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Review

Marine Operations in the Norwegian Sea and the Ice-Free Part of the Barents Sea with Emphasis on Polar Low Pressures

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Abstract: The Arctic Seas are attractive for shipping, fisheries, and other marine activities due to the abundant resources of the Arctic. The shrinking ice cover allows for the opening of activities in increasingly larger areas of the Arctic. This paper evaluates the possibility of executing all-year complex marine activities, here termed “marine operations”, in the Norwegian Sea and the ice-free part of the Barents Sea. The approach used during the preparation of this review paper is to identify constraints to marine operations so users can be aware of the limitations of performing such operations. The weather conditions in the Norwegian Sea and the Barents Sea are well known, and these seas are considered representative of ice-free or partly ice-free Arctic Seas with considerable marine activities. Similar conditions could be expected for other Arctic Seas during periods without ice cover. Marine operations require safe and stable working conditions for several days. The characteristics of marine operations are discussed, and the particulars of the Norwegian Sea and the Barents Sea physical environments are highlighted. Emphasis is on the wind and wave conditions in unpredictable polar low-pressure situations. Furthermore, situations with fog are discussed. The large uncertainties in forecasting the initiation and the tracks of polar lows represent the main concern for executing marine operations all year. Improvements in forecasting the occurrence and the path of polar lows would extend the weather window when marine operations could be carried out. Discussions of the potential for similar conditions in the wider Arctic Seas during ice-free periods are presented.

Keywords: marine activities; marine operations; physical environmental conditions; Norwegian Sea; Barents Sea; waves in polar low situations; polar low pressure; alpha factor; safe work conditions

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1. Introduction

1.1. Marine Activities

The term “marine activities” refers to all activities, operations, and matters related to sea transport, encompassing the movement of goods, passengers, and vessels across oceans, seas, and navigable waterways. In the past, all marine activities were dependent on weather forecasts based on limited knowledge [1]. The clouds and the wave conditions were the most important characteristics to be checked. Long swell waves indicate that a storm is approaching, as long waves have larger phase velocities compared to shorter waves. However, in the case of fast-moving polar low pressures, the time from the approach of swell waves to the occurrence of the storm will be short.

Along the coast of Norway, in the Norwegian Sea, there are numerous examples of large losses of fishermen at sea because of the lack of early storm warnings. Off the island of Gjeslingane, 210 people were lost in a storm in February 1625. A witch was identified and held “responsible” for the storm; she was burned to death [2]. In Lofoten in February

1848, 500 fishermen were lost [3]. Off the island of Titran in 1899, 140 persons were lost [4]. Numerous additional incidents could be listed.

Still, fishing vessels are lost in the ice-free Barents Sea under Arctic conditions. The loss of the British trawler Gaul in February 1974 (36 persons were lost) north of Norway caused controversy, as she possibly was sunk by a collision with a submarine; however, it was eventually concluded that the trawler capsized as she was flooded in large waves [5,6]. Whether the trawler had accumulated sea spray icing, reducing the stability, is unknown. On 28 December 2020, the Russian fishing boat Onega sank in the Barents Sea near Novaya Zemlya; 17 people drowned. The cause was sea spray icing during a heavy sea event [7].

The Norwegian Coastguard vessel KV Nordkapp accumulated 110 tons of ice east of Bear Island during a polar low pressure in late February 1987 [8]. Nobody was harmed, though. In general, sea spray icing is of considerable concern in the cold region [9].

Similar incidents related to marine activities are reported from other Arctic areas [10]. An example of a recent loss of a vessel is the loss of the fishing vessel Destination, which disappeared on the morning of 11 February 2017 while underway from Dutch Harbor to St. Paul (Alaska) [11].

It should be noted that the activities discussed above are characterized by the possibility of relocation when a storm warning is given. Improved weather forecasting, giving early storm warnings, is, therefore, of importance for all marine activities in all ice-free parts of the Arctic.

The interest in the Barents Sea is increasing due to vast fishing and mineral resources. Furthermore, the transport of goods and political considerations are becoming more important. An important reason for the increased interest is that the area covered with ice all year is shrinking due to climate change.

1.2. Marine Operations

In this paper, the term "marine operations" represents complex marine activities requiring several days of limited weather conditions. Marine operations include offshore drilling and production of oil and gas, offshore wind farms, offshore aquaculture, offshore construction, and offshore support services.

Safe drilling after oil and gas has been carried out in the Norwegian and the Barents Sea for several years. The drilling rigs must ride off the weather situations and must, therefore, be designed for all weather conditions. The drilling rigs are winterized, and stability calculations consider the possibility of sea spray and atmospheric icing [12]. Drilling at locations where drifting ice occurs has required ice management.

New types of marine operations have recently been introduced. These are the installation and operation of offshore wind turbines and aquaculture farms.

Shorter marine operations with durations of up to several days, like the installation of equipment to produce oil and gas or the installation of equipment on the seafloor, have been carried out in the Norwegian and the Barents Sea for several decades. However, these activities have been limited to being carried out during the milder summer season [13,14].

This paper will discuss the possibility of extending activities related to marine operations in the Norwegian Sea and the ice-free parts of the Barents Sea (Figure 1) to longer periods of the year.

Typical complex marine operations, like lifting and installation of equipment onto fixed or floating units, are limited to significant wave heights of 2.5 m, wave spectra peak periods in the range of 8 s to 10 s, and wind velocities below 5 m/s to 8 m/s. Different vessels have different work characteristics. Dense fog or freezing rain will, in many cases, prohibit such operations.

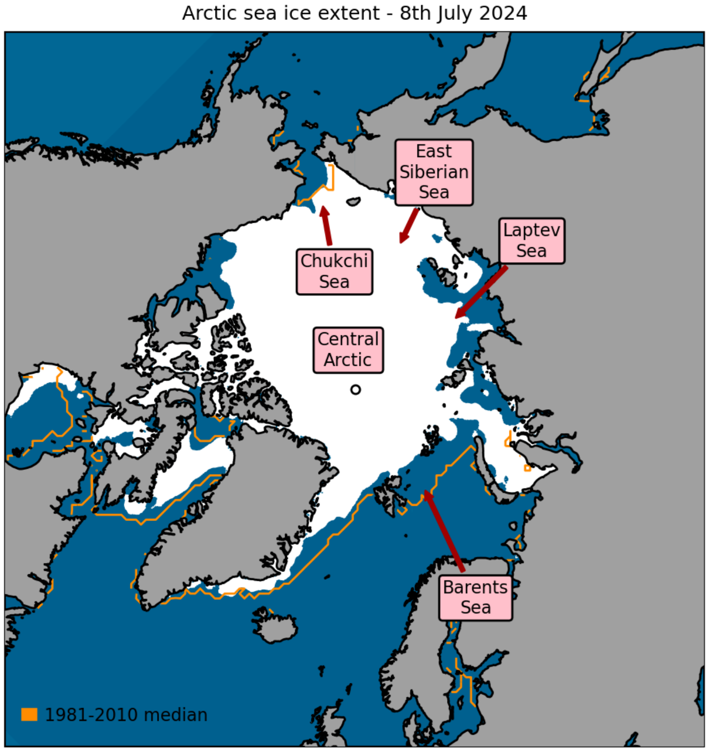

Figure 1. Arctic Sea ice extent on 8 July 2024, with 1981–2010 average extent indicated in orange [15]. Note that the Barents Sea was free of ice in mid-2024. The Norwegian Sea, along the coast of Norway to central Norway, is never covered with ice. Larger parts of the Barents Sea are ice-covered during the winter and spring. This includes the marginal ice zone, which is the transition zone between open waters and sea ice, where the sea ice concentration is between 15% and 80%; see [16] for a discussion of the ice cover of parts of the Barents Sea.

1.3. Objective of the Paper

The objective of the paper is to clarify that marine operations in the Norwegian Sea and the ice-free part of the Barents Sea, representing an important area of the Arctic Seas, are very challenging during the months when polar low-pressure situations can be expected and that improved weather forecasts could increase the available weather windows for such marine operations.

1.4. Method to Reach the Objective

The objective of the paper is met through a presentation of the characteristics of the physical environment in the Barents Sea (Section 2). A thorough discussion of polar low pressures is then given in Section 3, while in Section 4, a discussion related to marine operations during the season when polar lows could occur is presented. Discussions and conclusions are given in Section 5.

2. The Physical Environment of the Norwegian Sea and the Barents Sea, a Summary

2.1. Low Extreme Temperatures

Although seawater freezes at −1.8 °C, the temperatures above the unfrozen sea can be very low during the winter. Above the frozen sea, the temperatures are normally colder, as no heat is transferred from the seawater. For a map of the extremely low temperatures in the Barents Sea, see Figure 2 [17]. The map also covers the Norwegian Sea and the North Sea, which is towards the south. At the ice edge, rising warmer air above the water causes the creation of a low air pressure, whereby cold air from above the ice sheet will move towards the low-pressure location; a polar low pressure is formed [18]. When the air temperature is below −40 °C, cold-resistant steel must be used for all facilities staying above the water surface (including the superstructure of all vessels).

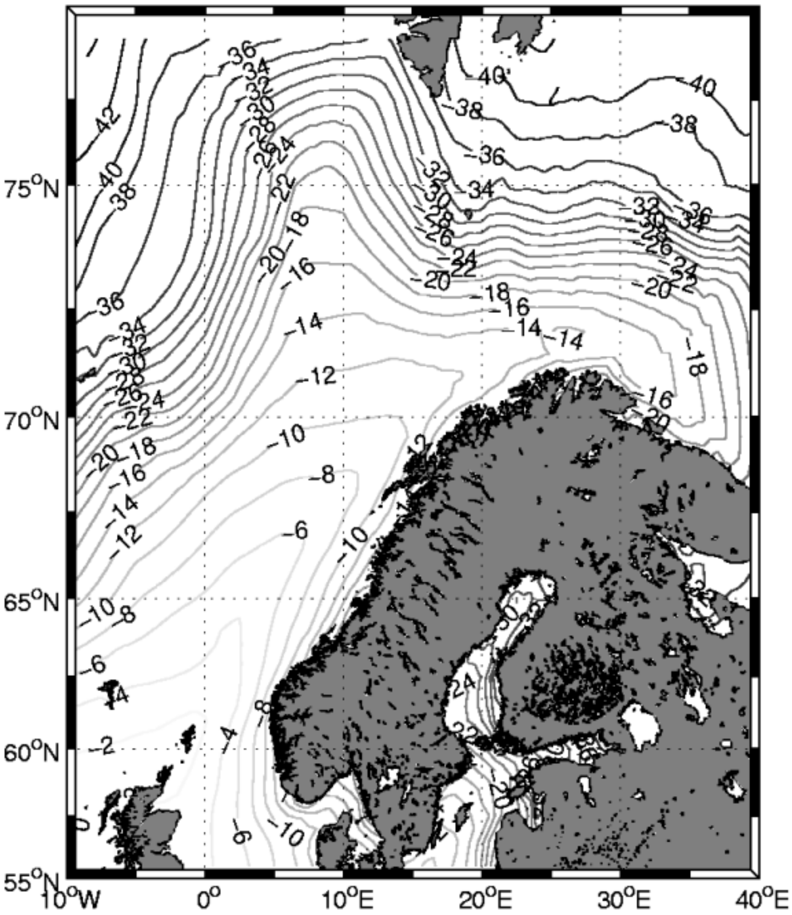

Figure 2. Minimum temperature 24-h duration at 2 m above Still Water Level (SWL with annual probability of exceedance of 10^{-2} on the Norwegian Continental Shelf and adjacent areas (=minimum in database $-2°$), data period 1958–2011 [17].

2.2. Higher Average Temperatures

The temperature in the Barents Sea is, however, in general mild, and during most of the year, the temperature is around zero degrees. Figure 3 shows the recorded temperature at Svalbard airport (at latitude 78.25 degrees north) over a 13-month period between October 2023 and October 2024. The temperature varied from $-26.9°$ to $20.3°$.

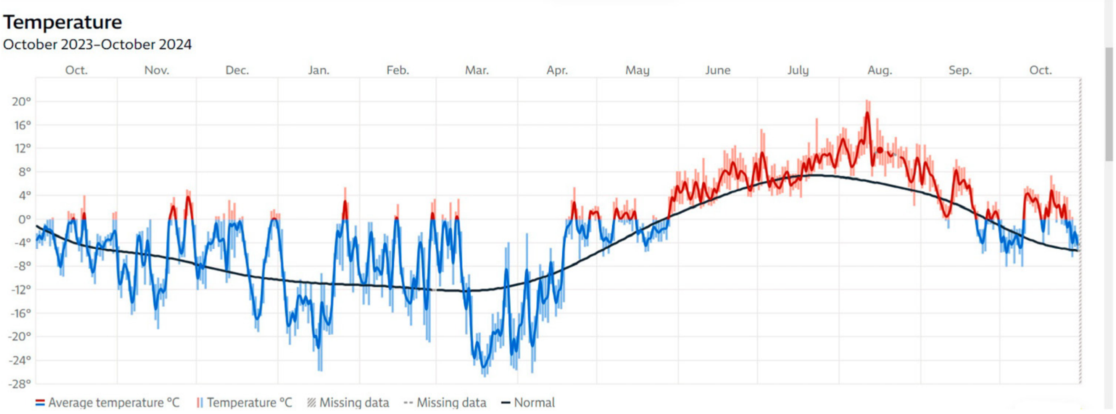

Figure 3. Temperatures measured at Svalbard Airport from October 2023 to October 2024. Red color: above zero degrees C. From: Norwegian Meteorological Institute [19].

2.3. The Ice Condition

The ice conditions in the Arctic are often characterized by the area covered with ice during the summer season. Due to global warming, the area extent of the ice cover is shrinking, Figure 4 [20]. Furthermore, the thickness of the ice cover is reduced, so the volume of the Arctic ice cover is shrinking quickly. The reduced ice cover allows for extended marine activities in the ice-free zone. To carry out complex marine operations in ice-covered areas or areas with drifting ice is extremely challenging, as the ability of vessels to withstand moving ice is difficult. Also, vessels transporting goods or passengers in ice-covered waters must be strengthened and have ice class. This applies to all transport through the Northern Sea Route between Bering Strait and the Kara Gate.

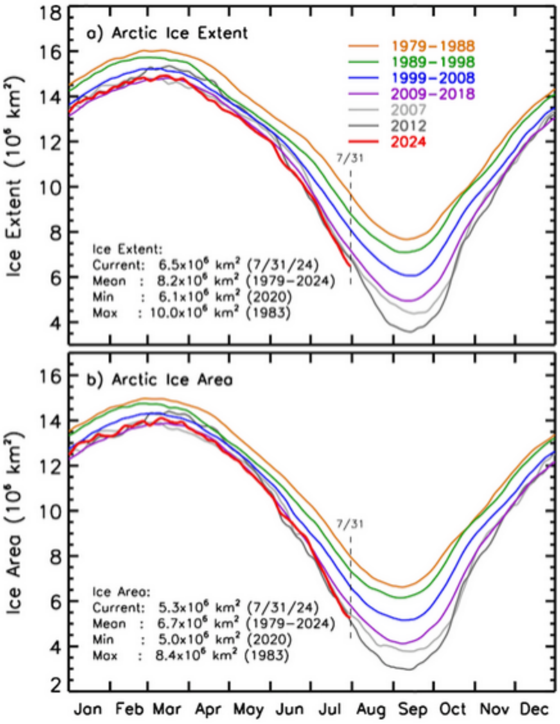

Figure 4. Ten-year averages between 1979 and 2018 and yearly averages for 2007, 2012, and 2024 of the daily (**a**) ice extent and (**b**) ice area in the Northern Hemisphere and a listing of the extent and area of the current, historical mean, minimum, and maximum values in km^2 [20].

2.4. The Sea Current

The value of the currents is of concern when carrying out operations in Arctic waters. The loading from the currents adds to the wave loading. The effects of current are of concern for lifting operations when installing equipment (including pipelines and cables) on the seafloor and for riser systems. At the surface, tidal currents are important and must be watched for station-keeping.

2.5. The Wind Climate of the Norwegian Sea and the Barents Sea

The extreme wind conditions in the study area are shown in Figure 5 [17]. Meteorologists can forecast large low pressures. Of more concern is the very rapidly approaching polar low pressure (polar hurricanes), which gives rise to a quick build-up of high waves with associated sea spray that can freeze to ice and danger the stability as well as the operability of vessels. It should, however, be noted that the execution of complex marine operations is limited to wind conditions far below the extreme values, although extreme values represent survivability conditions for vessels and equipment.

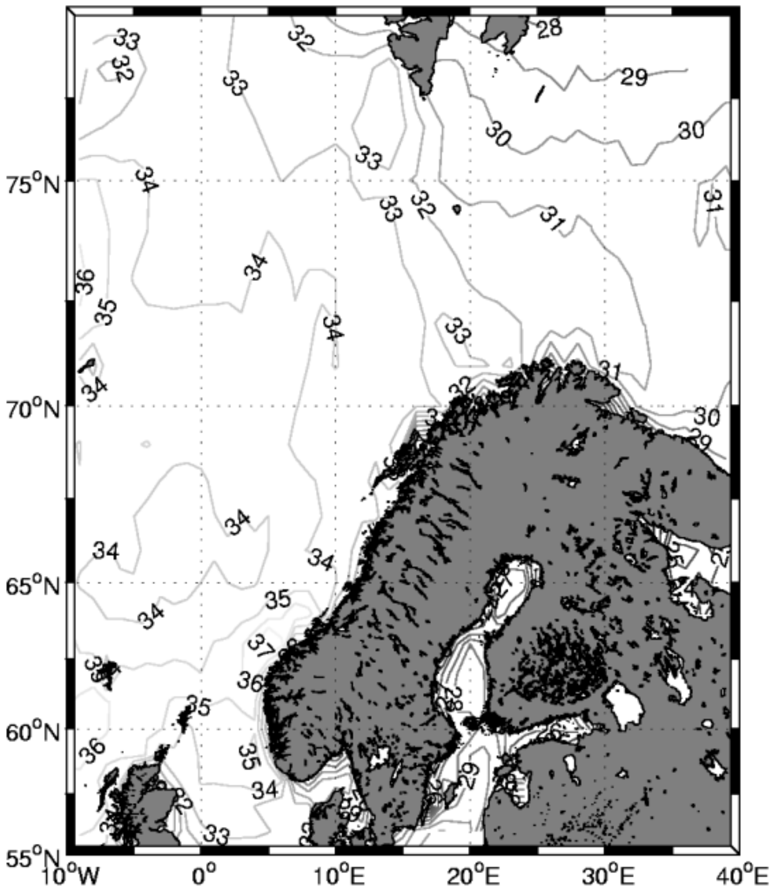

Figure 5. One-hour extreme wind speed contours at 10 m above Mean Sea Level (MSL), based on the NORA10 1958–2011 database, corresponding to an annual exceedance probability of 10^{-2}. The map covers the Norwegian Continental Shelf and adjacent areas [17].

2.6. Wave Climate of the Norwegian Sea and the Barents Sea

The wave climate is dependent on the fetch length. For a thorough discussion of the wave climate in the Norwegian Sea and the Barents Sea, reference is made to [17]. The value of the significant wave heights corresponding to an annual exceedance probability of 10^{-2} is lower in the Barents Sea than in the Norwegian Sea, as the longest fetch direction is from the southwest (while directly from the Atlantic Ocean in the Norwegian Sea). However, the spectral peak periods are longer than in the North Sea for waves associated with the 10^{-2} annual probability significant waves due to longer fetch length than in the North Sea. During normal operations, the waves are also longer than in the North Sea. This influences the equipment selected for operations in the Barents Sea, as the vessels used to carry out marine operations will have higher response values in heave, roll, etc., in longer waves.

The wave conditions in several Arctic Seas are expected to be influenced by climate change. This is because the shrinking ice cover leaves a larger open sea area with a longer fetch, allowing higher waves to form [21]. This phenomenon might also affect the Barents Sea. The concern is highest during the fall season when the fall storms set in.

2.7. Fog and Freezing Rain

Fog limits the possibility of carrying out complex marine operations, as many operations require clear visibility to ensure safe work conditions. Fog occurs often over cold water during the summer period, and as fog normally is associated with a lack of wind, the occurrence of fog represents severe limitations to the possibility of carrying out weather-restricted marine operations.

Similar concerns are present during situations with freezing rain. Safety functions are often compromised during freeing rain situations, and operations must be put on hold. For a discussion of these phenomena, see [22–24].

3. Unpredictable Polar Low-Pressure Situations

3.1. Background to Polar Lows

Polar low weather conditions do not normally represent the extreme design conditions for marine facilities. However, polar low pressures are restraining marine operations in the Arctic Region. According to [18], "a polar low is a small, but intense, maritime cyclone that forms poleward of the main baroclinic zone (the polar front or other major baroclinic zone). The horizontal scale of the polar low is approximately between 200 and 1000 km and surface winds near or above gale force". The concerns are related to the rapid formation of polar lows, their fast movements, and the associated difficulties in forecasting their initiation and tracks. Considerable research efforts have been made to increase the knowledge about polar lows. The Norwegian Metrological Institutes in Tromsø and Oslo have carried out several projects. Prominent Norwegian researchers have been G. Noer [25,26] and J. E. Kristjánsson [27]. Further references shedding light on Polar Low Pressures are referred to, see [28–33]. Due to the concerns related to Polar Lows, marine operations with durations of more than a few days are to be restricted during the polar low season.

3.2. Polar Low-Pressure Occurrence

The occurrence of polar low-pressure situations is shown in Figure 6 [34]. Note that the Norwegian Sea and the Barents Sea are highly affected areas for polar lows. Polar lows are not expected in the Arctic seas north of Russia, Canada, Greenland, and Alaska. However, the decrease in sea ice extent would probably change this, and new areas where polar lows can be expected will emerge [35]. Polar lows are already experienced north of Svalbard [36,37].

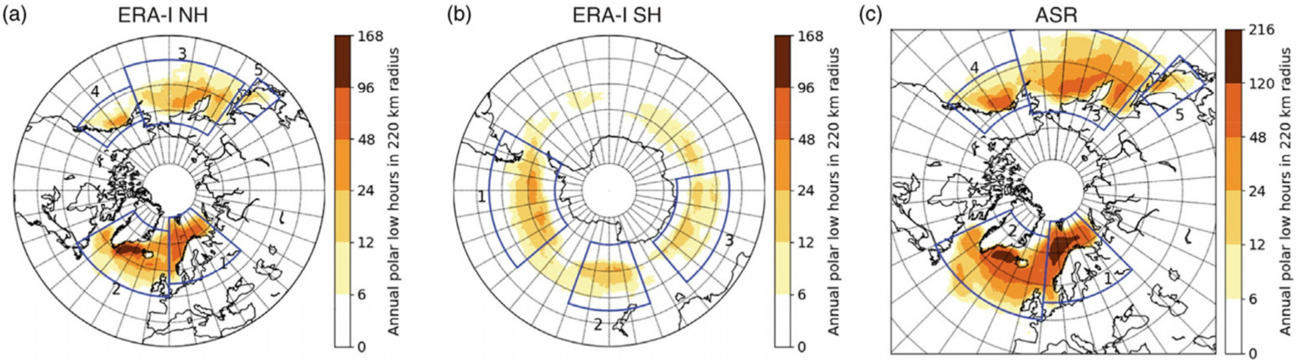

Figure 6. Annual mean occurrence of polar low (PL) activity for the Northern and Southern Hemispheres, respectively. A black contour encircles regions with more than 24 h of polar low activity per year [35]. The figure is obtained by applying an objective tracking algorithm to data from (**a**,**b**) ERA-I and (**c**) Atmospheric System Research, ASR. The color represents the annual average of PL duration within a radius of 220 km, which is calculated by multiplying the number of detected PL points by the temporal resolution of the reanalysis.

A detailed map showing the occurrence of polar lows in the Norwegian and Barents Seas is shown in Figure 7 [38]. The figure also shows the monthly distribution of polar low pressures. The probability of a polar low from mid-May to mid-September is low. For further information, see [39]. It is expected that some polar lows originating in the Russian part of the Barents Sea are not registered in Figure 7.

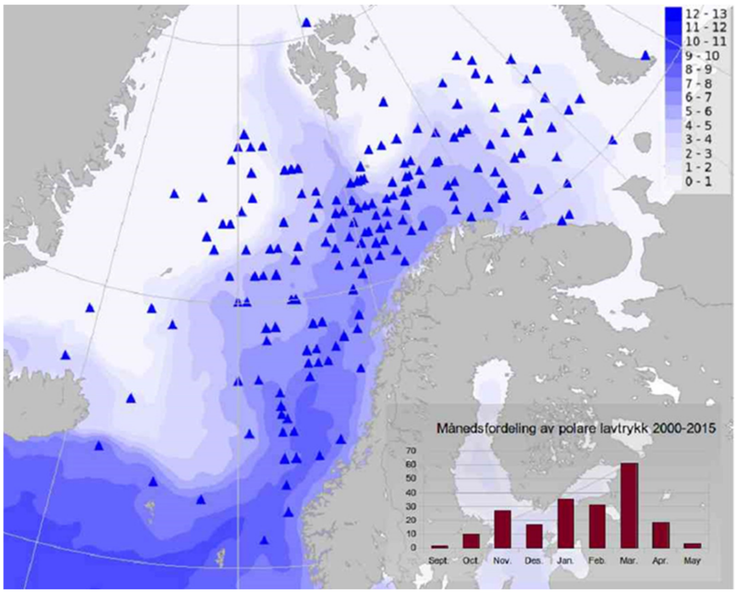

Figure 7. Polar lows during the period from 2000–2015. The triangles represent points where Polar lows have formed. The blue coloring shows the mean sea temperature in January and indicates a typical winter temperature distribution. These low-pressure systems often form when air flows from pack ice and cold surfaces to the relatively warmer sea [3].

3.3. The Tracks of the Polar Lows

The tracks of the polar lows are difficult to forecast. Figure 8 shows the tracks of polar lows over a 14-year period [40]. Figure 9 shows the tracks from 2015 to 2017 [41]. Furthermore, the tracks often shift direction, and the forecasters must inform the public that the tracks of the polar lows can cover a wide area. Figure 10 shows the forecast for the track of a polar low on 5 March 2021; a large area might be affected within a day [42]. One day later, this special warning was canceled. If all activities had been stopped in the area where the polar low could pass, these measures would have been wasted.

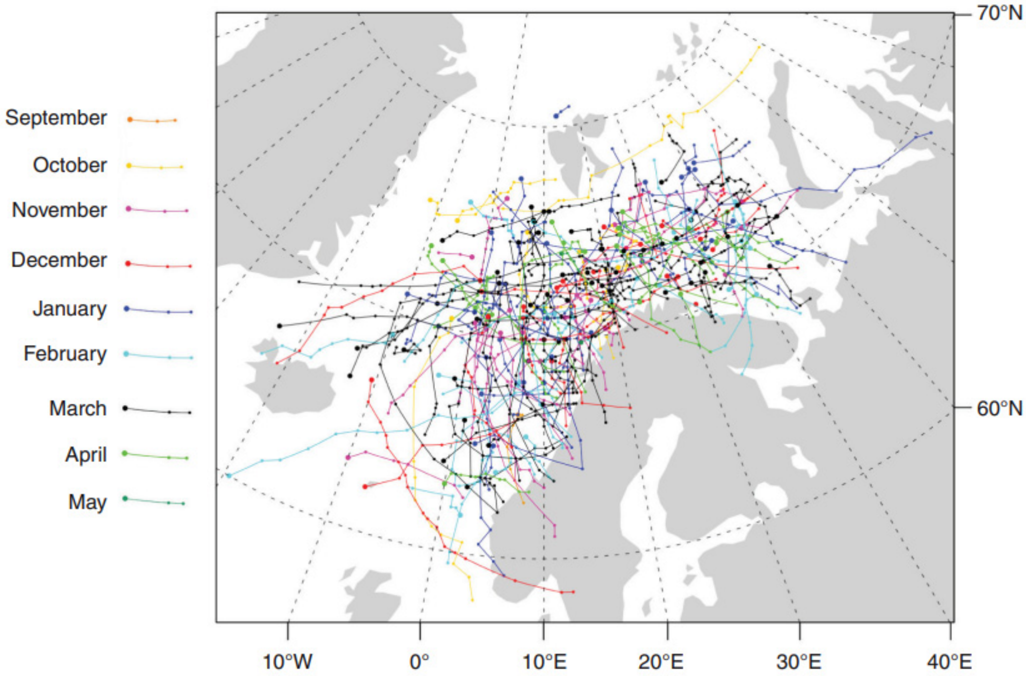

Figure 8. Polar tracks over the Nordic Seas during the winters of 1999/2000 to 2012/13 [40].

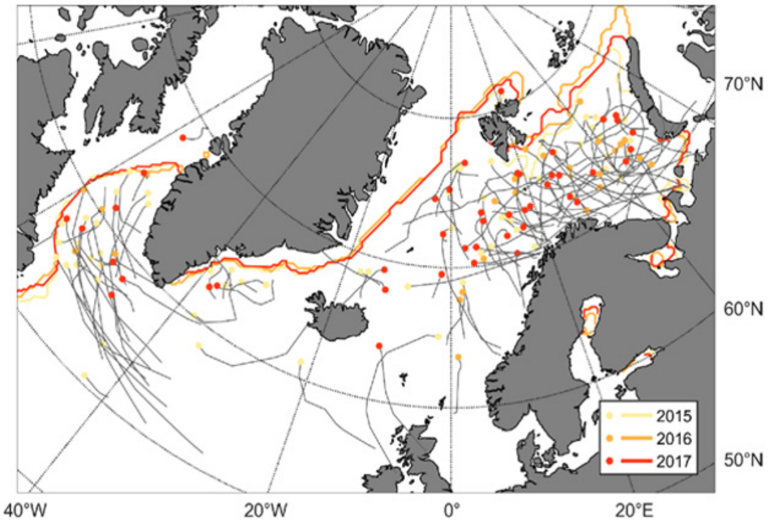

Figure 9. Tracks for polar low pressures during 2015–2017 [41]. The further south an operation shall be carried out, the lower the probability of encountering a polar low pressure. Legend: Thick colored circles represent locations of the first observation of a polar low, and colored lines represent median sea ice extent. The thin grey lines indicate the trajectories of the identified polar lows.

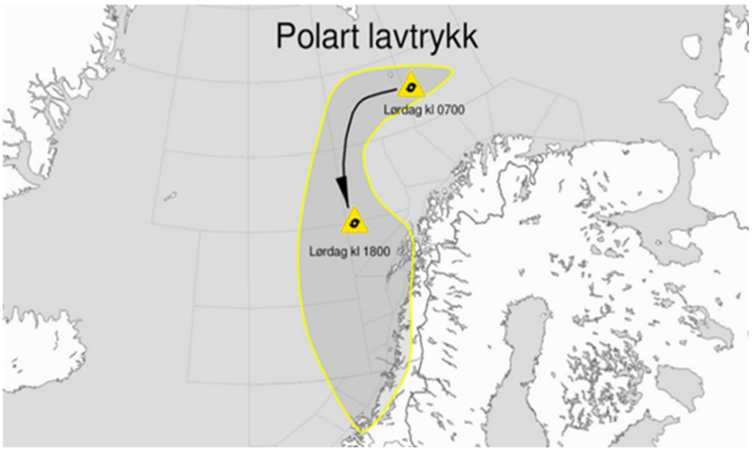

Figure 10. Possible track for a polar low pressure on 5 March 2021 [42]. Legend: Polart lavtrykk = Polar low pressure. Lørdag = Saturday.

A thorough discussion of the uncertainty in forecasting the tracks of polar low pressures is given in [43]. It is highlighted in [43] that dual and multiple polar low pressures occur and that polar low pressures also might occur a few days apart. For an approach to forecast polar lows, see [44].

3.4. Waves in Polar Lows

The waves in polar lows are normally lower than the extreme design waves; however, they are larger than in situations where most marine operations can take place. As the polar lows are quickly approaching, adjusting to a new weather situation could be challenging when a marine operation is ongoing.

Certain situations are very challenging, occurring when any wave component whose group velocity, c_g, is near the speed, V, of the polar low will remain in the moving fetch for a long duration. This phenomenon is known as group velocity quasi-resonance, trapped fetch (commonly used by tropical cyclone modelers), dynamic fetch, or extended fetch [45]. During these situations, energy is efficiently fed into the wave field [46,47].

Data from a polar low situation occurring on 26 December 2015 are analyzed in [46]. The data suggests that the significant wave height (H_s) increased from 1.78 to 9.00 m between 00 UTC and 14 UTC, while the maximum wind speed was 16 m/s. According to [47], "it should be noted that in a relatively stationary fetch, a significant wave height of 9.00 m is not likely for a maximum wind speed of 16 m/s". Wave forecasts from two wave models, WAM4 and WAM10, were considered, and the forecasted H_s using the traditional wave models underestimated the measured H_s. The example shows, however, that the uncertainty in forecasting waves in polar lows can be high. According to [47], "it is not advisable to perform marine activities, including fisheries, anywhere within the horizontal extent of a polar low, and along the predicted track of a polar low". A similar situation was also confirmed by G. Noer regarding a polar low pressure in 2012 [48].

3.5. Additional Characteristics of Polar Lows

Due to the rapidly increasing wave heights, sea spray will freeze on all vessels in the path of the polar low. Furthermore, polar lows are normally followed by precipitation in the form of wet snow that will freeze to ice when hitting the vessel, adding to the amount of ice [8]. In this situation, vessel stability can be compromised, particularly for vessels with low initial stability or narrow vessels. Note that for the narrow vessels, the up-righting moment is low during vessel roll [49]. Thus, it can be concluded that polar low pressures represent a combination of the factors presented in Section 2 and are thus the most critical factor limiting marine operations to seasons outside the polar low season.

4. Marine Operations During the Season When Polar Lows Could Occur

Marine activities that can be moved outside the tracks of polar lows are not in danger, provided the weather forecast is given in time to evacuate the forecasted track. Research related to forecasting polar lows is, therefore, of utmost importance for all Arctic marine activities during the winter months.

The marine construction industry often carries out operations based on weather forecasts in case the operations have a duration of or can safely be aborted within three days. This is the case, for example, in the North Sea Area. When meteorologists forecast a probable polar low pressure, marine operations that have a duration of more than a considerably shorter time, say 24 h, could be at risk. Procedures to wait on the weather must be implemented. In case a quick abortion of the operation is possible with a safe recovery, operations may start for operations above this anticipated time.

To handle the uncertainties in weather forecasts, DNV [50] has introduced a factor limiting the allowable weather when a marine operation can be carried out, the OPLIM, by an alpha factor. The duration of the marine operation is called the reference period, TR, which is the sum of the Planned Operation Period, TPOP, and a Contingency Time, TC. The weather forecast (WF) for the Reference Period shall thus be OPWF = α × OPLIM; see Figure 11 [50]. For guidance regarding the development of the alpha factor, see [51].

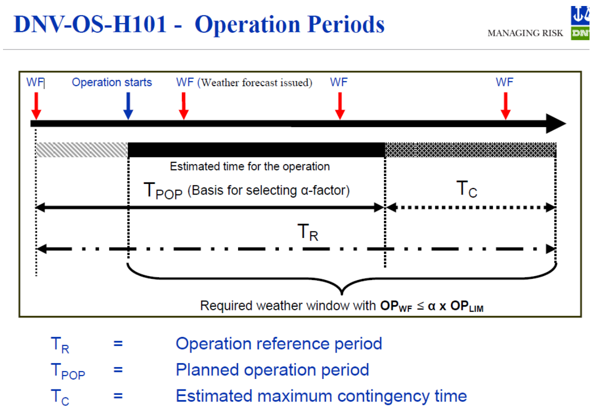

Figure 11. Definition of Alpha Factor [50].

An example is given as follows:

- We assume that the operational limitation of a specific vessel for a marine operation, the OPLIM, is 2.5 m significant wave height;
- We assume that the uncertainty in the weather forecast (the alpha-factor) is by analysis of statistical data of the goodness of forecasts, found to be 0.8 at this location during the season, for an operation with a duration of 3 days;
- Then, the weather forecast required to start the operation, the OPWF = 0.8 × 2.5 m = 2.0 m significant wave height for the coming 3 days.

It can be noted that the alpha factor does not account for the wave period. Long swell waves could excite the motion of the vessel considerably, and judgment must be exercised prior to starting the operation.

In areas where the weather uncertainty is larger, the value of the alpha factor would be very low, indicating a large reduction of the operational limit of the equipment (vessel) used for the operation. This applies to the season when polar lows could be expected. In such circumstances, long periods of "waiting on weather" (WoW) could be expected. Notice that the uncertainty may be reduced somewhat by employing a "meteorologist on-site" or providing onsite data by employing wave measurements on-site.

It is not considered realistic to identify suitable alpha factors for the harsh weather season in the Barents Sea [48]. Marine operations requiring several days should be suspended in areas and during periods when polar lows are likely to occur.

During the summer period, however, the concept of identifying alpha factors for the Barents Sea should be encouraged to ensure that efficient and safe marine operations are conducted.

5. Discussion and Conclusions

Past events have shown that the weather situation in the Arctic is uncertain, and that weather forecasting must be focused when planning marine activities, in particular, complex marine operations requiring limited weather conditions for a period of several days. From mid-September to mid-May, the occurrence and the tracks of polar low pressures in the Arctic Seas are uncertain and may not be forecasted by traditional methods. This paper emphasizes the situation in the Norwegian Sea and in the Barents Sea; however, similar conditions exist in other areas where a polar low can be expected. It should be noted that with the shrinking ice coverage during the summer months, larger areas of the Arctic will be open for marine activities, and it could be expected that complex marine operations will take place in the extended ice-free waters. The Norwegian Sea and the ice-free parts of the Barents Sea are the areas of the Arctic with the highest activity, and learning from these areas should be relevant to other areas as well.

Marine operations that require more than 24 h of accurate weather forecasts should not be initiated during the period when polar lows could be expected and when the weather forecast is very uncertain. Alternatively, in case a quick and safe abortion of the operation is possible, work can be planned. Marine operations in the Arctic must, therefore, be planned during the summer months. This will ensure the safety of the personnel involved as well as the vessel and equipment.

It is concluded that the way forward to increase the period when marine operations can be conducted is to carry out extended research to improve the forecast related to better understanding the initiation and tracks of polar low pressures. Further satellite coverage of the Arctic will enhance the meteorologists' ability to improve forecasts. The availability of frequent satellite information with an update every few hours will be important for the progress in accurate forecasting. At the time of initiation of the marine operation, the area could then be declared free of polar lows for an extended time so marine operations with a duration of longer periods (up to 2–3 days) could be started. It is noted that few satellites at present orbit the earth in this area, and the costs of increasing satellite coverage must be considered.

The meteorologist should also be prepared to forecast the occurrence of multiple polar lows in an area or the initiation of another polar low following closely after the passing of the first event.

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