Evaluation of the polar lows forecast system

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About this document

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Cover picture: A NOAA-9 polar orbiter satellite image (visible band) of a polar low over the Barents Sea on 27 February 1987. The southern tip of Spitsbergen is visible at the top of the image. The polar low is centered just north of the Norwegian coast.Picture title. Credits: This image is in the public domain because it contains materials that originally came from the U.S. National Oceanic and Atmospheric Administration, taken or made as part of an employee's official duties.

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Summary for publication

Polar lows (PLs) are relatively small (a few to a few hundred kilometres in their radii) cyclones over oceans in high latitudes. They are associated with extreme winds and snowfall which present challenges to maritime and coastal activities. PLs are not reproduced well in reanalyses data nor by climate models that are used for seasonal predictions and long-term climate change projections. Therefore the work done in Blue-Action *WP1 Improving long range forecast skill of risks for hazardous weather and climate events* and this Case Study (CS3) has focused to **marine cold-air outbreaks (MCAOs) in which cold Arctic air overlays warmer sub-Arctic open waters, creating a condition of large-scale atmospheric instability**.

We first established the connection between PLs and MCAOs in the Barents Sea. Although not all MCAOs have PLs, we find that there is an approximately 70% probability of PLs occurring in a month when the MCAO frequency is at +0.5 standard deviation above normal (500 hours per month for MCAO), increasing to over 90% at +1.0 standard deviation (600 hours per month for MCAO). Results from additional analyses are then presented to show the links between MCAOs and other weather patterns such as cyclones and blockings in the Nordic regions.

This Case Study relies closely on research in Blue-Action WP1. Investigation by Afargan-Gerstman et al. (2020) finds the potential of sudden stratospheric warmings (SSWs) as a precursor for MCAOs. They link this to the ability of SSWs to modify tropospheric atmospheric circulations that favour MCAOs. The existence of a precursor is important for understanding predictability of MCAOs and evaluation of MCAOs prediction by models.

Evaluation of the seasonal hindcast simulated using the Max Planck Institute for Meteorology's MPI-ESM-MR model indicates that there is a predictive skill for MCAOs up to only 20 days (Polkova et al. 2020). Combining a statistical model using sea surface temperature and sea ice condition in the Barents Sea in the prediction steps allows sub-sampling of more skillful hindcast members, and results in extending the lead time to 40 days. Schaffer (2020) analysed the same hindcast experiments and found promising predictability of extreme minimum 2-metre air temperature and wind chill index during summertime.

Work carried out

The main challenges faced by this case study with respect to polar lows can be summarised as:

A. **Limitations in the data**: Reanalysis data that we normally rely on (e.g. ERA-Interim) do not resolve or record all polar lows (Laffineur et al. 2014, Michel et al. 2018, Smirnova and Golubkin 2017, Stoll et al. 2017, Zappa et al. 2014). The high-resolution Arctic System Reanalysis (ASR) data are available for 2000-2016, while measurement-based (from satellites) datasets for polar lows such as STARS (Noer et al. 2011, available 2002 to 2011), Rojo et al.'s (2015) (updated for

2000 to 2019), and Smirnova et al.'s (2015) (available 1995-2009) are also for limited number of years. The limitations in the data make it difficult to build robust statistics about extreme and highly localised events. Furthermore, climate models that are commonly used for seasonal (or at longer lead time such as multidecadal or climate projections) forecasts do not represent polar lows spatial scales and process properly.

B. **No objective definition and detection for polar lows:** There is no scientific consensus that is accepted and used by all researchers (Stoll et al. 2017), on the definition of polar lows within the spectrum of mesoscale cyclones (a few to 2000 kilometres length scales). Previous researchers have also used a variety of algorithms for polar lows detections. For this reason, the existing published studies and datasets related to polar lows or 'proxies' for polar lows (such as marine cold air outbreaks) have differences between them.

C. **Non-standardised previous studies:** Because of **A.** and **B.** above, the very many previous studies have applied varying methods on different data. For this reason, it can be difficult to synthesize and build on previous knowledge.

This case study originally concerned investigating prediction or predictability of polar lows statistics (it is impossible to predict individual weather events at long lead time) at monthly to seasonal timescales. Because of the challenges described above and considering the resources available in this case study, we have resolved to **focus on the predictability of marine cold air outbreaks (MCAOs).** MCAOs are large scale phenomena which are known to have links to polar lows.

We first established the relationship between MCAOs and polar lows. Further analyses on the relationships of MCAOs and other major weather patterns are presented. Then the prediction skills of MCAOs and severe weather conditions in the Barents Sea in a dynamical seasonal forecast system are evaluated.
Details in the analyses and evaluations are presented in the next section "Main results achieved". Relevant results from WP1 of Blue-Action are also summarised there. The following work components are listed here with the main lead researchers.

- Relationship between MCAOs and polar lows (led by Martin King, Uni Research/NORCE);
- Relationship between MCAOs and cyclone frequencies (led by Martin King, Uni Research/NORCE);
- Identifying precursors for MCAOs in the Arctic (led by Hilla Afargan Gertsman, ETH Zurich);
- Occurrence of severe weather conditions in the Barents Sea in observations and re-forecasts (led by Laura Schaffer, Universität Hamburg);
- Predictability of west Barents MCAO frequencies in a dynamical seasonal forecast model (led by Martin King, Uni Research/NORCE, and Iuliia Polkova, Universität Hamburg);
- Prediction skill for MCAOs from a state-of-the-art seasonal prediction system (led by Iuliia Polkova, Universität Hamburg);
- Elements of a "Minimum Viable Product" (contributed by Øivin Aarnes, DNV-GL).

Main results achieved

Relationship between MCAOs and polar lows

Here, we present the relationship between marine cold air outbreaks (MCAOs) frequencies and polar lows in the western Barents Sea (10-30E, 70-78N). This region was selected by DNV-GL to be of interest. MCAO values are calculated using ERA-Interim according to the method of Kolstad (2017), as the potential temperature at the surface minus that at the 850hPa level. MCAO events are then identified also according to the criteria given by Kolstad (2017). We used polar lows tracked by Rojo et al. (2015, updated for 2000-2019, http://doi.org/10.5281/zenodo.3882618) using Very High Resolution Radiometer satellite data. Monthly MCAO and polar lows frequencies can then be studied.

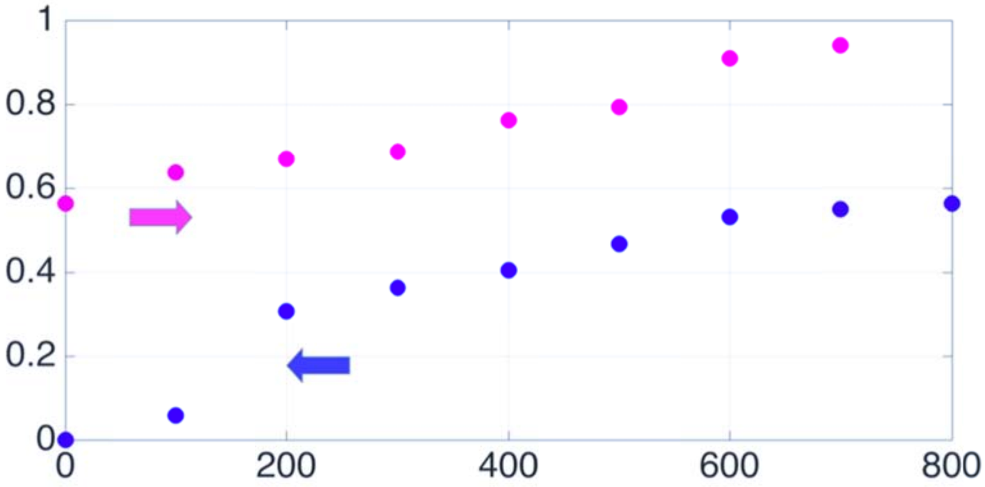


Figure 1: *Probability of having polar lows within a month (y axis) vs. MCAO frequency (hours/month, x axis) for ONDJFMA. Blue (bottom) dots indicate the polar low probability (y axis) for MCAO frequency less than the value on x axis. Magenta (top) dots indicate the polar lows probability (y axis) for MCAO frequency greater than the value on x axis. Mean MCAO frequency is about 400 hours/month, and 1 SD is about 200 hours/month. Original data from Rojo et al. (2015) and ERA-Interim for 2000-2019.*

Figure 1 indicates the probabilities of polar lows occurring (y axis) according to MCAO frequencies less than (blue dots) or greater than (magenta dots) the values on the x axis. It is seen, for example, for MCAO frequencies above 600 hours/month (about +1 standard deviation), the probability of polar lows occurring during a month is around 0.9. Below 200 hours/month of MCAO frequencies (about -1 standard deviation), however, see polar lows probability of about 0.3 during a month.

Polar lows are relatively small and rare events (on average not more than 9 hours per month for the Oct to April months for western Barents) that have large variations over time and the locations they occur. Therefore, it is difficult to predict them in monthly to seasonal timescales. The small sample available for polar lows also makes statistical analysis challenging to do. However, we do find that as the MCAO monthly frequency increases, the probability of polar lows occurring becomes very high, as described above.

Relationship between MCAOs and cyclone frequencies

Extra-tropical cyclones are associated with heavy precipitation and strong wind. They most often occur over the oceans forming the so-called midlatitude storm tracks, and can make landfall and cause substantial damage on infrastructure.

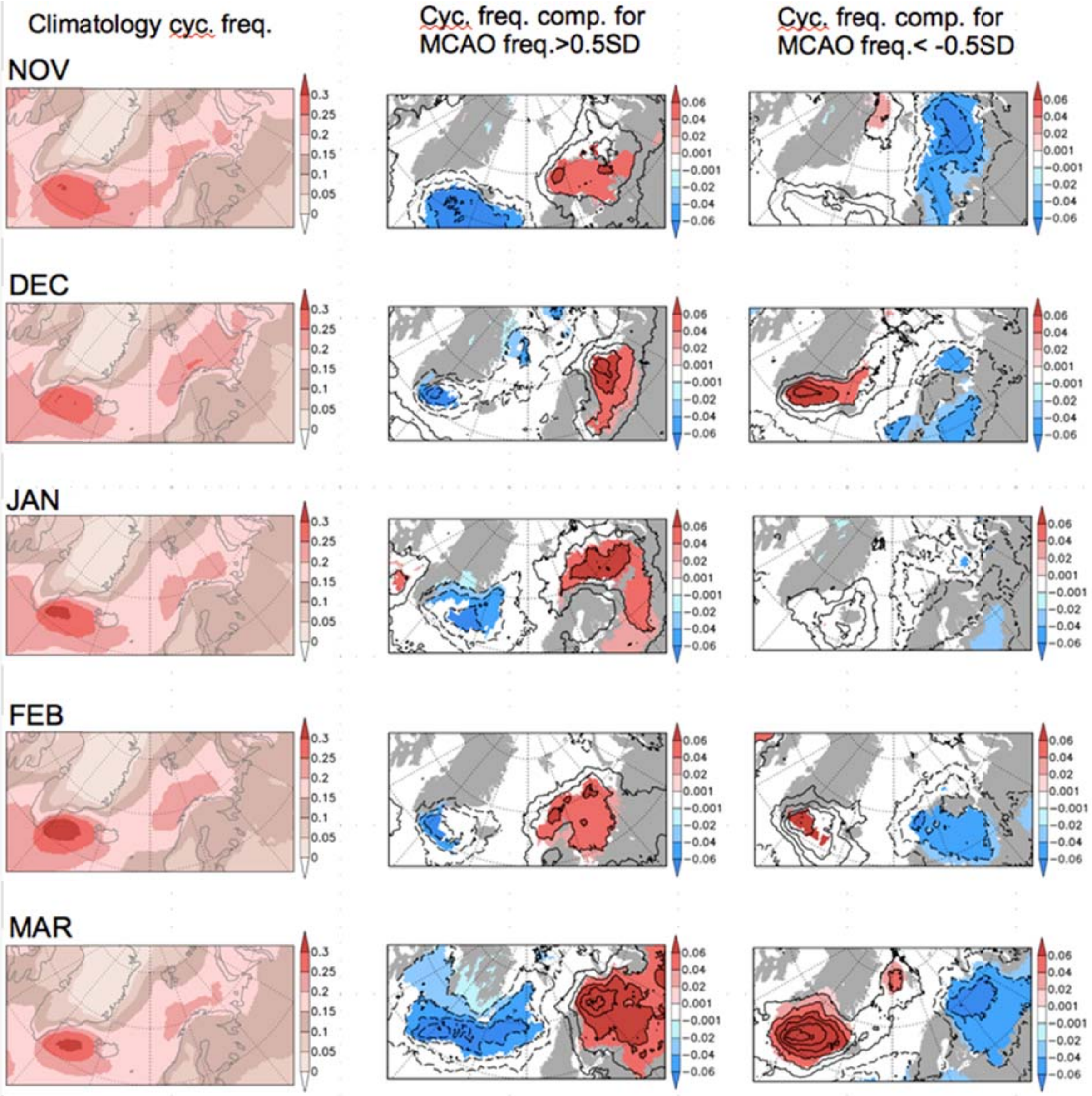


Figure 2: *Cyclones are detected based on Wernli and Schwierz (2006). Left: Climatology cyclone frequency. Middle: Composite of anomalous cyclone frequency for west Barents MCAO frequency greater than +0.5 S.D. Right: Composite of anomalous cyclone frequency for west Barents MCAO frequency less than -0.5 S.D. Unit=fraction of a month. Shading in middle and right columns also indicates statistical significance at 95% based on two-tailed t test. Original data source: ERA-Interim, cyclone frequency data calculated by C. Spensberger (GFI, UiB).*

The analysis presented in Fig. 2 uses cyclones detected by the method of Wernli and Schwierz (2006); the original cyclones data was prepared by Clemens Spensberger (GFI, University of Bergen, Norway). Common cyclone detection methods applied to reanalysis data such as ERA-Interim obtain cyclones of the order of a few hundred kilometres and larger in radii. Therefore, the larger polar lows are detected as the smaller cyclones, and included in the cyclones data used here.

Shown on the left column are mean cyclone frequencies (in fraction of a month) for the months of Nov to Mar. Cyclones are most active over the oceanic region southwest of Greenland, and secondarily over the Norwegian and Barents seas. On the middle and right columns are composites of anomalous cyclone frequencies for MCAO frequencies above +1 S.D and below -1 S.D. respectively. They show a dipolar pattern with strong anomalies over the active cyclone regions near Greenland and over northern Scandinavia. The Barents Sea and neighbouring land areas have above (below) normal cyclone frequencies during high (low) MCAOs months. At these thresholds the anomalous cyclone frequencies in Barents Sea are up to 30% of the climatologies.

Analyses aggregating all the Nov-Mar months, composites of blockings, spatial properties related to MCAOs and polar lows, as well as MCAOs' correlations with many common climate indices are provided in the supplementary data (http://doi.org/10.5281/zenodo.4192837). Supplementary information and data on methods, analysis scripts, as well as the polar lows monthly frequency are provided below.

Supplementary information and data are available in open access:

- King M.P., 2020, Blue-Action D5.13 Supplementary data, documentation and figures, http://doi.org/10.5281/zenodo.4192837
- King M.P., 2020, Monthly frequency of polar lows in the Atlantic sector based on STARS, http://doi.org/10.5281/zenodo.3757122
- King M.P., 2020, Monthly frequency of polar lows in the Atlantic sector based on Rojo et al. 2019, https://doi.pangaea.de/10.1594/PANGAEA.903058, http://doi.org/10.5281/zenodo.3882618

Identifying precursors for MCAOs in the Arctic

Within the WP1, we studied the occurrence of marine cold air outbreaks (MCAOs) in the North Atlantic and their connection to the large-scale circulation patterns over the North Atlantic and Europe. In particular, we investigated how the frequency and the magnitude of such MCAOs are modulated after the onset of extreme events in the stratosphere. These extreme events, known as Sudden Stratospheric Warmings (SSWs) can potentially lead to improved prediction skill on subseasonal timescales due to the long-lasting circulation anomalies associated with stratosphere–troposphere coupling in winter.

We focus on three regions of enhanced MCAO frequency: the Barents Sea, the Norwegian Sea and the Labrador Sea. By analysing the regional atmospheric conditions in DJFM between 1979 to 2019, we find that a positive 500 hPa geopotential height anomaly over Greenland and a negative geopotential height anomaly over Scandinavia (can be described by a zonal dipole index), accompanied by increased storminess and northerly surface winds over the Barents Sea and to the east of the Barents Sea, are strong indicators of enhanced MCAO intensity in these regions. In contrast, the opposite geopotential height anomaly pattern (i.e. lower geopotential height anomaly over Greenland and higher geopotential height anomaly over Scandinavia) and increased storminess in the Irminger Sea are found to be associated with stronger MCAOs in the Labrador Sea. These circulation patterns highlight the connection between MCAOs in the Arctic and the cold sectors of cyclones, in agreement with previous studies (e.g. Fletcher et al. 2016, Papritz and Grams 2018).

In a study by Afargan-Gerstman et al. (2020) (Deliverable 1.3), we have examined the stratospheric influence on the large-scale atmospheric conditions in the Arctic, and thereby on the occurrence of MCAOs in this region. After stratospheric extremes, we find that the correlation between the zonal dipole index (ZDI) and MCAOs is significantly higher than the correlation in climatology. These changes are associated with increased storminess over Scandinavia and northern Europe, and anomalously strong surface winds over the Norwegian and Barents Sea.

The relation between the occurrence of MCAOs in the Barents Sea region and the dominant mode of variability in the North Atlantic/European sector - the North Atlantic Oscillation (NAO), and the Scandinavia-Greenland dipole pattern, as represented by the ZDI index (see Afargan-Gerstman et al., 2020 for index definition) is examined (Fig. 3). These patterns largely correspond to the first and the second empirical orthogonal function (EOF) of mean sea-level pressure in the northeast Atlantic (Lee et al. 2020). Stronger MCAOs in the Barents Sea (indicated by light-blue marker color) are found during periods of negative NAO phase and positive Scandinavia-Greenland pattern, whereas weaker MCAOs (red marker color) are associated with a positive phase of the NAO and negative Scandinavia-Greenland pattern.

These findings are in agreement with previous studies that have found a negative correlation between the NAO and MCAO indices in the Barents Sea region (r=0.42, Kolstad et al. 2009), and a positive correlation with the Scandinavia-Greenland pattern (r=0.63, Afargan-Gerstman et al. 2020). These results highlight the importance of the large-scale circulation patterns over the North Atlantic, and the Scandinavia-Greenland pattern in particular, for creating the necessary conditions for MCAOs over the Barents Sea. In addition, the coupling with the stratosphere provides motivation for improved subseasonal prediction of cold air outbreaks and their associated impacts.

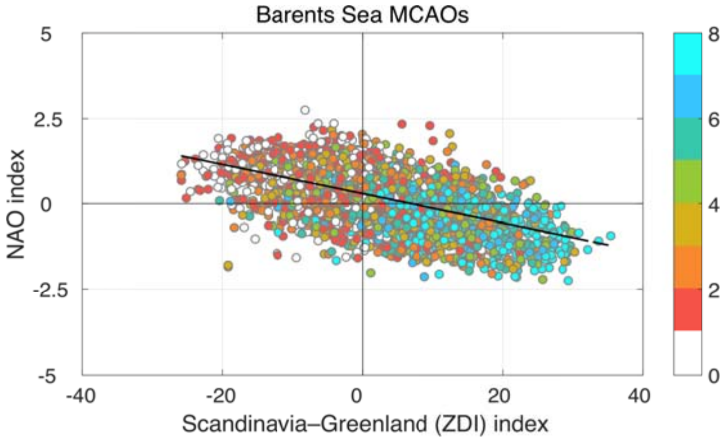


Figure 3: *The dependency of the daily Barents Sea MCAO index (indicated by colour) in the NAO index and the Scandinavia-Greenland pattern (as represented by the ZDI index) in ERA-Interim reanalysis (1979-2019). The black line shows the linear correlation between the NAO and ZDI indices (r=0.54).*

Occurrence of severe weather conditions in the Barents Sea in observations and re-forecasts

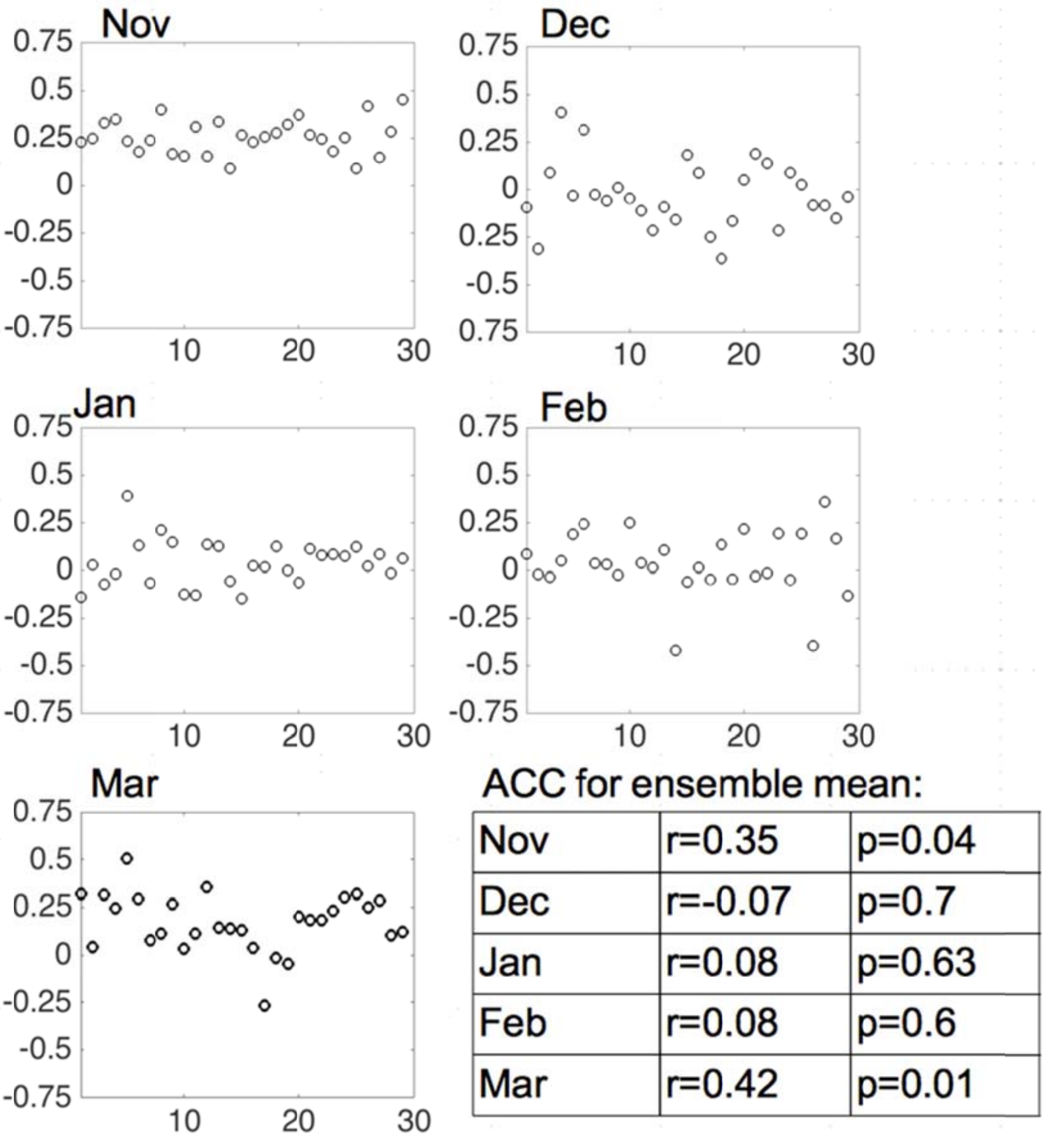
Within the WP1 we studied ship-related severe weather conditions in the Barents Sea. The decline of the Arctic sea ice resulted in an increase in ship traffic in the Barents Sea. To ensure sustainable practices in this region, it is necessary to prevent shipping accidents caused by extreme weather conditions, which primarily occur in the winter months. Hence, maritime operations mainly take place in the summer months, meaning June, July and August. If climate predictions were available for maritime services, they could improve advanced planning and risk assessment for maritime operations. Assuming that the occurrence of future extreme events follows the same pattern as past extreme events, the analysis of the spatial scale and location of past extreme events is crucial. Therefore, we analyze in which region of the Barents Sea past summer extreme events in terms of cold 2-meter temperatures (T2min), high wind speeds and high wind chill indexes (WCI) frequently occurred. This analysis is based on the ERA-Interim reanalysis referred to as observations. Furthermore, we evaluate how well a seasonal prediction system based on the Max-Planck-Institute Earth-System-Model (MPI-ESM-MR) can predict past extreme events compared to observations.

Considering observed summer extreme events over the period of 1980-2016, there are both large-scale events mostly for T2min and high WCI, as well as small-scale events for wind speed extremes. Both extreme T2min and WCI events frequently occur in the north-eastern Barents Sea, in contrast to extreme wind speeds which have no specific area of high frequency occurrence. The seasonal prediction system is able to predict the large-scale T2min and WCI extremes, but does not reproduce the small-scale extreme wind speeds. To show how climate predictions can be used by maritime services, we develop a user-friendly likelihood map of the Barents Sea showing predicted probabilities of extreme T2min, wind speeds and WCI. We demonstrate the map usage on a testing period and achieve a good agreement between predicted and observed probability of occurrence for extreme T2min and WCI. If future extreme events occur in the same pattern as past extreme events, the risk to encounter extreme

T2min and WCI in that testing period is high in the north-eastern Barents Sea and low near the Norwegian coast.

Our results show the suitability of the seasonal prediction system to detect the spatial scale and location of large-scale extreme events. Moreover, the likelihood map can be used by maritime services to improve management of maritime operations in terms of risk assessment by incorporating predictions. Thereby it provides the probability of occurrence of extreme weather in a user-friendly format (Schaffer 2020).

Predictability of west Barents MCAO frequencies in a dynamical seasonal forecast model



ACC for ensemble mean:

Nov	r=0.35	p=0.04
Dec	r=-0.07	p=0.7
Jan	r=0.08	p=0.63
Feb	r=0.08	p=0.6
Mar	r=0.42	p=0.01

Figure 4: Anomalous Correlation Coefficients (ACCs) for hindcast of MCAOs using Max Planck Institute for Meteorology's Earth System Model in the mixed resolution configuration. This hindcast was initialised for 1 Nov with 29 members ACCs for both the 29 members individually and the ensemble means are shown here.

We show here preliminary evaluation of the prediction skill of MCAO monthly frequencies in a dynamical model (MPI-ESM-MR; Giorgetta et al. 2013). The 29-member hindcast was initialised for 1 Nov. Shown in Fig. 4 are the Anomalous Correlation Coefficients (ACCs) of the hindcast and ERA-Interim values. The result indicates that there is a moderate skill at the monthly timescale for November, but the skill disappears thereafter. There is a re-emergence of ACC in March, which is at a relatively long lead time of more than 4 months from the 1 Nov initialisation. This particular aspect, however, was not investigated further in WP 1 and case study. It is not known whether this is a spurious effect or there is a possible physical process (such as through the stratosphere or ocean mixed layer) that provides this long lead time predictability.

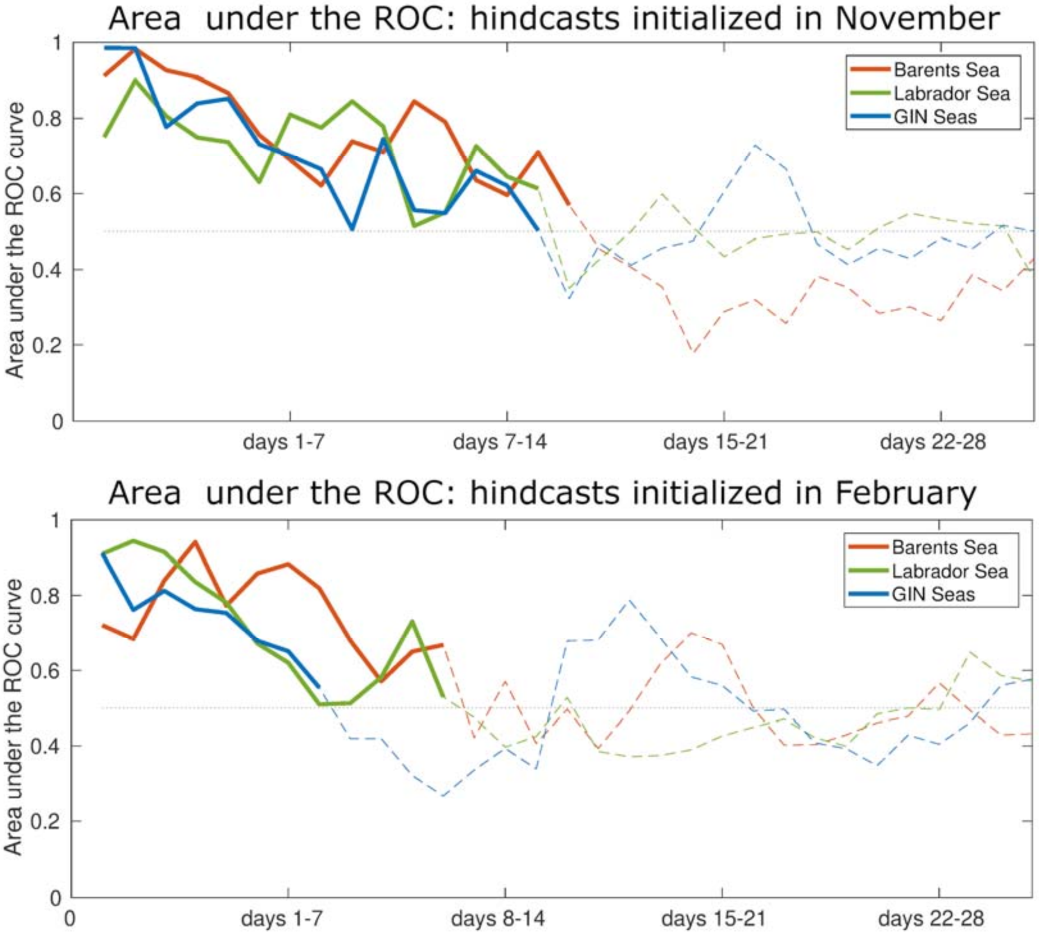
This hindcast with respect to MCAOs is studied in-depth by Polkova et al. (2020, under review in QJRMS) and is also summarised in the following section.

Prediction skill for MCAOs from a state-of-the-art seasonal prediction system

Within the WP1 we analysed the relationship between polar lows (PLs) and conditions in which these mesocyclones develop, namely marine cold air outbreaks (MCAOs). We further focused on analysing predictability of MCAOs from a seasonal prediction system. Additionally, we analysed biases and prediction skill for other relevant climate variables in the North Atlantic and the Arctic sectors. The seasonal prediction system is based on the state-of-the-art Earth System Model from the Max Planck Institute for Meteorology in mixed resolution configuration (MPI-ESM-MR; Giorgetta et al. 2013). The prediction set-up is designed and previously analysed by Baehr et al. (2015) and Dobrynin et al. (2018).

The main areas of interest for this study were the Norwegian and the Barents Seas - the regions of high MCAO and PL activity. The prediction skill assessment finds that in these regions sea surface temperature (SST), surface air temperature and sea ice concentration (SIC) show skill at seasonal timescale; whereas sea level pressure and surface winds are skillfully predicted only up to a month ahead (Fig. 5). The skill for MCAOs is constrained to about 20 days and seems to be limited by the predictability timescales of the atmospheric circulation (Fig. 6). The biases of the seasonal prediction system suggest that the model simulates warmer SSTs and somewhat colder air temperature aloft. This contributes to a stronger vertical instability of the air column, which results in the MCAO bias indicating more frequent MCAO events (Fig. 7). The results of this analysis is summarised in the study by Polkova et al. (2020, under review in QJRMS), which is also a deliverable of the project D1.4.

Based on the study by Afargan-Gerstman et al. (2020) (Deliverable 1.3) and earlier studies on MCAOs (Terpstra et al. 2016, Lien et al. 2017 and Claud et al. 2007), we narrowed down the list of conditions driving changes in MCAOs on subseasonal timescale. Among them are the local SST (in the Norwegian and the Barents Seas), the atmospheric pattern over Scandinavia and Greenland, Arctic SIC. We confirmed this set of predictors using the causal detection algorithm by Runge et al. (2016) and Kretschmer et al. (2016). This step resulted in a statistical prediction for MCAOs. Combining a dynamical prediction with the statistical prediction for MCAOs enabled extending the skill for 20 days to 40 days in the Norwegian and the Barents Seas. These results are also described in the study by Polkova et al. (2020, under Review in QJRMS). The improved MCAO prediction is based on the set of the ensemble members initialized on the 1st of November over 1980-2017 which follow the evolution as suggested by the local SST changes preceding initialization. This approach follows the idea of the study by Dobrynin et al. (2018), where the authors improved winter North Atlantic Oscillation (NAO) predictions based on the knowledge of the autumn NAO predictors. This means that based on the knowledge of the local SST anomaly from observations, an anomalous MCAO frequency can be predicted up to 4 weeks ahead.


Area under the ROC: hindcasts initialized in November

Area under the ROC: hindcasts initialized in February

Figure 5: The MCAO prediction skill as a function of lead time in days for November-initialized (upper panel) and February-initialized (lower panel) hindcasts. The skill metric is represented by the area under the relative operating characteristics curve (ROC) for the Barents (red solid and dashed), Labrador (green solid and dashed) and Greenland-Iceland-Norwegian (GIN; blue solid and dashed) Seas MCAO events (MCAO index > 0 K and > 2 days). Solid curves indicate hindcasts outperforming the climatology forecast. The skill is calculated with respect to ERA-Interim over 1980-2017.

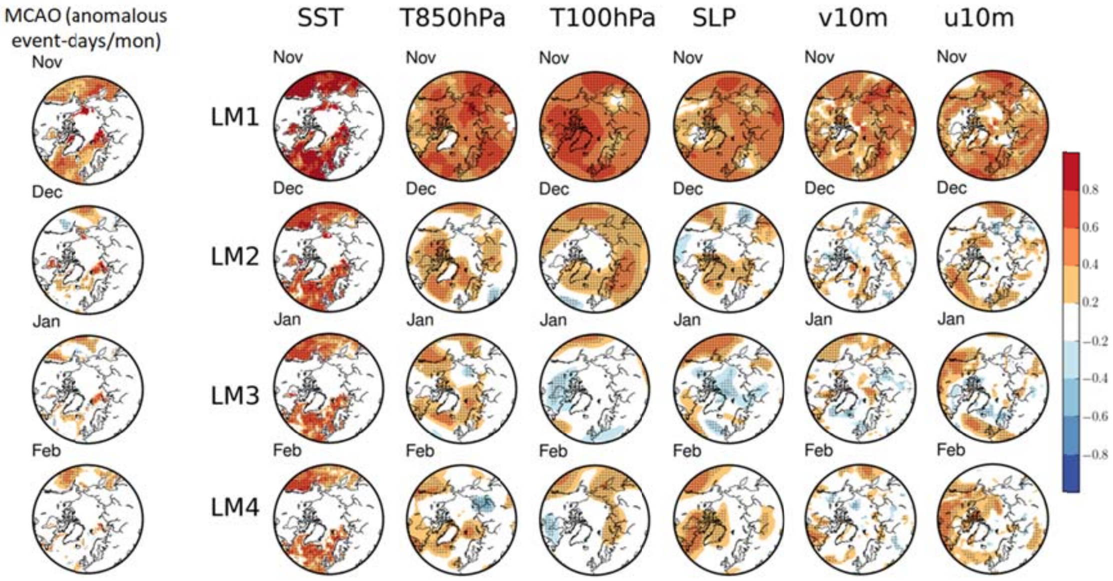


Figure 6: Prediction skill in terms of correlation coefficient between the ERA-Interim and MPI-ESM-MR for different variables (in columns) and lead months (in rows). Figure from Polkova et al. (2020, submitted to QJRMS).

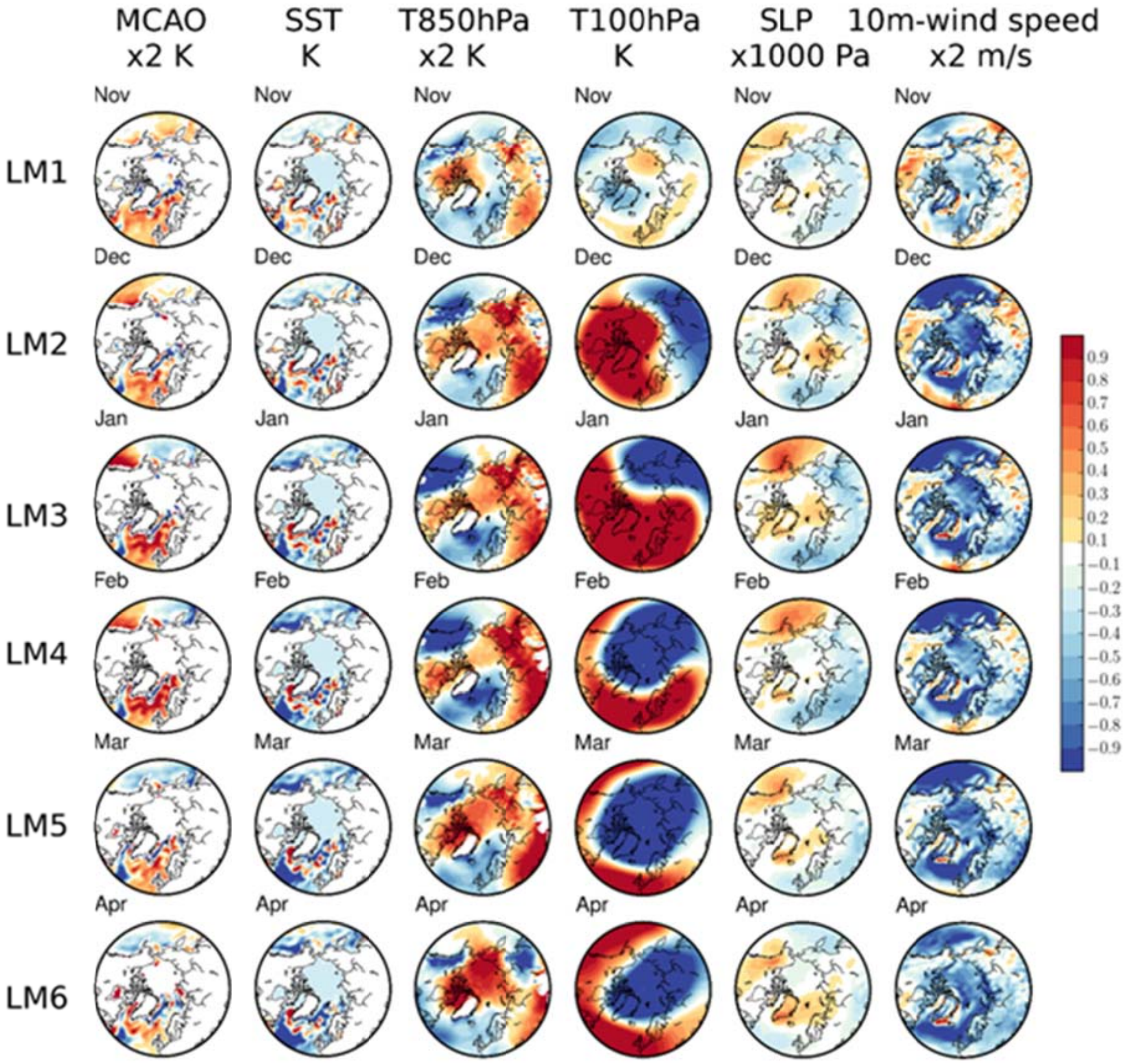


Figure 7: Monthly bias for MPI-ESM-MR seasonal predictions for different lead months from November to April (LM1-LM6). The bias is calculated with respect to the ERA-Interim climatology spanning the period Nov-1980 to Apr-2017. Figure from Polkova et al 2020 (submitted QJRMS).

Elements of a "Minimum Viable Product"

The idea behind a *climate service to communicate risk* is to convey useful climate information to relevant audiences. This information must be tangible in a way that it translates to direct decision support and action, enabling mitigation measures and/or adaptation responses. With an Arctic landscape in change, accompanied by rapidly changing weather conditions and an onset of increasing severe and extreme weather events, there is a need to foresee potentially dangerous conditions emerging.

The climate service developed as part of this case study, aims to synthesize science on Arctic extreme weather events into valued information. The information portrayed in maps is meant to facilitate risk understanding while also giving notion to the underlying factors contributing to elevated risk. In turn, the work conducted herein, shall contribute to and facilitate transfer of science to knowledge in a way that enables smooth uptake and dissemination.

For the purpose of the service, it is obvious that the prediction system it builds on is central. The success and recognition of a service rests on how well the service is perceived to speak the truth. Information delivered through a service is only as good as the quality of predictions and the data it projects. Thus, for continued work, emphasis should be on evaluation, verification and knowledge building of these links:

The Link between MCAOs and Polar Lows

- The case study has studied the relationship between MCAOs and PLs under the assumption that MCAOs are a precondition to PLs.
- A recent study (Terpstra et al., 2020) suggests two thirds (2/3) of MCAOs in the North Atlantic are accompanied by mesoscale marine cyclogenesis. The most intense of polar mesoscale cyclones (PMCs) are referred to as polar lows in the mature phase.
- Strength in signal (MCAO intensity) relates to likelihood for polar low development.
- Despite retreating ice cover, and increasing temperatures, we see an increasing trend in MCAO frequency and intensity [in the Barents Sea in winter months].

The MCAO Index and atmospheric stability

- The atmosphere is generally stable if potential temperature increases with altitude.
- The MCAO index measures **atmospheric instability condition** which causes convection within the boundary layer over the open ocean (Kolstad, 2017).
- This atmospheric instability is believed to be a main cause to development of polar lows.
- The index describes air-sea **potential temperature difference** from sea level (potential ocean skin temperature) and an altitude corresponding to atmospheric pressure 850 hPa (about 1.5 km above sea level, just above the boundary layer).
- A positive MCAO index indicates atmospheric instability conditions favourable for mesoscale cyclogenesis and stormy weather. Yet, a classification scheme on intensity of marine cold air outbreaks, and other factors, could help build thresholds pointing to severity of storms.

Other drivers to storminess in the Nordic Seas

To fully grasp the interconnectedness, and in context of this study, it is worthwhile to mention a few other drivers:

- Atmospheric circulation and blocking patterns, Greenland blocking and Atlantic ridge blocking.
- The effect of polar jet stream meandering.
- Arctic melt and freshening of Arctic waters' influence on thermohaline circulation and the region's storminess.

- Polar vortex anomalies and associated sudden stratospheric warming (SSW) events.
- Arctic-stratospheric pathways and stratospheric-tropospheric coupling.
- The North Atlantic Oscillation (NAO); its positive (negative) phase and influence on winter weather regimes in the Nordic Seas.

Progress beyond the state of the art

Forecasting of small-scale, marine cyclones, known as polar lows, in the Arctic for more than a few days in advance has been a long-standing challenge for meteorologists and atmospheric scientists. These cyclones often lead to severe weather conditions at high latitudes, accompanied by strong winds, heavy snowfall and freezing sea-spray (Landgren et al. 2019). The occurrence of marine cold air outbreaks can provide indication on the large-scale conditions needed for the occurrence of polar lows.

Due to their relatively short lifetime (2-3 days) and small scale (200-1000 km), there is a limitation to the forecast skill of polar lows. We have therefore focused on identifying the driving forces for the large-scale conditions, achieved through an analysis of marine cold air outbreaks (MCAOs).
By taking this approach, our study was able to provide advancement beyond the state of the art, as follows:

- A first systematic assessment of the relation between MCAOs and polar lows
- Identify the driving factors for MCAOs, and their statistical relation to the dominant circulation patterns in the North Atlantic.
- Evaluate the seasonal forecast skill of a dynamical model for MCAOs in the North Atlantic

Impact

How has this work contributed to the expected impacts of Blue-Action?

- Improve capacity to predict the weather and climate of the Northern Hemisphere, and make it possible to better forecast extreme weather phenomena, in particular the marine cold air outbreaks (MCAOs), describing the conditions in which these weather extremes are likely to form.
- Improve the capacity to respond to the impact of climatic change on the environment and human activities in the Arctic, both in the short and longer term.
- Contribute to a robust and reliable forecasting framework that can help meteorological and climate services to deliver better predictions, including at sub-seasonal and seasonal time scales.
- Improve stakeholders’ capacity to adapt to climate change and contribute to better servicing the economic sectors that rely on improved forecasting capacity, in particular key business stakeholders operating in the shipping sector.

Contribution to the top level objectives of Blue-Action

This deliverable contributes to the achievement of the following objectives and specific goals indicated in the Description of the Action:

- Objective 1: Improving long range forecast skill for hazardous weather and climate events
- Objective 3: Quantifying the impact of recent rapid changes in the Arctic on Northern Hemisphere climate and weather extremes

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Dissemination and exploitation of Blue-Action results

As indicated in the Description of the Action, the audience for this deliverable is the general public (PU). The deliverable is made available to the world via CORDIS and OpenAIRE.

Despite of this deliverable being for the "general public":

- The key results contained in this report have been mostly shared with the teams of the Blue-Action WP1 and WP5 in the project, for the benefit of the case study CS3 on the polar lows.
- Transfer of data and results is mostly targeted to the improvement of the prototype service set up by partner DNV GL, this is going to be described more in detail in the upcoming deliverable D5.12.
- Some of the results of this deliverable are going to be shared at the Sustainable Ocean Summit 2020 by the partner DNV GL.