How grid-spacing and convection representation affected the wind speed forecasts of four polar lows

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Abstract
The horizontal resolution in numerical weather prediction models can have a large impact on the quality of polar low forecasts. However, there are few studies on the effect of the horizontal grid spacings which are currently in operational use at the European Centre for Medium-Range Weather Forecasts (ECMWF). Here, we evaluate the 10 m wind speed forecasts for four polar lows in November and December 2016 against remote and in situ observations. We study the 18 km grid spacing, used in the ensemble, 9 km for the current operational deterministic model runs, and 5 km for the planned future deterministic runs. The 9 and 5 km versions fall within the range of grid spacings that resolve convection partly but not fully. Therefore, we also do sensitivity tests with and without deep convection parametrization. Finally, we examine the added value from the operational limited-area model AROME-Arctic with 2.5 km grid spacing. The 18 km version performed worst in magnitude of wind speed, but it did forecast the locations of the polar lows as well as the other models. Thus, the ensemble can be used for polar low probability products. The 5 and 9 km versions with parametrized convection were the best-performing models over the ocean, while AROME-Arctic was the best model along the coast and over land. The 5 and 9 km versions with resolved deep convection produced fewer but larger convective cells with patches of both under- and overestimation of wind speed. The fact that there was almost no difference between the 9 and 5 km grid spacing, but a clear impact from the handling of convection, suggests that, to improve polar low forecasts in the ECMWF deterministic runs, special attention to convection is needed.

KEYWORDS
Arctic, AROME, convection, ECMWF, polar lows, verification, wind speed

1 INTRODUCTION

Polar lows – short-lived mesoscale cyclones that form over ice-free parts of the polar oceans during cold-air outbreaks (Rasmussen and Turner, 2003) – can cause strong, gusty winds and heavy snow showers that lead to hazards like turbulence for aircraft, high waves for ships, icing on ships, aircraft and offshore installations, low visibility,
and increased avalanche risk. Historical records indicate that polar lows have taken countless lives along the Norwegian coast, due to their hazardous nature and sudden appearance. Even though the availability of satellite imagery and gradually improving models have led to vastly more accurate and reliable polar low forecasts in recent decades, risks associated with polar lows still exist and there is still a strong need to further improve the forecasting capabilities of such events (Jung et al., 2016). This paper presents a study of the effect of horizontal resolution and parametrization of convective processes on 10 m wind speed during four recent polar lows in the Nordic and Barents Seas region.

To forecast polar lows operationally, the Norwegian Meteorological Institute (MET Norway) utilises the limited-area model AROME-Arctic (Müller et al., 2017b; Køltzow et al., 2019) for short-range time-scales, and the deterministic High RESolution (HRES) and ensemble forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF) for medium-range time-scales. Polar low forecasting in the Arctic poses several challenges. The sparse observation network in the area makes model initialisation uncertain. In addition, the proximity to sea ice and often shallow planetary boundary layers (PBLs) also make it difficult to correctly simulate the formation and propagation of polar lows (Valkonen et al., 2008; Vihma et al., 2014; Jung et al., 2016). The small spatial scales (Furevik et al., 2015; Jung et al., 2016) and rapid developments (Furevik et al., 2015; Jung et al., 2016) of polar lows also challenge both forecasters and the models that they use.

Historically, global models have had resolutions which are too coarse to represent polar lows explicitly (Mallet et al., 2013; Zappa et al., 2014). Instead, forecasters would identify large-scale situations that increased the risk of polar lows, rather than the polar lows themselves (e.g., Kolstad, 2011; Mallet et al., 2013; Zappa et al., 2014). As the horizontal resolution of models has improved, the ability to explicitly resolve polar lows has also increased. However, with a model grid spacing that is small enough to partly resolve convection, it poses the challenge of whether to still use a parametrization of deep convection or let the model resolve deep convection explicitly. This conundrum is often referred to as the ‘grey-zone’ problem (e.g., Clark et al., 2016, gives an excellent review).

In this grey zone, the ideal convection parametrization would be aware of the horizontal grid spacing so that it could correctly distinguish between the convective scales that are resolved dynamically and those that need to be parametrized (Field et al., 2017). However, most existing convection parametrization schemes are not formulated in this way. Rather, they are simply turned off for the finer resolutions. When the parametrization is on, other issues appear, such as interaction with other parametrization schemes (Tomassini et al., 2017) and rapid error growth with lead time (Judt, 2018; Malardel and Bechtold, 2019). To understand the effects of these issues, several studies have been performed. Field et al. (2017) compared a number of operational numerical weather prediction (NWP) models with grid spacings of 1 to 16 km and convection parametrization turned on and off for a cold-air outbreak case-study. They found that there was a larger spread between models with parametrized convection, while models with explicit convection agreed better with each other. McInnes et al. (2011) studied how the horizontal resolution affected the forecast quality for two polar low cases. For the first case (also studied by Wagner et al., 2011), which had stronger baroclinicity, the forecasts became significantly better with finer grid spacing, while for the second case, which had weaker baroclinicity and a stronger convective character, all the forecasts failed for all the grid spacings they tested.

The aim of this study is to better understand the ability of global models like ECMWF HRES to simulate polar lows, and what added value high-resolution limited-area models like AROME-Arctic may provide relative to those global models. We perform three sensitivity experiments with the ECMWF HRES model and compare the 10 m wind speed to the wind speed in operational models as well as to in situ and remotely sensed observations. We focus on two episodes with two polar lows each in November and December 2016, and the area of interest can be seen in Figure 1. In the sensitivity experiments, we change the horizontal grid spacing and turn off deep convection parametrization so that deep convection gets explicitly resolved by the model dynamics. We then compare the model 10 m wind speeds to in situ meteorological measurements along the Norwegian coast, and satellite scatterometer observations over open ocean. To examine the structure of convective cells, we also compare the results to synthetic-aperture radar (SAR) images. This provides insights into the strengths and weaknesses of the models in polar low situations, which will be useful both for NWP users who need to know how to interpret the forecasts, and to model developers who aim to improve performance during polar lows.

## METHODS AND DATA

### 2.1 Polar low cases

We selected two dates, 27 November 2016 and 8 December 2016, both of which featured multiple polar lows. One of the lows affected the coast of northern Norway, and the other spent most of its life-span over the Barents Sea. At
first glance, both cases are quite similar, but the November cases were dominated by barotropic forces and resided in the cold air on the polar side of the jet stream, while the December cases were dominated by baroclinicity and propagated along the jet stream in a strong baroclinic zone. By including two different types of polar low that occurred in the same area, we investigate if there are differences in the models’ ability to represent different types of polar-low dynamics. Table 1 shows the diagnostic radius (Section 2.3) and the model initialisation times for the cases. The cases that made landfall on the coast of northern Norway are denoted by L, while the cases that did not make landfall are denoted by NL.

2.1.1 | Barotropic cases: 27 November 2016

On 26 and 27 November 2016, northeasterly cold air was flowing out from ice-covered areas over the Barents Sea (Figure 2), and the model indicates that a trough was present at 500 hPa. This situation was associated with an unstable lower atmosphere with mostly unorganised convective cells. Early in the morning of 27 November, an organised surface trough formed. Later in the same morning, the trough split up into three distinct low centres which developed into polar lows. These were located well inside the cold air masses, and while there was some weak baroclinicity present, they were mostly barotropically driven. Two of the polar lows had a clear eye in the middle of a circular cloud structure. These are included in this study. Figure 3a,b show the tracks and the diagnostic radii for these two lows plotted on top of a composite image representing the wind speed from ECMWF HRES and AROME-Arctic.

The November L polar low was the westernmost of the two lows. It started to develop as convective clusters east of Svalbard. As the upper trough rotated around its centre over the Barents Sea, the western flank moved south and advected the polar low with it, sweeping past the Norwegian coast. It was the weakest polar low in this study, but it is included because it made landfall, which enables the use of coastal observations for verification.
### TABLE 1  Overview of polar low cases from two dates during November and December 2016

| Polar low case | First observed          | Model initialisation time | Radius (km) |
|---------------|-------------------------|---------------------------|-------------|
| November L    | 1300 UTC, 27 November 2016 | 0000 UTC, 27 November 2016 | 60          |
| November NL   | 0700 UTC, 27 November 2016 | 0000 UTC, 27 November 2016 | 250         |
| December L    | 1100 UTC, 8 December 2016 | 0000 UTC, 8 December 2016  | 250         |
| December NL   | 0500 UTC, 8 December 2016 | 0000 UTC, 8 December 2016  | 125         |

*Note: NL polar lows did not make landfall, but dissipated in the Barents Sea. L polar lows made landfall on the Norwegian coast.*

![Synoptic overview of polar lows](image)

**FIGURE 2**  A synoptic overview of the barotropic November polar low cases at 0500 and 1500 UTC. The red dots marked “PL” show the location of the polar low pressure centres. (a, b) show NOAA infrared satellite pictures and AROME-Arctic mean sea level pressure (blue contours). (c, d) show mean sea level pressure (black contours) and 1,000–500 hPa thickness (blue shading). Both are derived from AROME-Arctic. The square in (a) shows the approximate area covered by Figure 9a.

On the other hand, the November NL case had the deepest polar low centre on this day. It developed close to the centre of the upper-level trough and kept rotating with the upper-level air in the eastern parts of the Barents Sea, just inside the AROME-Arctic domain. When the upper-level trough weakened, the polar low dissolved into disorganised convective clouds and showers. This polar low did not make landfall, but its remnants, now as disorganised showers, reached the southern tip of Novaya Zemlya.

#### 2.1.2 Baroclinic cases: 8 December 2016

On 8 December 2016, a strong baroclinic zone stretched southeastward from the Fram Strait to the southern part of the Barents Sea (Figure 4). Both polar lows on this day propagated along this zone. They were stirred by the jet stream and exited the jet stream to the left, into the cold air on the northern side. The baroclinicity was strong. Figures 3c,d provide an overview of their tracks, diagnostic radii and simulated wind speed.
**FIGURE 3** Maximum 10 m wind speed (m·s$^{-1}$) in each grid box during the time period when the polar lows were active. The lines show the tracks of the polar lows, and the circles show the storm-following circular regions used in the analysis. (a) shows AROME-Arctic (AA) during the November polar low case, (b) shows the ECMWF deterministic model with 9 km horizontal grid spacing (EC9) for the November case, (c) AA for the December case and (d) EC9 for the December case.

**FIGURE 4** As Figure 2, but for the baroclinic polar low cases in December at 0800 and 1800 UTC. The square in (b) shows the approximate area covered by Figure 10b.
TABLE 2 Overview of model experiments

| Experiment | Model       | Grid spacing | Grid                  | Description               | Hydrostatic? |
|------------|-------------|--------------|-----------------------|---------------------------|--------------|
| EC18       | ECMWF       | 18 km        | Spectral, TCo639      | Ensemble control run      | Yes          |
| EC9        | ECMWF       | 9 km         | Spectral, TCo1279     | Operational               | Yes          |
| EC9N       | ECMWF       | 9 km         | Spectral, TCo1279     | No deep convection        | Yes          |
| EC5        | ECMWF       | 5 km         | Spectral, TCo1999     | Smaller grid box size     | Yes          |
| EC5N       | ECMWF       | 5 km         | Spectral, TCo1999     | 5 km, no deep convection  | Yes          |
| AA         | AROME-Arctic| 2.5 km       | Arakawa-A             | Operational               | No           |

Note: The first five experiments are different model set-ups from the European Centre for Medium-Range Weather Forecasts (ECMWF). The last experiment is the operational limited-area model for short-range forecasts in the geographical region of the polar low cases.

The December L case was one of the 5% strongest polar lows recorded since 2000 and is described in more detail by Müller et al. (2017a). The observed wind speed at landfall was 25–30 m s\(^{-1}\).

The weaker sibling of December L, December NL, passed along the coast of northeastern Norway and the Kola Peninsula before it continued eastward further into the Barents Sea, where it dissolved outside the AROME-Arctic domain.

2.2 Model experiments

Table 2 shows a summary of the NWP models and the experiments that we performed. EC18, EC9 and AA are all in operational use by MET Norway.

The ECMWF operational global forecasts are produced with the ECMWF Integrated Forecasting System (IFS), described in detail by ECMWF (2018). The current operational grid spacing for the ECMWF high-resolution, deterministic forecast (HRES) is approximately 9 km (TCo1279) in the horizontal, and with 137 vertical levels reaching up to 0.01 hPa (approximately 80 km). All forecasts used in this comparison are coupled to the NEMO (Nucleus for European Modelling of the Ocean; Madec 2008) ocean model with 0.25° resolution. The ocean coupling is described in Mogensen et al. (2017) and references therein.

The initial conditions are created separately for the atmosphere and the ocean. The atmospheric initial conditions are produced with a four-dimensional variational data assimilation (4D-Var; Rabier et al., 2000) and background-error statistics generated by an ensemble of 4D-Var assimilations (EDA; Bonavita et al., 2012). The oceanic initial conditions are provided by the ECMWF OCEAN5 operational three-dimensional variational data assimilation system (Zuo et al., 2018). The cloud and large-scale precipitation scheme is based on Tiedtke (1993), but has been substantially upgraded with separate prognostic variables for cloud water, cloud ice, rain, snow and cloud fraction, and improved parametrization of microphysical processes (Forbes and Ahlgrimm, 2014). The parametrization of convection is based on the bulk mass-flux approach (Tiedtke, 1993; Bechtold et al., 2008), with a modified CAPE closure leading to an improved diurnal cycle of convection (Bechtold et al., 2014). The momentum transport by convective downdraughts are included in the parametrization scheme (recently discussed in Malardel and Bechtold, 2019) and the resulting gustiness is contributing to the model wind gusts ECMWF (2016). The scheme includes a scaling factor dependent on the horizontal resolution (Malardel and Bechtold, 2019), which scales the convective mass flux for a 5 km grid to about 65% of the non-scaled flux. The convection scheme separately considers shallow, mid-level and deep convection, with an experimental option to switch off the deep convection part.

Ensemble forecasts are run with the aim of estimating the range of possible future states (e.g., Leutbecher and Palmer, 2008). At ECMWF, the ensemble consists of 50 perturbed forecasts and one unperturbed member with a grid spacing of 18 km (TCo639) and 91 vertical levels.

In this study the ECMWF simulations are mainly based on model cycle 45r1. In addition to the operational configuration (hereafter referred to as EC9), we also performed simulations with a higher horizontal grid spacing of 5 km (TCo1999), which will be referred to as EC5. To test the impact of the deep-convection parametrization scheme, we turned it off for both 9 km (EC9N) and 5 km (EC5N) grid spacing. In this comparison we also use the operationally produced unperturbed control forecast (EC18). These experiments produced output every third hour.

AROME is a limited-area model that was developed for the Mediterranean area by Météo-France, and is further described in Seity et al. (2011). HARMONIE-AROME is a version of this model which is in operational use by Denmark, Estonia, Finland, Iceland, Ireland, Lithuania, the Netherlands, Norway, Spain, and Sweden (Bengtssson et al., 2017). AROME-Arctic (referred to here as AA), is a set-up...
of HARMONIE-AROME with the Arctic domain shown as a black rectangle in Figure 1. This is MET Norway’s model for forecasts in the maritime Arctic (Müller et al., 2017b; Køltzow et al., 2019).

AA has a horizontal grid spacing of 2.5 km and 65 vertical levels, with the highest one at 0.9 hPa. Deep convection is resolved dynamically, while shallow convection is parametrized with the EDMFms scheme (Bengtsson et al., 2017). The dynamical core is non-hydrostatic, and it uses the three-dimensional variational data assimilation from Brousseau et al. (2011). The boundary conditions are taken from ECMWF HRES. Sea surface temperature is fixed and retrieved from the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA; Donlon et al., 2012).

This study uses 3-hourly AA forecasts from the operational archive (https://thredds.met.no/; accessed 22 September 2020).

2.2.1 Remote-sensing observations

Over the open seas in the Arctic region, there are few in situ observations available. There are sporadic buoy and ship measurements, as well as the observations taken at the islands of Bjørnøya, Hopen and Jan Mayen, and the offshore platform Goliat, but to obtain the spatial and temporal coverage required for the type of studies we are doing here, remote-sensing observations are crucial. To evaluate the magnitude of the wind speed over open ocean, we use a wind product from the Advanced SCATterometer (ASCAT) instrument on the polar-orbiting Metop-A and Metop-B satellites. The data were retrieved from the ECMWF’s MARS archive. To ensure that the observations are independent of each other, ECMWF assimilates only 25% of the scatterometer data. In this study however, all available observations are used, not just those that were selected for assimilation into the model. The scatterometer wind speed in this archive is derived from backscatter measurements using a Geophysical Model Function as described in De Chiara et al. (2017). The horizontal grid spacing of the wind product is 25 km, the accuracy is better than 2 m s\(^{-1}\), and the bias is less than 0.5 m s\(^{-1}\) (EUMETSAT OSI SAF, 2019).

While ASCAT observations enable us to evaluate the magnitude of the wind speed, their footprint, or horizontal resolution, is too coarse to examine details in the wind pattern on the ocean surface. For this purpose, we used Synthetic Aperture Radar (SAR) data retrieved from https://satwinds.windenergy.dtu.dk/ (accessed 22 September 2020). For some elevations and view angles of the SAR satellite, the part of the image that was closest to the satellite got disproportionately strong signals compared to the part that was furthest away. When this effect is strong, it obscures the surface pattern in the image. To remove this kind of effect, we divided each row of pixels in the image with the mean value of that row.

2.3 Diagnostic methods

We evaluated the temporal development of the polar lows by following their minimum sea level pressure at each time step. At each time step we also identified the maximum wind speed within a certain radius. The radius was chosen subjectively to make sure that it was large enough to include the maximum wind speed associated with the polar low, but not too large that it might include strong wind speeds associated with other features such as the background flow, another polar low or a synoptic low. Due to the different extents of the four polar low cases, different radii were chosen for each of them (Table 1 and Figure 3).

3 RESULTS

3.1 Polar low tracks

Figure 5 shows the tracks of the simulated polar lows in all the experiments, together with manually compiled observed tracks from satellite images (black). For the November southern polar low (Figure 5a), most of the experiments are in agreement with each other, but the tracks are all located too far to the south compared to the observed track. For the November northerly polar low, the EC experiments agree well with each other, while the AA forecast is located further to the north. However, none of them captured the observed track, which is further west. For the December polar lows, Figure 5b shows that all the experiments created similar tracks which are in good agreement with the observed track.

Figure 3 shows the simulated maximum wind speed during the life-span of the polar lows (24 hr for the November case and 30 hr for the December case), for (a, c) AA and (b, d) EC9. In both cases, AA produced considerably stronger maximum winds than EC9 in most of the model domain, and in particular along the storm tracks. The bands of high wind speed northwest of the polar low tracks in Figure 3a are areas of strong convection but without the cyclonic characteristics of polar lows. The smaller area with higher wind speed southeast of Svalbard in Figure 3c was created by a weaker mesoscale cyclone.
FIGURE 5 Tracks for the the low pressure centres for the (a) November and (b) December polar low cases. Observations are estimated from infrared satellite images and the operational model analyses. The remaining tracks are derived from the model experiments: AROME-Arctic (AA), ECMWF model version with 5 km grid spacing and explicit deep convection (EC5N), ECMWF with 5 km grid spacing and parametrized deep convection (EC5), ECMWF with 9 km grid spacing and explicit deep convection (EC9N), and ECMWF with 18 km grid spacing and parametrized deep convection (EC18)

3.2 Wind speed comparisons with scatterometer data

Figure 6 shows wind speed comparisons between ASCAT and three of the model runs for the November case. Although ASCAT wind speeds are derived from satellite data and are not in situ observations, ASCAT provides a reference that the models’ wind speeds can be evaluated against. The structures of the ASCAT wind speed in Figure 6a reveal that both the polar low in the eastern part of the Barents Sea and the trough further west produced high wind speeds in areas with strong convection (cf. the satellite images in Figure 2a,b). Figures 6b–d show the difference in wind speed between ASCAT and three of the model experiments. Several ‘dipole’-like features are seen. For instance, in the Greenland Sea west of Svalbard, an area of overestimated wind speed occurs just southeast of an area of strong underestimation. An area of overestimation occurs east of the small island Bjørnøya. Between this area and the track of the polar low in the Barents Sea (green line) is an area of underestimation, while there is an overestimation of wind speed just around the polar low track, and then underestimation east of that again. Figure 5a and a comparison between Figures 6a and 3a,b reveals that this is due to a displacement of the polar low and the areas of strongest wind speed (and convection) in the model experiments. The pattern is most pronounced in AA (Figure 6b) and least pronounced in EC9 (Figure 6c). EC5N (Figure 6d) produced a slightly noisier picture with the overall magnitude of error between EC9 and AA. EC5 produced a very similar pattern to EC9, and EC9N similar to that of EC5N (not shown). EC18 (not shown) was also similar to EC9, but with a slightly lower magnitude of the errors.

The ASCAT wind speeds during the life-span of the December cases are shown in Figure 7a. For all the experiments, the error is smaller in areas that were more affected by baroclinicity (cf. Figure 4). In those areas, AA has patches of both under- and overestimation, while EC9 mostly underestimates the wind. This underestimation is stronger in EC5N. An exception to this occurs in the Barents Sea west of Novaya Zemlya and north of the easternmost polar low track (purple line). Here Figure 4 shows that the conditions were more convective, and the area was well inside the cold air mass for a longer part of the time period in consideration. We see how all the model experiments have patches of overestimated wind speed in this area. The error is largest in AA and smallest in EC9. As in the previous case, EC5 and EC18 produced results that were similar to EC9, and EC9N was similar to EC5N (not shown), while EC18 was similar to EC9 but with slightly smaller magnitude of the errors.

In summary, Figures 6 and 7 indicate that the EC5 and EC9 experiments has the lowest overall error with respect to ASCAT observations. This is confirmed by the mean absolute error over the full datasets (Table 3). For the November cases, this measure was 2.08 m s⁻¹ for AA, 1.45 m s⁻¹ for EC9 and 1.49 m s⁻¹ for EC5N. For the December cases, the corresponding numbers were 1.93 m s⁻¹ for AA, 1.59 m s⁻¹ for EC9 and 1.65 m s⁻¹ for EC5N. Since EC5N and EC9 had both positive and negative errors, they cancelled out so that the mean error for these experiments were smaller than for EC5 and EC9, however, the mean absolute error (MAE) is larger. The EC18
(a) ASCAT (m/s)

(b) AA - ASCAT (m/s)

(c) EC9 - ASCAT (m/s)

(d) ECSN - ASCAT (m/s)

**FIGURE 6** (a) shows scatterometer wind speed (m·s$^{-1}$) from all available satellite passages during the time period when one or both of the November polar low cases were active. The data were filtered to include only observations that occurred within 60 min windows centred at the times when model output was available. Where data points overlap, the points with the highest wind speed are plotted on top. (b–d) show the differences (m·s$^{-1}$) between ASCAT wind speed and the wind speed from the nearest grid point in the model for (b) AROME-Arctic (AA), (c) ECMWF with 9 km grid-spacing and parametrized deep convection (EC9), and (d) ECMWF with 5 km grid-spacing and explicit deep convection (EC5N). The purple and green lines show the tracks of the polar low pressure centres.

**FIGURE 7** As Figure 6, but for the December L and December NL cases.
### Table 3

Mean error, Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) from a comparison of ASCAT-derived wind speed over ocean and the nearest grid point from model experiments.

| Experiment | 27 November 2016 | 8 December 2016 |
|------------|------------------|-----------------|
|            | Mean error | MAE    | RMSE | Mean error | MAE    | RMSE |
| EC18       | −0.97       | 1.47    | 2.04 | −0.96       | 1.64    | 2.12 |
| EC9        | −0.91       | 1.45    | 2.03 | −0.80       | 1.60    | 2.05 |
| EC9N       | −0.80       | 1.57    | 2.20 | −0.67       | 1.68    | 2.21 |
| EC5        | −0.91       | 1.44    | 2.02 | −0.81       | 1.60    | 2.07 |
| EC5N       | −0.83       | 1.49    | 2.11 | −0.69       | 1.65    | 2.15 |
| AA         | −0.88       | 2.08    | 3.01 | −0.69       | 1.93    | 2.12 |

**Note:** Duration of the comparison-period is 24 hr for the November case and 30 hr for the December case. Values are given in m·s⁻¹. Lowest and highest values in each column are in bold.

### Table 4

Summary statistics from a comparison of 10 m wind speed between coastal in situ observations and the model experiments during the November L polar low case.

| Experiment | Mean | Max | 95th percentile | Mean error | RMSE | N |
|------------|------|-----|-----------------|------------|------|---|
| Obs        | 9.0  | 19.0| 16.0            | —          | —    | 28|
| EC18       | 7.9  | 15.3| 13.8            | −1.1       | 2.2  | 28|
| EC9        | 7.3  | 14.5| 13.0            | −1.7       | 2.6  | 28|
| EC9N       | 7.8  | 13.9| 13.4            | −1.2       | 3.0  | 28|
| EC5        | 6.9  | 15.0| 13.4            | −2.1       | 2.9  | 28|
| EC5N       | 7.7  | 17.4| 14.0            | −1.3       | 2.9  | 28|
| AA         | 9.0  | 15.7| 14.1            | 0.0        | 2.8  | 28|

**Note:** This summary includes the four stations with reliable data that were affected by the polar low that swept past the coast of Finnmark on 27 November 2016. The polar low affected the coastal areas over a period of 18 hr. Values are given in m·s⁻¹, and the column N shows the total number of observations from all stations. Lowest and highest values in each column are in bold.

Experiments also had low mean absolute errors (1.47 m·s⁻¹ for the November case and 1.64 for the December case), but the mean error shows that it underestimated the wind speed more than the other models.

#### 3.3 Wind speed comparisons with coastal observations

The statistics in Tables 4 and 5 include all the Norwegian stations that are part of the World Meteorological Organization’s observation network and were affected by the polar lows. Most of the stations sample every hour, but to align the data with the sampling frequency of the ECMWF experiments, we include only every third hour in this study. One difficulty when comparing models with different resolutions against in situ stations, is that the land–sea mask and representation of topography can differ between the models. This is especially sensitive in coastal regions where the nearest grid point in one model can be handled as a land-point while being a sea-point in another model. There can also be local variations of wind speed in the area due to small-scale obstacles that the model cannot resolve, such as cliffs, creeks, etc. To partly circumvent this problem, we selected the closest land grid point instead of the closest grid point for all but five stations (see below). A model point is considered to be a land point if the value of the land–sea mask for the used resolution is above 0.5, which is in line with the handling in the model code. Note that the grid point still can include an inland water body. The exceptions from these selections are three stations situated at lighthouses on small islands where the closest land grid point was more than 50 km away from the station, and two stations that were situated right at the shoreline. During the entire time period in this study, these stations experienced onshore winds and the observed winds can be assumed to have a footprint from the sea. However, even if using grid points of the same surface type reduces the differences in surface properties between the experiments, there will still be differences in
Table 5 shows the results for the November case. Each station and time step gave a data pair with the observation and model output, but as the southernmost of the two November polar lows (the only one that had an impact on the coast) was small, only 28 observations were affected by the low and will be used here. The mean wind speed is lower in all the ECMWF models than in the observations. AA is closer to the observations than the ECMWF models. The EC5N experiment gives better results than EC5, and EC9N performs better than EC9. This is also the case for the 95th percentile and the mean error, but the RMSE is somewhat lower for EC9 than for EC9N while it is similar for EC5 and EC5N. The mean and 95th percentile show that the maximum value of 17.4 m s⁻¹ for EC5N is an outlier.

The results for the December case are shown in Table 5. As this polar low was larger than the polar low in November, a total of 119 observations could be used for this case. The 95th percentile of all these 119 values is shown in the third column. The mean observed wind speed (i.e., averaged over all the 119 samples) is substantially higher (at 11.8 m s⁻¹) than the simulations. AA (at 10.2 m s⁻¹) is closer to the observations than any of the EC models. The second best performing model is EC18 (8.5 m s⁻¹). We note that EC9N has higher mean wind speeds than EC9, and EC5N produces stronger winds than EC5. The highest overall observed wind speed is 30 m s⁻¹. All the models underestimate the wind speed; the highest simulated wind speeds range from EC18 (19.5 m s⁻¹) to AA (25.0 m s⁻¹). The 95th percentile is a more robust metric than the maximum, but the same discrepancy between observed and simulated wind speed is evident. The 95th percentile of the observed wind speeds is 21 m s⁻¹. AA performs best with 17 m s⁻¹. The 95th percentile for the ECMWF models ranges from 15.4 to 20.7 m s⁻¹. The mean error and the RMSE for the December case corroborate what the other metrics conveyed, namely that AA performs best.

### 3.4 Maximum wind speeds

Figure 8 presents a summary of the maximum wind speed near the polar low centres in all the experiments. Each dot represents the maximum wind speed within the diagnostic circles (Table 2) following the storms at each time step. The general picture is that AA produces the highest maximum wind speeds, and EC18 the lowest. There are small differences between EC9 and EC5, but both models with deep convection switched off – EC9N and EC5N – give higher wind speeds than their standard counterparts, EC9 and EC5. Sadly, only three time steps among all four polar lows had enough ASCAT coverage within their diagnostic circles to produce a comparable measure from satellite data. Therefore, ASCAT is not included in Figure 8.

### 3.5 Comparisons with SAR images

While ASCAT provides a good estimate of surface wind speed, its horizontal resolution is too coarse for an accurate analysis of spatial wind speed patterns. For this purpose, we use SAR backscatter. Since wind estimates from SAR are less reliable than ASCAT, this analysis will be of a more qualitative nature, where we study the structure of convective cells rather than wind speed and direction.

A SAR image and model data for the November case are shown in Figure 9. Bjørnøya is seen near the middle of the top part of each picture. The approximate area shown in Figure 9a is marked by a square in Figure 2a. The structures in the SAR image in (a) are due to downdraughts...
from convective precipitation as described in Alpers et al. (2016). While there are some small-scale structures in AA’s wind speed field (Figure 9b), it is clear that the model does not capture the wealth of convective cells apparent in the SAR image. Even less structure is seen in the standard ECMWF models in Figures 9c,e. However, the wavy shapes of the sea level pressure contours in AA, EC9 and EC5 do indicate a tendency to produce small-scale troughs. When deep convection parametrization is turned off in the ECMWF model, more small-scale features emerge, made clear by an increased waviness of the pressure contours and an increase in the number of localised wind speed maxima for both EC9N (Figure 9d) and EC5N (Figure 9f).

In Figure 10a, a SAR image of the December case is shown for a section of the Norwegian Sea. The island of Bjørnøya is seen in the top right corner of the panel, just outside the frame of the the SAR image. The approximate area shown in Figure 10a is marked by a square in Figure 4b. As described in section 3.1, the comma-like feature near Bjørnøya (upper black circle) is a small, convective mesoscale cyclone that originated east of Svalbard and moved southwards past Bjørnøya in the cold airflow behind the large polar low. It appears to be present in the form of a weak trough in AA (Figure 10b). In the standard ECMWF experiments EC9 and EC5, the feature is also weak and located too far to the north (Figures 10c,e, respectively). With convection switched off in EC9N (Figure 10d), the feature becomes stronger and more similar to the SAR images. In EC5N (Figure 10f), the small-scale closed low-pressure system is deeper than in EC9N.

The SAR image in Figure 10a also shows the presence of multiple small-scale convective cells in the cold air to
The wind speed patches and sea level pressure contours for AROME-Arctic (Figure 10b) suggest that the model produced some developments on this spatial scale. In EC9N (Figure 10d) and EC5N (Figure 10f), we see fewer but larger convective cells. AA, EC9N and EC5N all have a diagonal stripe of higher wind speed northwest of the patch that corresponds to the December L polar low in the lower right corner (lower black circle in (a)). This stripe is missing in the experiments with parametrized deep convection. As we do not have sea level pressure data derived from the SAR image, it is difficult to qualitatively assess which of the model runs performs best. However, it is clear that the lack of local structure seen in the standard ECMWF experiments (Figures 10c,e) is unrealistic.

4 | DISCUSSION AND CONCLUSIONS

We have compared the 10 m wind speed accuracy in two operational numerical weather prediction models during four polar lows in the Barents Sea. The two models are the global ECMWF model and the limited-area model AROME-Arctic. From ECMWF both the version with 18 km horizontal grid spacing (used in the ensemble) and the one with 9 km grid spacing (used for their deterministic HRES runs) are included. In addition to the operational forecasts, we also conducted three sensitivity tests with ECMWF by changing the horizontal grid spacing to 5 km, turning off the deep convection parametrization scheme and doing both at the same time. The aim of the
study is to tell how well ECMWF is able to represent polar lows, what added value AROME-Arctic gives, and how horizontal grid spacing and convection parametrization affects forecast quality in polar low situations.

The results show that all the model experiments were able to represent the polar lows, but with different accuracy. The ECMWF version with 18 km horizontal grid spacing (the coarsest grid in the study) underestimated the wind speed more than the other experiments. The ECMWF versions with 5 and 9 km grid spacing (which falls within the convective grey zone) performed equally well regardless of whether the deep convection was explicitly resolved or parametrized. However, there was a clear difference in performance between explicit and parametrized deep convection. Over the ocean, the 5 and 9 km ECMWF versions with parametrized deep convection produced the most accurate wind speed of all the experiments when compared to scatterometer wind speeds. The AROME-Arctic and the ECMWF experiments with explicit deep convection produced higher maximum wind speeds but had larger mean absolute errors. Over land, all the model experiments underestimated the wind speed when compared to coastal in situ observations, but AROME-Arctic was closer to the observed values. This is likely due to a better representation of topographic effects in AROME-Arctic. Thus, the added value of AROME-Arctic is highest in areas of complex topography, which is consistent with the findings of Køltzow et al. (2019).

The similar performance between the ECMWF versions with 5 and 9 km grid spacing is surprising for two reasons: other studies, such as McInnes et al. (2011), found that for their models, horizontal resolution had the largest impact on forecast quality; and in the 5 km ECMWF version, the effect of the deep convection parametrization is only 65% of that in the 9 km version. Therefore, we expected the experiments with 5 km grid spacing to be more similar to each other than the experiments with 9 km grid spacing. This raises the question of whether the effect of the deep convection parametrization should scale down even more in the 5 km version.

A possible explanation for the higher wind speeds in AROME-Arctic and the ECMWF experiments with explicit deep convection is that the convective cells are dynamically resolved instead of parametrized. With no convection parametrization scheme that “consumes” Convective Available Potential Energy (CAPE), the model has to handle the instability dynamically. It does this by creating convective cells at a scale that the model can resolve, which leads to fewer but larger and more intense cells, again leading to a higher vertical momentum flux.

While the domain-wide quality of the wind speed forecasts was degraded in the experiments without parametrized deep convection, a qualitative comparison with SAR images showed that the structure of the convective cells became more realistic. We did not find the same improvement in the structure in the experiments with increased resolution. The ECMWF versions with explicit deep convection were even better than the convection-resolving AROME-Arctic model, which is specifically set up for the Arctic. This new insight provides a motivation for scrutinising the way convection is handled in AROME-Arctic, to ensure that it is able to reproduce and forecast extreme winds at small spatial scales, which represents an important part of the risk for maritime activities in the Arctic (Kolstad, 2015).

We have seen that both the ECMWF global forecasting system and the limited-area model AROME-Arctic are able to represent polar lows. The 18 km version of ECMWF mostly underestimated the surface wind speed, but since it could still simulate the lows, it is possible to use the ensemble with 18 km grid spacing to create polar low probability products. The difference in performance between the 9 and 5 km versions of the ECMWF model was negligible, but there was a clear difference between resolved and parametrized deep convection. Over the ocean, parametrized deep convection produced the more accurate wind speed, while the versions with explicit deep convection produced more realistic structure of convective cells. This result suggests a larger sensitivity for wind extremes to the convection parametrization than the model resolution for models in the grid spacing range of 5–10 km. The implication is that special attention to the convection parametrization is needed while developing the ECMWF model in terms of scale-awareness and momentum transport.

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