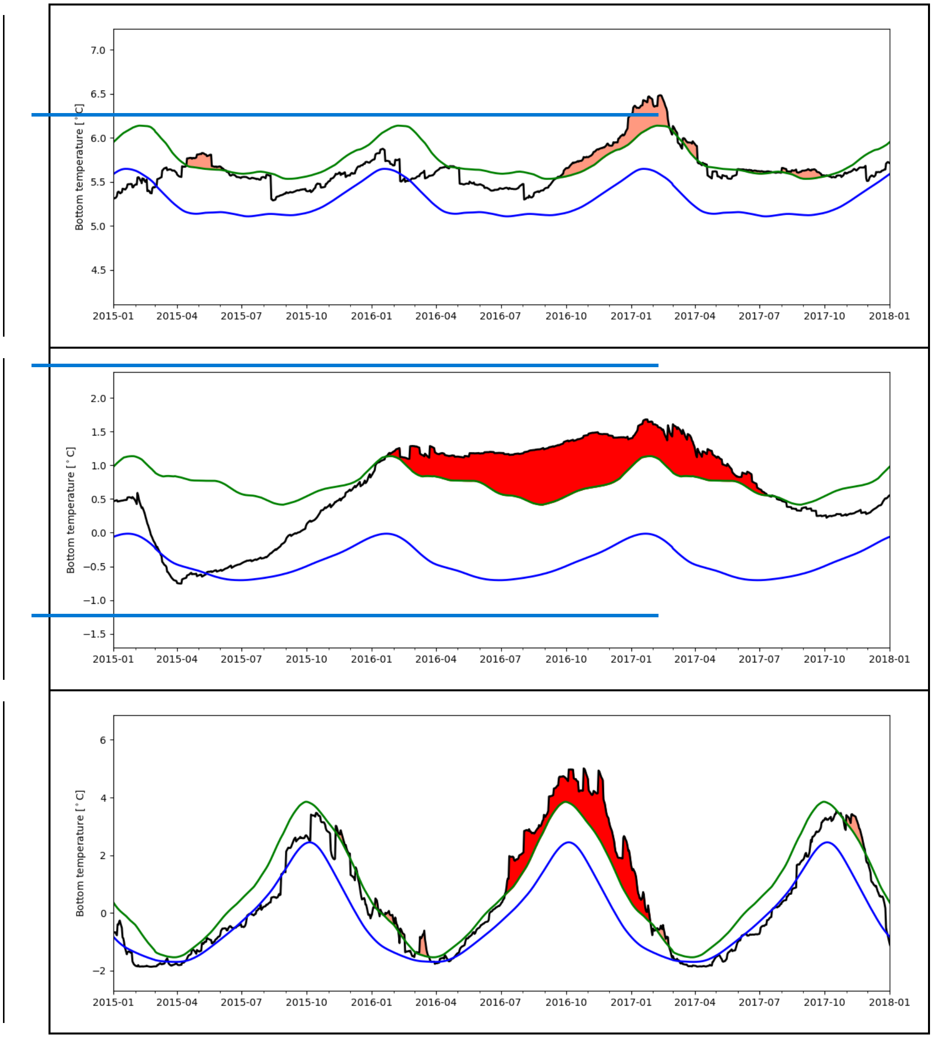
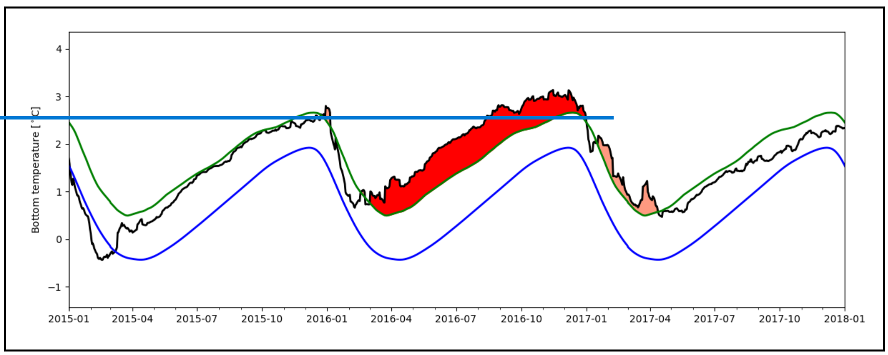


Figure 3: ~~(Top)~~ Time series (2015-2017; black lines) showing the temperature at ~~5-meter depth~~the surface (left column) and near the bottom (right column) spatially averaged over the Barents Sea. Blue lines show daily climatology. Green lines show the~~ upper~~ 90th percentile. The highest~~most~~ intens~~e~~ity marine heatwave in terms of cumulative degree days for the full 1991-202~~1~~2 period is shown in dark red shading. Other marine heatwaves are shown in pink shading. a) the full Barents Sea, surface; b) ~~Subpanels show the following sub-regions (from top to bottom): T~~the Bear Island Trough, surface; c) ~~T~~the ~~n~~North~~-~~east~~ern~~ Ba~~rent~~s~~ Sea~~in, surface; d) ~~T~~the Spitsbergen Bank, surface; e) ~~T~~the Pechora Sea, surface; f) the full Barents Sea, bottom; g) the Bear Island Trough, bottom; h) the Northeast Basin, bottom; i) the Spitsbergen Bank, bottom; j) the Pechora Sea, bottom. All panels show the period January 1st 2015 to January 1st 2018. Note the different scales on the y-axes.




Bottom temperature [°C]
2015-01
2015-04
2015-07
2015-10
2016-01
2016-04
2016-07
2016-10
2017-01
2017-04
2017-07
2017-10
2018-01



~~**Figure 4: Same as Figure 3, but showing near-bottom temperatures.**~~

3.1 Preconditioning and atmospheric forcing of 2016 MHW event

Leading up to the onset of the 2016 MHW, the inflow of warm Atlantic Water to the Barents Sea was above average during the whole of 2015 (ICES, 2022). However, ~~D~~during the ~~subsequent~~ following winter of 2015/16, the turbulent (latent and sensible) heat loss~~, however,~~ ~~(~~was between 20 and 70 W~~/~~m^{-2} below the 1993-2021 average in the southern Barents Sea (25-45E; 71-75N; i.e., along the Atlantic Water pathway through the Barents Sea; Fig. 4a)~~)~~, w~~as~~hich was ~~below~~the lowest ~~the climatological average~~for the period ~~(~~1993-2021~~) in the southern Barents Sea~~. The reduced heat loss to the atmosphere occurred ~~(i.e., along the Atlantic Water pathway through the Barents Sea)~~ despite the preceding increase~~d~~ in advect~~ion~~ed ~~of~~ oceanic heat (Fig. ~~5~~4a,e). Note, that during the winter months, the solar radiation can be neglected due to the Polar Night conditions in the Barents Sea region. Moreover, wind-driven mixing during winter breaks down the upper water column stratification, connecting the surface with the deeper layers. ~~Furthermore, for the analysis period (1993-2021), the area-averaged turbulent (latent and sensible) heat loss in the southern Barents Sea (25-45E; 71-75N) was also the lowest during the onset of the 2016 MHW event (not shown).~~ Thus, the 2016 MHW event was preceded by an increased Atlantic Water heat transport and reduced heat loss to the atmosphere ~~resulted in the development of this strong MHW event during 2016~~. While we did not perform a closed heat budget calculation, we note that the oceanic heat carried by the downstream outflow from the Barents Sea has previously been reported to be smaller than the inflow by an order of magnitude (e.g., Gammelsrød et al., 2009; Smedsrud et al., 2013), and that a previous study found that increased oceanic heat advection to the Barents Sea lead to increased ocean heat content in the interior Barents Sea (Lien et al., 2017).

In the following winter of 2016/17, i.e., during the dec~~ay~~line of the 2016 MHW event, the turbulent heat loss and outgoing longwave radiation in the northern Barents Sea (25:45E; 76-80N; Fig. ~~5~~4b,e,f) reached the largest values in the 1993-2021 period. This was~~,~~ ~~possibly due to~~likely enhanced by a record low winter sea ice extent (ICES, 2022) and negative cloud cover

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anomaly in the northern Barents Sea (not shown). ~~However~~I, ~~i~~n the southern Barents Sea, however, no ~~obvious changes in~~ heat loss anomaly at~~from~~ the ocean surface ~~i~~was observed during the winter 2016/17 (Fig. 4~~5~~b),~~.~~ ~~Rather, the decay of the MHW event in the southern Barents Sea appears to be caused by the decrease in~~but the Atlantic Water transport ~~across~~through the Barents Sea Opening decreased during 2016 (ICES, 2022). Thus, the ~~onset and decay of the~~ 2016 MHW event in the Barents Sea can be linked to the combined ~~influence~~ effect of increased Atlantic water transport into the Barents Sea, as well as ~~and~~ reduced oceanic heat loss in the southern Barents Sea during the onset and increased oceanic heat loss ~~and~~in the northern Barents Sea during the decline.

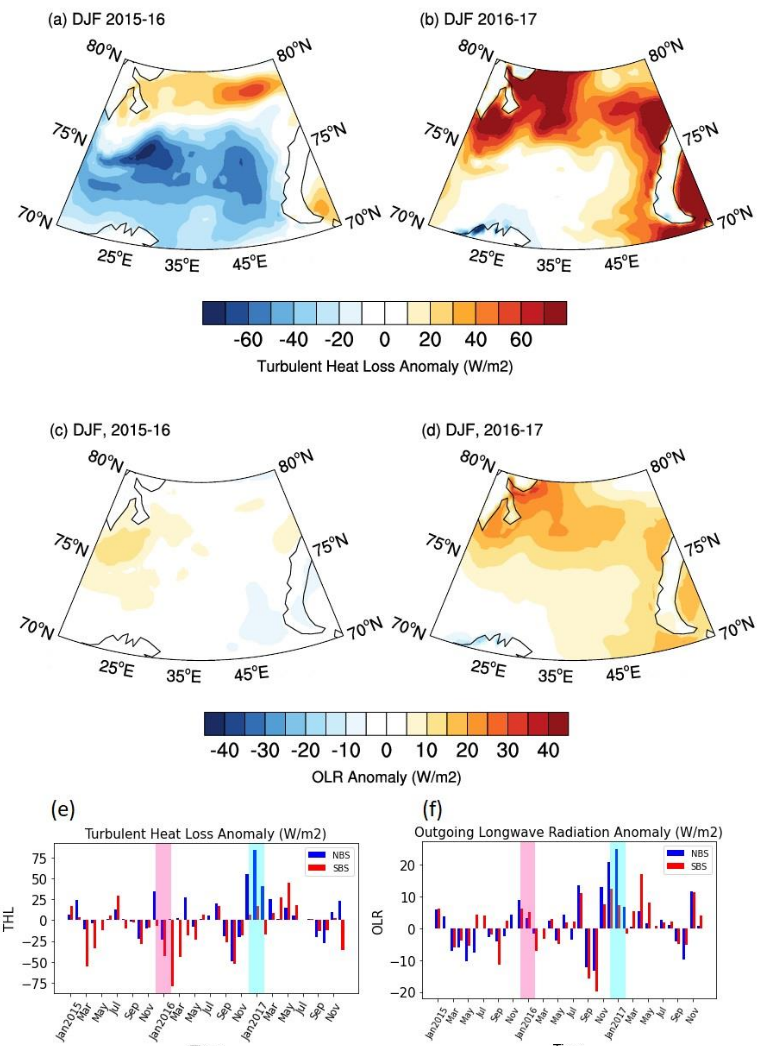
(a) DJF 2015-16
(b) DJF 2016-17
80°N
75°N
70°N
25°E
35°E
45°E
-60 -40 -20 0 20 40 60
Turbulent Heat Loss Anomaly (W/m2)
(c) DJF, 2015-16
(d) DJF, 2016-17
-40 -30 -20 -10 0 10 20 30 40
OLR Anomaly (W/m2)
(e)
Turbulent Heat Loss Anomaly (W/m2)
THL
NBS
SBS
Time
(f)
Outgoing Longwave Radiation Anomaly (W/m2)
OLR
Time

Figure ~~4~~5: Atmospheric preconditioning leading up to the MHW depicted in Fig. ~~3~~2. (a,b) DJF (December(-1), January, February (0)) turbulent (latent + sensible) heat loss anomaly (W/m2) for 2016 (a) and 2017 (b). Same as (a,b) but for Outgoging Longwave Radiation (OLR). Positive values indicate upward fluxes. Monthly mean turbulent heat loss (e) and OLR (f) over northern (blue, 25:45E; 76-80N) and southern (red, 25-45E; 71-75N) Barents Sea. The onset (DJF, 2015-16) and decay (DJF, 2016-17) phase of the 2016 MHW event are shaded in pink and cyan colours. Data: ERA5

3.2 Effect of changing baselines

Next, we investigated the effect of changing the ~~baseline~~ climatological average period from 30 years (1991-2020) to 25 years (1996-2020) and 20 years (2001-2020) when calculating the MHW statistics for both the surface and the bottom (Tables 3-5)~~,~~. ~~using the results from the ROMS regional hindcast. Common for all the four sub-regions is that the frequency of MHW occurrences decreased by approximately one half (two thirds in the north-eastern Barents Sea) when changing the baseline from the 1961-1990 climate normal to the 1991-2020 climate normal (Table 3). On the other hand, the decadal trend in the number of occurrences not only increased, but are also statistically significant to the 95% level ($p < 0.05$) in all regions. Oppositely to the frequency, the average maximum intensity was comparable when using the two different baselines in most of the sub-regions (Table 4). As an exception, in the Pechora Sea, the average intensity increased, especially near the surface, when using the 1991-2020 climate normal as baseline. The explanation for the increase in maximum intensity when comparing with a higher climatological average temperature is that several weaker warm events were no longer classified as MHW (not shown).~~

For all regions, including the Barents Sea as a whole, we found that the frequency of surface MHWs decreased with decreasing length of the climatological average period. For near-bottom MHWs, the results were less clear except for a decrease in frequency in the two shallow bank regions (the Spitsbergen Bank and the Pechora Sea). Similarly, for the intensity at the surface, there was a general trend of decreasing average intensity with decreasing length of the climatological average period. There was also a trend of decreasing intensities near the bottom, except for in the two shallow bank regions. As opposed to the average frequency and intensity, the average duration seemed less dependent on the length of the climatological average period. Near the bottom, however, the duration was sensitive to the climatological average period length due to the low number of MHWs and the dominance of the 2012 and 2016 MHW events.~~On average, the MHW duration decreases when changing the baseline from the 1961-1990 climate normal to the 1991-2020 climate normal, although the differences are small in the Bear Island Trough and on the Spitsbergen Bank (both in the western Barents Sea; Table 5). A striking difference between the two western sub-regions and the two eastern sub-regions is the transition from more well-mixed condition to more of a stratified two-layer system, causing a decoupling between the surface and bottom conditions. As a result, near-bottom MHW show~~

~~considerably longer duration than surface MHW in the north-eastern Barents Sea and in the Pechora Sea, whereas in the Bear Island Trough and on the Spitsbergen Bank the duration near the surface and near the bottom are comparable. Indeed, when using 1961-1990 as the baseline in the north-eastern Barents Sea, the most severe MHW in terms of cumulative degree days appears at the end of the 60-year period with the last five years (starting March 10, 2015) of the timeseries representing an MHW (not shown). Thus, the area has entered a state of permanent MHW when choosing this older baseline, which explains the strongly positive trend in duration (129 days per decade; Table 5). Moreover, several MHW events appear throughout the 60-year period, including one MHW event at the start of the timeseries in 1961 (not shown). When the baseline is changed to the 1991-2020 period, two distinct MHW appear, in 2016 and 2018, with the 2016 event being the most severe and no MHW event is detected prior to 2007.~~

Table 3: Number Average frequency of marine heatwaves events per year during the period 1961-2020 +/- the decadal trend for two different baseline periods, 1961-1990 and 1991-2020. The baseline period 1991-2020 is also used for the detrended, full time series (1961-2020). The trend is provided in boldface if significant to 95% (p < 0.05), or in italics if not significant (p > 0.05). Values for the surface are shown on top and values for bottom are shown below. BIT: Bear Island Trough; SB: Spitsbergen Bank; PS: Pechora Sea; NEBS: North-Eeastern Barentsin Sea.

Baseline \ Area	FULL	BIT	SB	PS	NEBS
19691 - 1992020	0.90 + 0.82 0.16 + 0.12	21.3072 + 0.299 20.159 + 0.0635	1.473 + 0.2089 10.7084 + 0.2238	1.38 + 01.1637 0.592 + 0.1354	1.859 + 01.2930 0.163 + 0.11
1996 1- 2020	0.84 + 0.85 0.44 + 0.18	01.953 + 0.3190 0.590 + 0.2839	01.8216 + 0.2178 0.801 + 0.1944	01.5709 + 01.2210 0.523 + 0.2247	01.6344 + 01.336 0.2231 + 0.219
2001 – 2020	0.59 + 0.66 0.19 + 0.14	1.19 + 0.64 0.53 + 0.37	1.09 + 0.82 0.59 + 0.35	0.84 + 0.89 0.25 + 0.23	1.28 + 1.22 0.25 + 0.24

Table 4: Same as Table 4, but3 but showing average maximum intensity (in °C).

Reference period \ Area	FULL	BIT	SB	PS	NEBS
19691 - 1992020	1.41 + 0.22 1.07 – 0.13	1.392 +- 0.057 10.3864 + 0.043	1.2710 +- 0.0412 1.0722 + 0.0346	21.373 + 0.208 1.316 + 0.079	1.0857 +- 0.167 01.6273 +- 0.092
19961 - 2020	1.35 + 0.23	1.395 +- 0.025	1.5726 +- 0.107	2.3022 + 0.0849	1.4758 - 0.285

Reference period \ Area	FULL	BIT	SB	PS	NEBS
	0.96 + *0.17*	**10.561** +- *0.051*	**1.2617** + **0.1058**	**1.5416** + *0.053*	**01.7148** -+ *0.1067*
2001 - 2020	**1.26** + *0.32* **0.85** + *0.06*	**1.31** – *0.08* **0.51** + *0.00*	**1.49** – *0.13* **1.17** + **0.51**	**2.01** + *0.35* **1.15** – *0.10*	**1.49** – *0.29* **1.43** – *0.01*

Table 5: Same as Table 34, but showing average duration (in days).

Baseline \ Area	FULL	BIT	SB	PS	NEBS
19961 - 19922020	**32.7** + *16.2* **214.1** – *135.8*	**2519.21** + *51.23* **3052.31** + *7.56.2*	**3216.13** + **65.6** **332.76** + *51.45*	**250.57** + *164.75* **762.96** + *158.37*	**6317.05** + *227.68* **222.084** + *12974.4*
19961 - 2020	**39.5** + *16.2* **139.2** + *32.0*	**2018.0** +- *30.16* **3720.28** + *529.18*	**1628.45** + *74.65* **28.67** +- *73.85*	**3702.88** + *1024.00* **55.1** + *3.1*	**3317.30** -+ *03.17* **1099.29** - *2836.93*
2001 - 2020	**38.0** – *13.9* **136.4** – *2.1*	**19.8** – *1.0* **37.8** + *24.0*	**15.6** – *0.07* **36.6** – *8.4*	**20.8** + *1.7* **101.6** + *0.7*	**15.3** + **6.8** **122.4** – *41.1*

4 Discussion

We have estimated average MHW frequency, durationduration, and intensity nearat the surface and near the bottom in the Barents Sea, based on an ocean reanalysis for the period 1991-20221. Moreover, we have investigated the impact of changing climatological average period baselines length when estimating MHW statistics in the Barents Sea, based on a regional hindcast for the period 1961-2020. We fouind two dominating and pervasive MHW events that in the Barents Sea in the last 30 years generally experiences few, but pervasive MHWs that affected the whole region.

Previous studies of MHWs, including in the Barents Sea, have mainly focused on the ocean surface due to the availability of satellite remote sensing sea surface temperature data (e.g., Mohamed et al., 2022). Our results indicate identified significant MHW events also near the ocean bottom in the Barents Sea, exemplified by MHW events in part related to changes in sea-ice conditions,, and that the bottom expressions of the MHWs tend to have lower frequency and intensity but last longer duration compared to surface MHWs. Note, however, that these statistics need to be interpreted with care, especially the statistics on near-bottom MHWs due to the low number of events (5 near-bottom MHWs were detected in the Barents Sea during 1991-2022). Among other things, this severely affected the statistical significance of the trend estimates. Nevertheless, the longer duration near the bottom was more pronounced in the eastern parts of the Barents Sea, as represented by the Pechora Sea and the Northeast Basin. We have shown that, in the north-eastern Barents Sea, the ocean bottom layer appears to have entered a

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~~state of permanent MHW when using a 1961-1990 baseline. Moreover, the average duration of bottom MHW~~s~~ are approximately three times longer or more than for surface MHW~~s~~ in this sub-region, independent of the choice of baseline.~~ One likely~~The~~ explanation ~~for the strong MHW signal near the bottom in this area~~ is ~~likely~~ the strong reduction in sea-ice formation i~~o~~n the shallow Pechora Sea in the south-eastern Barents Sea and on the Novaya Zemlya Bank adjacent to the Northeast Basin, ~~nearby banks~~ and thus a reduction in the ~~sinking~~formation of cold, brine-enriched ~~surface~~ water. Th~~is~~e eastern Barents Sea ~~area~~ is one of the regions that has experienced the largest changes in the sea-ice cover in recent decades (e.g., Yang et al., 2016; Onarheim and Årthun, 2017) and has thus experienced a strong reduction in the formation of cold, brine-enriched bottom water. Midttun (1985) observed very cold and saline water in the deeper parts of the Northeast Basin following cold winters in the 1970s, while Lien & Trofimov (2013) reported no such bottom water following the warmer winter of 2007/08 ~~sinking into the deeper parts of the north-eastern Barents Sea (Midttun, 1985; Lien & Trofimov, 2013)~~. Occasional presence of such cold bottom water further west in the Barents Sea, adjacent to the Bear Island Trough, has been hypothesized to cause differences in the position of the Polar Front at the bottom, as detected by bottom living organisms, compared to higher in the water column based on~~with~~ hydrographic properties in the pelagic zone (Jørgensen et al., 2015). Thus, the transition indicated by bottom MHWs in the ~~north-~~eastern Barents Sea may have a profound impact on bottom fauna by allowing boreal species with less resilience to below-zero temperatures to settle.

Previous findings by Mohamed et al (2022), based on satellite remote sensing sea-surface temperature data, contrasted the Spitsbergen Bank area showing no trend in MHW frequency and ~~cumulative~~ duration with the Pechora Sea area showing significant trends in both frequency and duration. None of the two regions showed significant trends in MHW ~~mean~~ intensity. Our findings agree with those of Mohamed et al. (2022) that the Pechora Sea has experienced a positive trend in ~~both~~ MHW frequency and not in intensity, but our results showed no significant trend in ~~and~~ duration, at the surface. ~~However, o~~Our results indicated that there is ~~n~~also a significant, positive trend in MHW ~~duration~~ frequency near the bottom in the Pechora Sea (but not in intensity and duration). Moreover, our results ~~do~~ showed positive trends in both the MHW frequency and duration on the Spitsbergen Bank (at the surface), although we did not find a statistically significant trend in MHW intensity ~~on the Spitsbergen Bank~~. But our results indicated a positive trend in the MHW intensity near the bottom on the Spitsbergen Bank. Note, ~~H~~however, that the Spitsbergen Bank is also the area where the TOPAZ reanalysis show~~s~~ed the largest bias and RMS deviation, as well as the lowest correlation, when compared with in-situ temperature observations. Thus, we cannot draw firm conclusions whether our results for the Spitsbergen Bank area contradict the findings of Mohamed et al. (2022).

Our findings that the strong 2016 MHW event was preceded by stronger than average Atlantic Water inflow and anomalously weaker ocean-to-atmosphere heat loss further suggest that MHWs may become more frequent and severe in terms of intensity and duration in a future Barents Sea with continued increase in oceanic heat advection from the North Atlantic (e.g., Årthun et al., 2019) in combination with reduced ocean-to-atmosphere heat loss within the Barents Sea (e.g., Skagseth et al., 2020).

5 Data availability

A list of the data products utilized in this paper, along with their availability and links to their documentation, is provided in Table 1.

6 Author contribution

All authors contributed to the design, analysis, and writing of the paper.

7 Competing interests

The authors declare that they have no conflict of interest.

8 Acknowledgements

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