Evaporation Duct Height Climatology for Norwegian Waters Using Hindcast Data

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ABSTRACT

Knowledge of the atmospheric propagation conditions in the marine boundary layer is essential when planning and conducting military naval operations. Propagation in the radio frequency spectrum is dependent on the refractive conditions, which are determined by the vertical distribution of water vapour, air temperature and atmospheric pressure. The evaporation duct, caused by negative gradients of refractivity in the atmospheric layer above the sea surface, is of particular interest. The evaporation duct height (EDH) may be estimated using bulk models based on the semi-empirical Monin-Obukhov similarity theory (MOST) describing the atmosphere's stability. In this study, we have used hindcast data produced by the numerical weather prediction model High Resolution Limited Area Model (HiRLAM) to develop climatology for atmospheric stability, in addition to climatology for EDH in Norwegian waters by combining the hindcast data with the bulk model Naval Atmospheric Vertical Surface Layer Model (NAVSLaM). The monthly median EDH and modified refractivity profiles (M-profiles) with their corresponding variations can be used for input into tactical decision aids (TDAs) for estimating radar performance for use in medium and long term operations planning. Our results show that the Norwegian waters are dominated by unstable atmospheric conditions during the winter months of November and January, with median EDH of 6–7 meters. From April to July, unstable conditions are only present at 40–60 % of the time near the coast of Norway. Since bulk models are much more sensitive to variations in stable atmospheric conditions, and can possibly give erroneous results, users are advised to show caution when applying bulk models in these months. The lowest median EDH occurs in late spring or early summer, with a median EDH of 4–5 meters, while the highest median EDH occurs in September with 7–8 meters. The distribution of EDH varies significantly throughout the year, and calculations of radar detection ranges show that they can vary up to several kilometres within a month due to the variations in EDH.

1.0 INTRODUCTION

In the atmospheric marine boundary layer, propagation of electromagnetic waves in the radio frequency (RF) spectrum is – among other mechanisms – dependent on the refractive conditions. Shipborne radars operating in the frequency band of 3–18 GHz are especially affected, and are subject to trapping during extreme super-refractive conditions caused by an evaporation duct [1]. Trapping of radar waves can lead to extended radar range beyond the normal radar horizon, but also to adverse effects such as poorer coverage above the trapping layer and increased sea clutter return. Understanding the prevailing refractive conditions and its effect on radars is therefore essential when planning and conducting military operations at sea.

The refractive conditions are determined by the vertical distribution of water vapour, air temperature and atmospheric pressure. Vertical profiles of these meteorological parameters are used to compute a modified refractivity profile (M-profile) and its corresponding evaporation duct height (EDH). Since measuring refractivity profiles at sea is challenging, M-profiles and EDH are usually calculated using bulk models. One such bulk model is the Naval Atmospheric Vertical Surface Layer Model (NAVSLaM) [2], developed by the Naval Postgraduate School. To calculate the M-profiles and the EDH in bulk models, the parameters relative humidity, wind speed, pressure and air temperature at a known height – as well as sea surface temperature – are needed.

NAVSLaM, like most bulk models, is based on the semi-empirical Monin-Obukhov similarity theory (MOST) [3], which describes the turbulence properties within the atmospheric surface layer. Bulk models based on MOST are sensitive to variations in atmospheric stability, and the empirically derived functions differ for the different models. Bulk models have traditionally been “open ocean” models, where unstable conditions are most common. In a coastal environment, however, the stability of the atmosphere is more variable due to more complex dynamics and influences from land. This makes it both more difficult to measure the conditions reliably *in-situ*, and to accurately represent them in models. Furthermore, bulk models based on MOST tend to be much more sensitive to their input values in stable conditions, as opposed to unstable conditions [4]. The models are expected to perform better in unstable conditions, i.e. when the air-sea temperature difference (ASTD) is negative (ASTD<0), than in stable conditions (ASTD>0). The calculations of EDHs and M-profiles are therefore more reliable in unstable conditions.

Long-term meteorological data produced by numerical weather prediction (NWP) models are needed to calculate the average refractive conditions and its predicted variations. Climatology of EDH can contribute to a better understanding of the refractive conditions in several ways. In a long or medium term planning perspective, climatology is necessary for assessing RF propagation and communications in naval operations. If timely EDH forecasts or *in-situ* measurements are not available, climatology of EDH can provide insight into the expected conditions even on a tactical level. Furthermore, monthly distributions of stable/unstable conditions can contribute in assessing the reliability of the estimated EDH. Lastly, climatology of ASTD might be useful for planning experiments for validating bulk models in stable conditions.

We have developed monthly median EDH and M-profiles with their corresponding variations for Norwegian waters for input into tactical decision aids (TDAs). This has been achieved by using the NAVSLaM bulk model combined with a hindcast data archive produced by the NWP model High Resolution Limited Area Model (HiRLAM) [5,6]. We present the EDH results for the months of January, May, September and November, which cover the seasonal variations. We also provide climatology of ASTD for the same four months, which may be useful for highlighting areas and seasons where bulk models are expected to give a reliable EDH, i.e. unstable conditions. ASTD climatology also shows the regions and periods where current bulk models may have limitations. These limitations occur when faced with strongly stable conditions and thus *in-situ* measurements of M-profiles may be necessary for determining the EDH. We also show an example of how predicted radar detection ranges change with season and environment.

2.0 DATA AND MODELS

The area studied is mainly located in Norwegian waters (see Figure 1). The data used in this study are long-term hindcast data for Norway (NORA10) based on the numerical weather prediction (NWP) model HiRLAM [5,6] and are provided by the Norwegian Meteorological Institute. The data are produced on an 11x11 km^2 from 1958 until today, with one hour time step temporal resolution (model spatial coverage illustrated by blue box in Figure 1). The NORA10 dataset provides air and sea surface temperature, wind speed and relative humidity amongst a wide range of other meteorological data. For our purpose the air temperature (T) and the relative humidity (RH) is provided at 2 meter height, while the wind speed is given at 10 meter height.

In this study a subset (90x200 grid cells) is extracted from the original model domain (see Figure 1 – red box). The data are used to calculate air-sea temperature difference (ASTD) and for input into calculations of evaporation duct height (EDH) and modified refractive profiles (M-profiles) for the time period 1980 to 2015.

For this study we have chosen the model NAVSLaM [2] version 1.1 to produce EDH and M-profiles. NAVSLaM has shown superior performance compared to the Paulus-Jeske model [7,8], and has earlier been used to compute a global climatology for the U.S. Navy [8]. NAVSLaM version 1.1 has demonstrated better results in stable conditions than previous versions of NAVSLaM, but further validation with propagation data is needed to improve the model performance under such conditions [9]. The applicability of NAVSLaM in Norwegian waters needs to be investigated in future studies, since bulk models based on MOST may need to be empirically adjusted for each specific region of use [10].

Figure 1 Area covered by the HiRLAM NWP model (blue box) and the subdomain used in this study (red box).

3.0 RESULTS

3.1 Air-Sea Temperature Difference

The atmospheric stability, here given by the difference in air-sea temperature, is a significant input parameter in bulk models based on MOST. Figure 2 shows average occurrence of ASTD<0 in percent for January, May, September and November. ASTD is negative most of the time (70–100 %) in November and January, due to the cold air masses overlying the relative warmer ocean. During the spring (May), accumulated time with ASTD<0 decreases, especially for the southern part of the domain and along the Norwegian coast. This decrease is likely caused by land masses that heat more rapidly than the ocean in the spring/early summer. The warmer land masses affect the air temperature some distance offshore, causing ASTD>0. In September, ASTD<0 starts to become more prominent. This shows that one should use bulk models like NAVSLaM more carefully during the spring and early summer in the waters highlighted in this study.

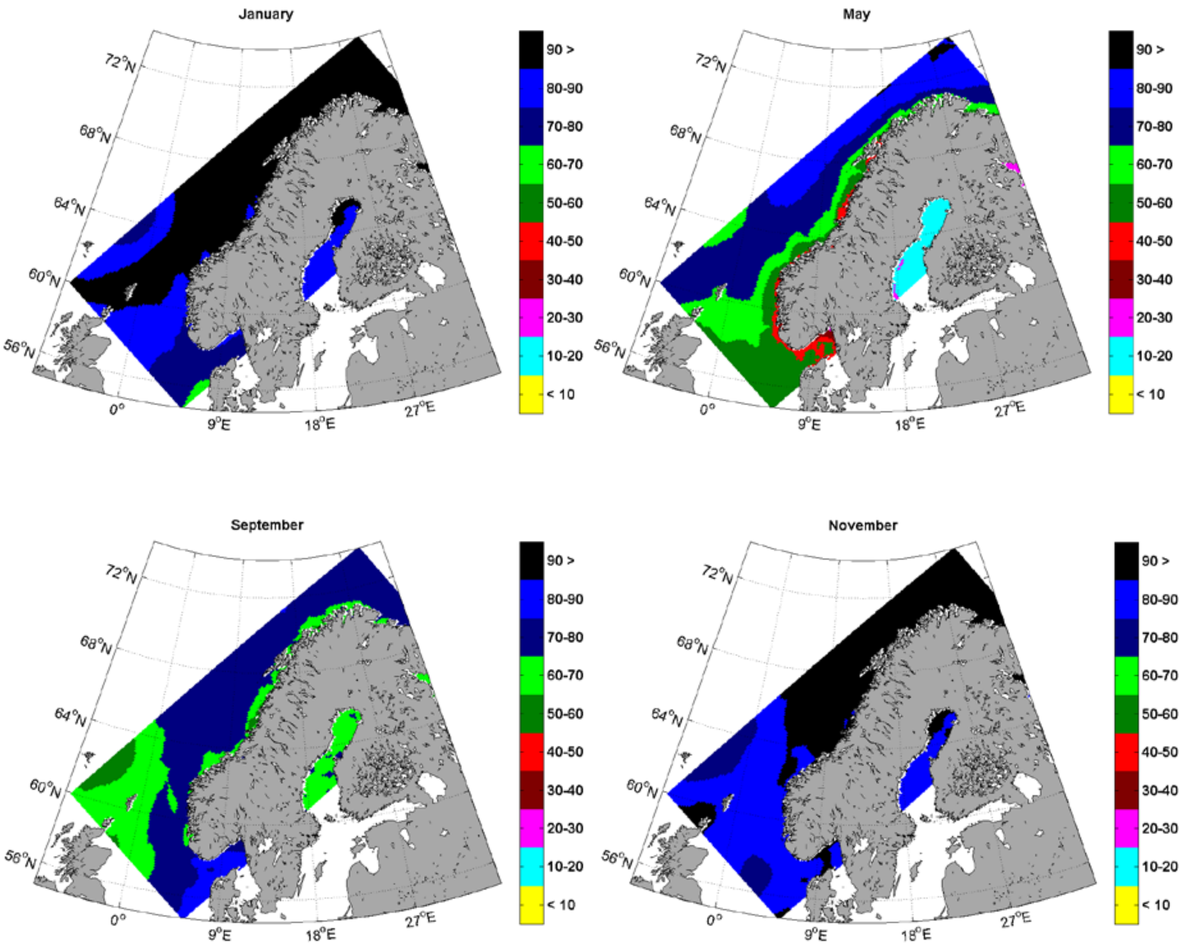

Figure 2 Occurrence of ASTD<0 in percent in January (upper left), May (upper right), September (lower left) and November (lower right). Based on the period 1980–2015.

3.2 Evaporation Duct Height

Median EDH for January, May, September and November is presented in Figure 3. The lowest median EDH is found in late spring/early summer (May), with heights mostly around 4–5 meters. In September, EDH is higher compared to May, and the largest median EDHs are found closest to the shore and decrease as we move offshore. In the south-eastern part of the domain median EDH is around 7–8 meters in September. Note that the area with highest median EDH is approximately similar to the area were ASTD<0 80–90 % of the time. In November and January, the situations are approximately the same for both months in the open ocean with median EDH around 6–7 meters. Close to the shore and in the south-eastern part of the domain median EDH is slightly lower in January compared to November.

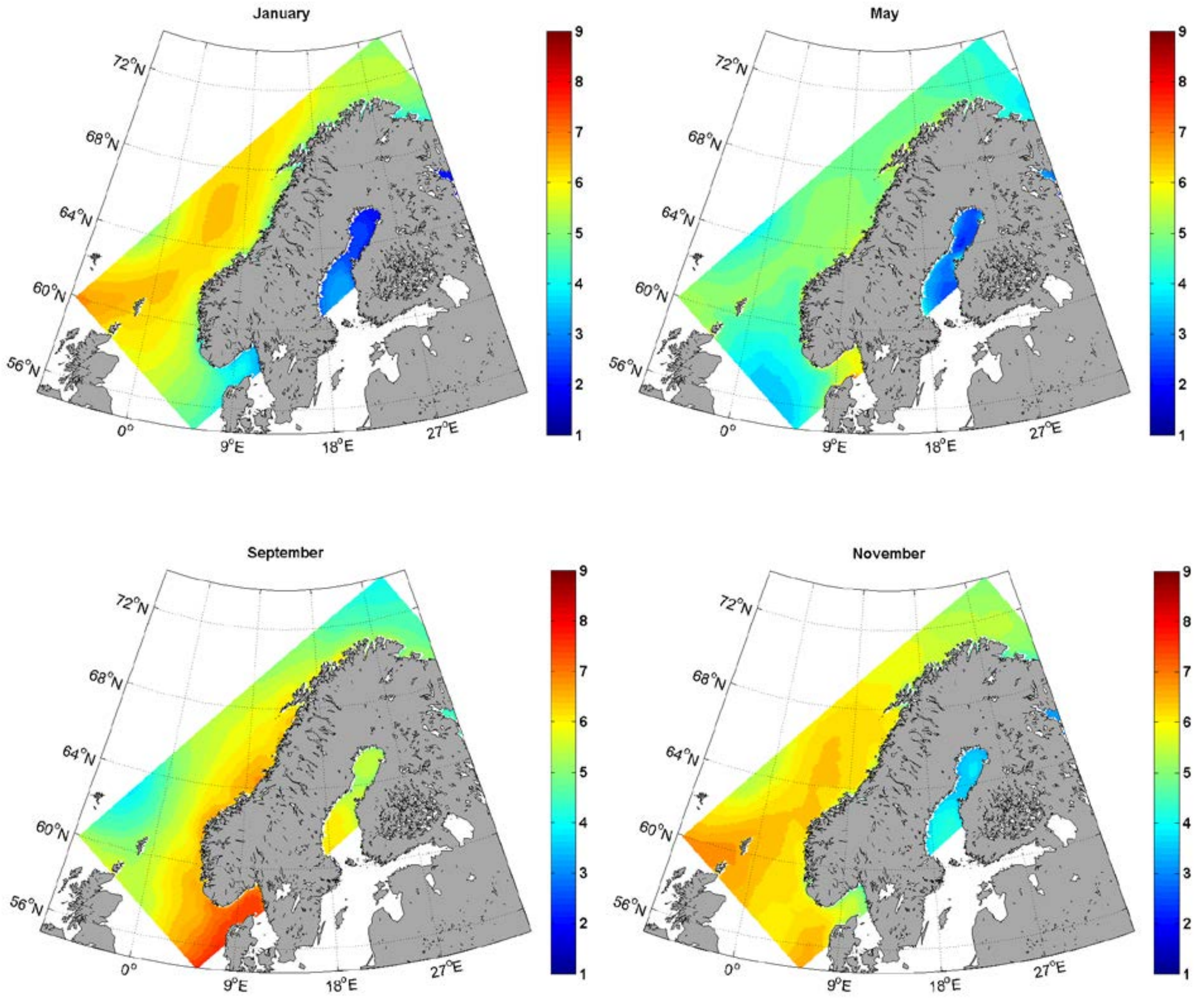

Figure 3 Median EDH in January (upper left), May (upper right), September (lower left) and November (lower right). Based on the period 1980–2015

The distribution in EDH is here represented by the difference between the 90th and 10th percentile and is presented in Figure 4. Overall, the distribution in EDH is larger in the south than in the north for all seasons. The least variation is found in January, with a maximum just above 6 meters in the southern part. Apart from areas close to the Norwegian coast, the greatest variation in EDH is found in September, where the variation lies in the interval from 6 to 9 meters. The large variations along the Norwegian coast found in May and September can be as much as 22 meters. The highly variable EDHs along the coast may be explained by a higher occurrence of stable situations for which NAVSLaM produces high EDHs. Such stable conditions are more prominent in the spring and summer season.

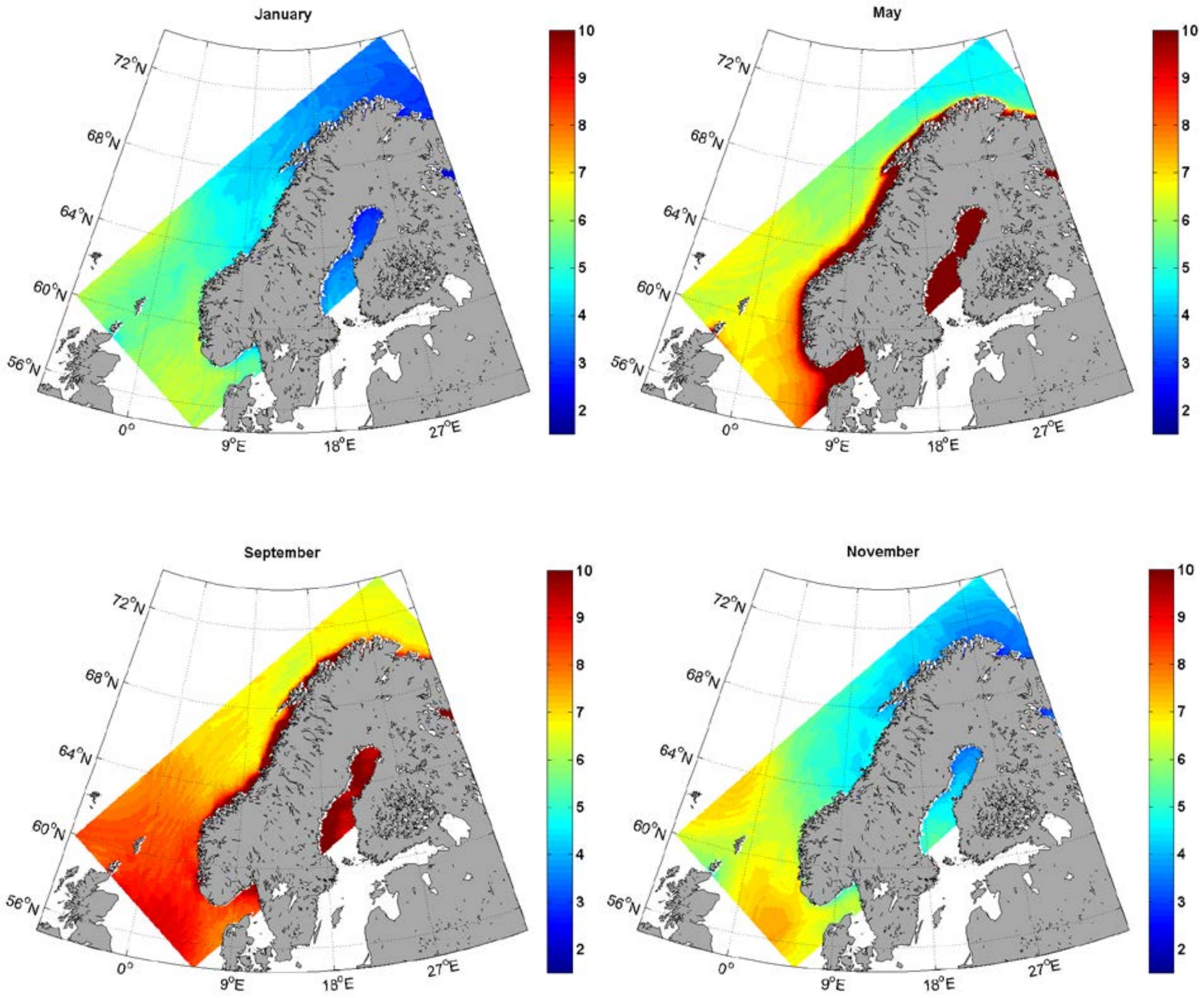

Figure 4 Difference between 90th and 10th percentile in January, May, September and November. Based on the period 1980–2015

The climatology that we have developed gives the opportunity to estimate the seasonal distribution of radar detection ranges for a given target within the model domain. The Advanced Propagation Model (APM) [11] is used to calculate propagation loss (PL) for a selection of M-profiles. APM is run with one single M-profile at the time together with the input parameters given in Table 1. We have chosen a PL of 140 dB as our target detection threshold. Figure 5 shows the distance distribution for when PL is 140 dB at 4 meter height for M-profiles at two selected locations in January and September. The locations are selected to represent open ocean (Figure 5 A and B) and near-shore (Figure 5 C and D) environments. Comparing Figure 5 A with B, we see that the difference in predicted detection range between January and September is small at the open ocean location. When comparing Figure 5 C with D, we see that the difference in predicted detection range varies significantly between January and September for the near-shore location. The most frequent ranges are 21 km (A: open ocean, January), 19 km (B: open ocean, September), 18 km (C: near-shore, January) and 19 km (D: near-shore, September). The standard deviations for the same four examples are 3.6, 4.6, 2.6 and 7.9, respectively. This may seem like a small variation, but a change of a few kilometers in detection range could for example be a deciding factor when defending against an incoming missile. Figure 5 emphasizes the importance of using a climatology which includes the variations of the EDHs and M-profiles.

Table 1 Radar parameters used in APM calculations

Radar parameter	Frequency (MHz)	Antenna height (m)	Antenna type	Polarization	Beam width (deg)	Antenna elevation (deg)
Value	9410	10	Gaussian	Horizontal	1.3	0

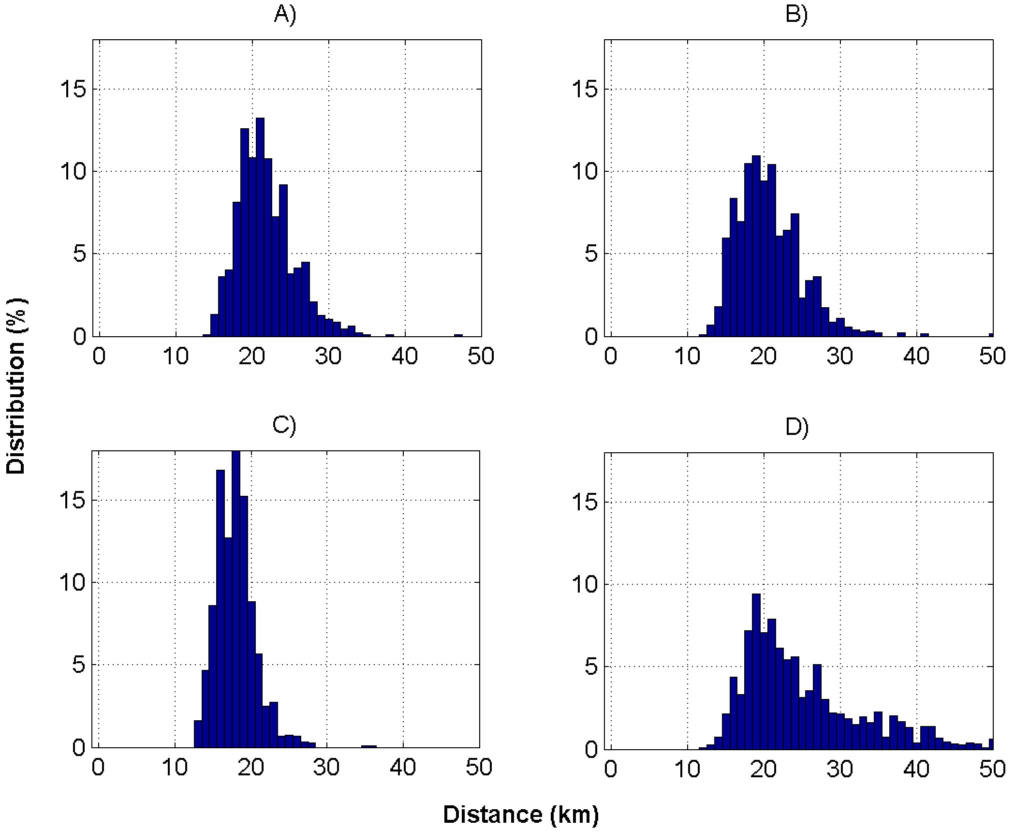

Figure 5 Distance to when propagation loss is 140 dB at 4 meter height at position 65.62 N 5.75 E (panel A and B) and 57.74 N 8.73 E (panel C and D) in January (panel A and C) and September (panel B and D).

4.0 CONCLUSIONS

We have developed climatology of monthly medians and distributions of evaporation duct height (EDH) and M-profiles, as well as monthly occurrences of negative air-sea temperature differences (ASTD), using hindcast data from the Numerical Weather Prediction Model HiRLAM and the evaporation duct bulk model NAVSLaM version 1.1. The climatology we have developed can be used for input to tactical decision aids (TDAs) for evaluating radio frequency (RF) propagation in Norwegian waters. Our results show that the ASTD is mainly negative in all Norwegian waters, indicating unstable atmospheric conditions, during the winter months of November and January. This indicates that the current bulk models based on Monin-Obukhov similarity theory (MOST) can successfully be applied in Norwegian waters during these months. The models however are less reliable in the months of April to July, and should be used with caution since ASTD is only negative for 40–60 % of the time near the Norwegian coast. The lowest median EDH is found in late spring/early summer (May), with heights mostly around 4–5 meters, while the highest median EDH is seen in September, with a median of 7–8 meter in the south-eastern part of Norway. The distribution of EDH varies significantly throughout the year, and is larger in the south than in the north of Norway. The least variation is seen in January with a maximum just above 6 meters, and the greatest variations – up to as much as 22 meters – are seen along the Norwegian coast in May and September. Due to the variations seen in EDH, we also see variations of several kilometres in predicted radar detection ranges from month to month and within a month. Thus, using a climatology which includes the variations of EDHs and M-profiles is important when assessing radar performance.

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