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Medium-Range Forecast Skill for Extraordinary Arctic Cyclones in Summer of 2008–2016

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Key Points:
- The forecast skill for 10 extraordinary Arctic cyclones in summer of 2008–2016 is assessed by operational medium-range ensemble forecasts
- The operational ensemble systems generally predict the position of Arctic cyclones accurately at 2.5–4.5 days before the mature stage
- The average forecast skill for the Arctic cyclones is lower than that for midlatitude cyclones in the Northern Hemisphere

Supporting Information:
- Supporting Information S1

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Abstract Arctic cyclones (ACs) are a severe atmospheric phenomenon that affects the Arctic environment. This study assesses the forecast skill of five leading operational medium-range ensemble forecasts for 10 extraordinary ACs that occurred in summer during 2008–2016. Average existence probability of the predicted ACs was >0.9 at lead times of ≤ 3.5 days. Average central position error of the predicted ACs was less than half of the mean radius of the 10 ACs (469.1 km) at lead times of 2.5–4.5 days. Average central pressure error of the predicted ACs was 5.5–10.7 hPa at such lead times. Therefore, the operational ensemble prediction systems generally predict the position of ACs within 469.1 km 2.5–4.5 days before they mature. The forecast skill for the extraordinary ACs is lower than that for midlatitude cyclones in the Northern Hemisphere but similar to that in the Southern Hemisphere.

Plain Language Summary The shipping on the Northern Sea Route has become more accessible due to the recent sea ice loss. Meanwhile, such human activity over the Arctic is exposed to risks of severe atmospheric phenomena, including Arctic cyclones (ACs). As the AC frequency reaches its peak in summer and ACs can affect the Arctic environments like sea ice and wave height, the planning of ship routes requires an accurate prediction of extraordinary ACs, particularly their positions. This study assesses the forecast skill of operational medium-range ensemble forecasts for 10 extraordinary ACs that occurred in the recent decade. The results show that average central position error of the predicted ACs is less than half of the mean radius of the 10 ACs 2.5–4.5 days before their mature stage, with a central pressure error of 5.5–10.7 hPa. The forecast skill for the extraordinary ACs is lower than that for midlatitude cyclones in the Northern Hemisphere but similar to that in the Southern Hemisphere. These results are useful for using and improving numerical weather predictions over the Arctic.

1. Introduction

Arctic cyclones (ACs) are long-lived cyclones occurring over the Arctic in summer (Tanaka et al., 2012). Overall, ACs have a warm and a cold core at upper and lower levels, respectively, and barotropic structure of vorticity, as well as polar lows (e.g., Sakamoto & Takahashi, 2005). The baroclinicity over the Arctic frontal zone (Aizawa et al., 2014; Crawford & Serreze, 2016, 2017) and the merging of cyclones and subsequent coupling of upper- and lower-level vortices (Simmonds & Rudeva, 2014; Tao et al., 2017) play an important role in the development and maintenance of ACs.

Cyclone activity has a large environmental impact over the Arctic (Simmonds et al., 2008; Simmonds & Keay, 2009). Two extraordinary ACs in August 2012 (AC12; Simmonds & Rudeva, 2012) and 2016 (Yamagami et al., 2017) caused sea ice reduction (Parkinson & Comiso, 2013; Petty et al., 2018). In addition, the prediction of AC12 significantly affected the prediction of sea ice (Ono et al., 2016). As the Northern Sea Route has become more accessible due to the recent loss of sea ice (Eguíluz et al., 2016), planning of ship routes requires accurate prediction of ACs, particularly their positions.

Numerous operational numerical weather prediction (NWP) centers routinely conduct ensemble forecasts with perturbed initial and/or boundary conditions to provide probabilistic information regarding high-impact weather and to estimate the weather forecast uncertainty. Previous studies have used medium-range ensemble forecasts to investigate the forecast skill for various atmospheric phenomena in the tropics and midlatitudes (e.g., Frame et al., 2011, 2013; Matsueda, 2009, 2011; Matsueda & Endo, 2011; Matsueda & Kyouda, 2016; Matsueda & Palmer, 2018). Yamagami et al. (2018) examined the forecast skill for AC12 and showed that the development and position at the mature stage could be predicted 2–3 days in advance. However, the forecast skill for other extraordinary ACs in summer has not yet been assessed. In this study, the forecast skill for extraordinary ACs that occurred in summer (June–August) during 2008–2016 is assessed using ensemble forecasts, with a focus on existence probability, central pressure, and position at the mature stage.

2. Methods

2.1. Data

We used medium-range ensemble forecast data from the five leading NWP centers: the Canadian Meteorological Centre (CMC), the European Centre for Medium-Range Weather Forecasts (ECMWF), the Japan Meteorological Agency (JMA), the U.S. National Centers for Environmental Prediction (NCEP), and the UK Met Office (UKMO), available via the The Interactive Grand Global Ensemble (Swinbank et al., 2016) data portal (see the supporting information Table S1 for details of each ensemble prediction system). These NWP centers show a higher forecast skill over the Arctic than the other NWP centers (Jung & Matsueda, 2016). The forecast data are interpolated into a spatial resolution of 2.5° and has a 6-hourly temporal resolution. Note that there are some data gaps for NCEP in 2016.

The ECMWF Reanalysis (ERA)-Interim data (Dee et al., 2011) were also used as observational data, with equivalent spatial (2.5°) and temporal (6-hourly) to the forecast data. ERA-Interim was used to detect extraordinary ACs and verify the forecast performance.

2.2. Detection of Extraordinary ACs in Summer

The detection of observed extraordinary ACs in summer during 2008–2016 consists of two steps. First, all cyclone centers over the Arctic were identified at each time using the method developed by Aizawa and Tanaka (2016). The method searches for cyclone centers based on an interpolated sea level pressure (SLP) field from a longitude-latitude grid to an equal-distance (40 km) *x*-*y* grid over the Arctic. The algorithm deems a grid as a candidate for a cyclone center when the SLP at the target grid is a local minimum, and the SLP is 2 hPa lower than the averaged SLP over grids between 500 and 550 km from the target grid. The cyclone centers detected by this method were similar to those by the method of Lionello et al. (2002).

Second, the centers of observed extraordinary ACs were selected from the identified candidates. The selection was based on the following three criteria: The central pressure was lower than 980 hPa, the central position was north of 70°N, and the areal-mean (within 800 km of the cyclone center) temperature anomaly at 250 hPa was higher than 5 K. The mature stage of each AC was defined as when the AC recorded the minimum central pressure. The time of the mature stage of the ACs was selected at 0000 or 1200 UTC on each day because all the NWP centers provided control analyses (defined as an initial field of a control forecast) for those times. The radius of each AC was measured in a similar manner as Yamagami et al. (2017).

2.3. Verification of the AC Prediction

The same detection method was applied to the forecast data. The existence probability of the ACs was assessed for each NWP center, at each forecast lead time. The existence of an AC at its mature stage was defined based on the cyclone center with $<$995 hPa enclosed by at least two closed contours (circular or elliptical) with 5-hPa contour interval. The existence probability was defined as the ratio of ensemble members predicting the existence of the AC to the total number of members.

The forecast skill for the ACs at their mature stage was subsequently assessed at each lead time. The forecast skill was measured as the root-mean-square error of central pressure and the great-circle distance of the central position between predicted and analyzed ACs. The forecast skill for each AC was measured by the ensemble mean of the errors for the members that predicted the existence of the ACs. In addition, the general forecast skill was measured by the average of the ensemble mean error for all ACs.

3. Results

3.1. Observed Extraordinary AC Events

Ten extraordinary ACs in summer during 2008–2016 were detected using ERA-Interim (Figure 1 and Table S2). Although an average of one or two extraordinary ACs occurred during these summers, no extraordinary ACs occurred in the summers of 2009, 2011, or 2014. Thus, the occurrence frequency of extraordinary ACs is

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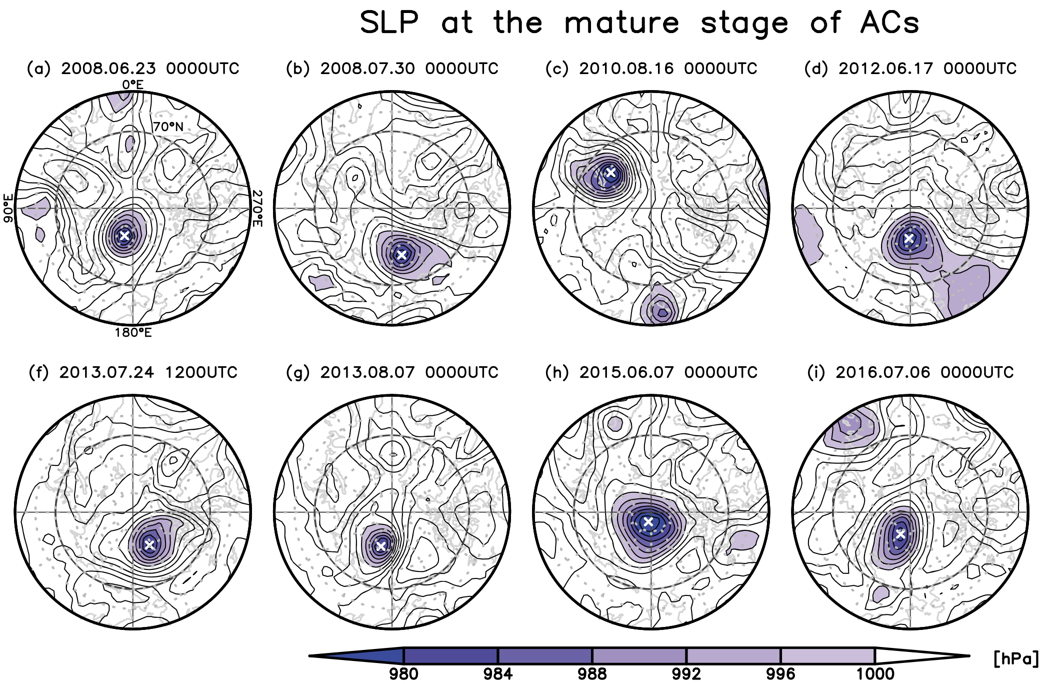

Figure 1. Analyzed sea level pressure (SLP) fields (European Centre for Medium-Range Weather Forecasts Reanalysis-Interim) for the extraordinary Arctic cyclones (ACs) at their mature stage. The time of the mature stage is provided in each panel. Shading is given for SLP <1,000 hPa. The crosses indicate the center of each AC.

dependent on year, owing to the strength of the upper-level polar vortex (e.g., Tao et al., 2017) and baroclinicity over the Arctic frontal zone (e.g., Crawford & Serreze, 2016).

Of the 10 ACs, the AC12 had the lowest central pressure at its mature stage (965.3 hPa, Figure 1e), followed by the AC in August 2016 (967.3 hPa, Figure 1j). The AC12 also had the lowest central pressure anomaly of −43.7 hPa. Interestingly, the AC in June 2015 (Figure 1h) showed the third lowest central pressure but the largest size (radius of 1,370.5 km) of all the ACs and the second lowest central pressure anomaly (−42.3 hPa). A correlation between the central pressure and radius of the ACs was −0.65, suggesting that the stronger AC tended to have the larger size. This means that the SLP gradient from the center to the outer edge of AC is similar among the AC events. Except for the AC in August 2010, the ACs reached their mature stage over the Pacific sector of the Arctic Ocean, where maximum cyclone deepening occurs frequently (Serreze & Barrett, 2008). Besides the ACs in August 2012 and 2016 (Parkinson & Comiso, 2013; Petty et al., 2018), the other ACs, especially long-lived ACs, also influenced sea ice and snow (Text S1).

3.2. Analysis Uncertainties for the ACs

As observations are limited over the Arctic (Jung et al., 2016), uncertainties in related analyses are larger over the Arctic than over the northern midlatitudes (Jung & Matsueda, 2016). Therefore, it is important to assess the difference between control analyses and ERA-Interim at the mature stage of the ACs.

Overall, the central position of each AC at its mature stage in the control analyses was comparable to that in the ERA-Interim (Figures 2a and 2b). The difference in central position between each control analysis and ERA-Interim was less than 90 km in the majority of events. The average differences for all AC events between ERA-Interim and the CMC, ECMWF, JMA, NCEP, and UKMO analyses were 36.7, 36.2, 42.6, 28.7, and 43.7 km, respectively. The largest difference (144.1 km) occurred between the ECMWF analysis and ERA-Interim for the AC in August 2016 (event j in Figure 2b), followed by 126.4 km between the CMC analysis and ERA-Interim for the AC in June 2008 (event a in Figure 2b), and 113.0 km between the UKMO analysis and ERA-interim for the AC in August 2016 (event j in Figure 2b). Although differences were larger for these ACs than for other ACs, differences were less than 15% of the radius of the individual ACs.

Regarding the analyzed central pressure (Figure 2c), the differences between each analysis and ERA-Interim were generally larger for the ACs from June 2008 to August 2012 (events a–e in Figure 2c) than for the ACs

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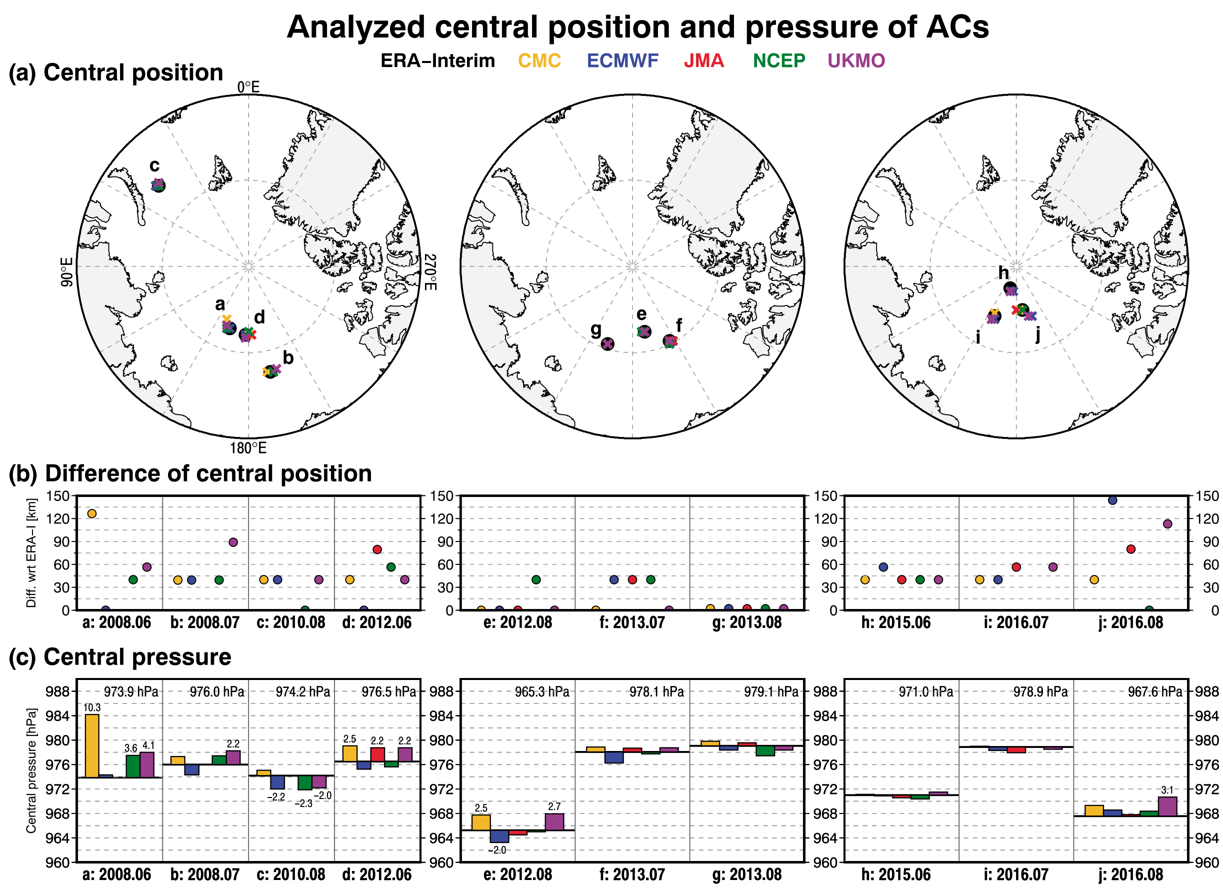

Figure 2. (a) Central positions of the analyzed Arctic cyclones (ACs) in the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA)-Interim (black circle) and control analyses (cross) of the Canadian Meteorological Centre (CMC; yellow), ECMWF (blue), the Japan Meteorological Agency (JMA; red), the National Centers for Environmental Prediction (NCEP; green), and the UK Met Office (UKMO; purple) and (b) the difference of central position between ERA-Interim and the control analysis. (c) Central pressures of the analyzed ACs for ERA-Interim (black horizontal line; the value is given at the top-right corner of each frame) and each control analysis (colored bars; differences >2.0 hPa between ERA-Interim and each analysis are given above or below each bar). The letters (a)–(j) for each symbol in (a) correspond to the AC events shown in (b) and (c), Figure 1, and Table S2.

from July 2013 to 2016 (events f–i in Figure 2c). The differences for the AC in August 2016 (event j in Figure 2c) were, however, similar to those for the first five events. The central pressures in the CMC and UKMO analyses were generally higher than those in ERA-Interim. In contrast, the central pressures in the ECMWF analysis were lower than those in ERA-Interim, except for the ACs in June 2008 and August 2016. The average differences for all the events between ERA-Interim and the CMC, ECMWF, JMA, NCEP, and UKMO analyses were 2.1, −0.9, 0.2, 0.0, and 1.2 hPa, respectively. For individual ACs, the largest difference (10.3 hPa) occurred between the CMC analysis and ERA-Interim for the AC in June 2008 (event a in Figure 2c), followed by 4.1 hPa between the UKMO analysis and ERA-Interim for the same AC. Excluding the AC in June 2008 reduced the average difference for the remaining nine ACs between the CMC analysis and ERA-Interim to 1.2 hPa.

These comparisons indicate that there were insignificant differences in both the central pressure and position of the ACs at their mature stage. Therefore, ERA-Interim was treated as the observed conditions for verifying the forecasts in the following subsections.

3.3. Example of Cyclone Track Ensemble Forecasts

In June 2015 (Figure 1h), an AC migrated into the Arctic from the Atlantic at 1800 UTC on 2 June and reached its lowest central pressure of 971.0 hPa over the central Arctic Ocean at 0000 UTC on 7 June. All ensemble members initialized at 1200 UTC on 2 June accurately predicted the initial position and subsequent north-eastward path of the AC (Figure 3). However, the predicted tracks began to differ between members when

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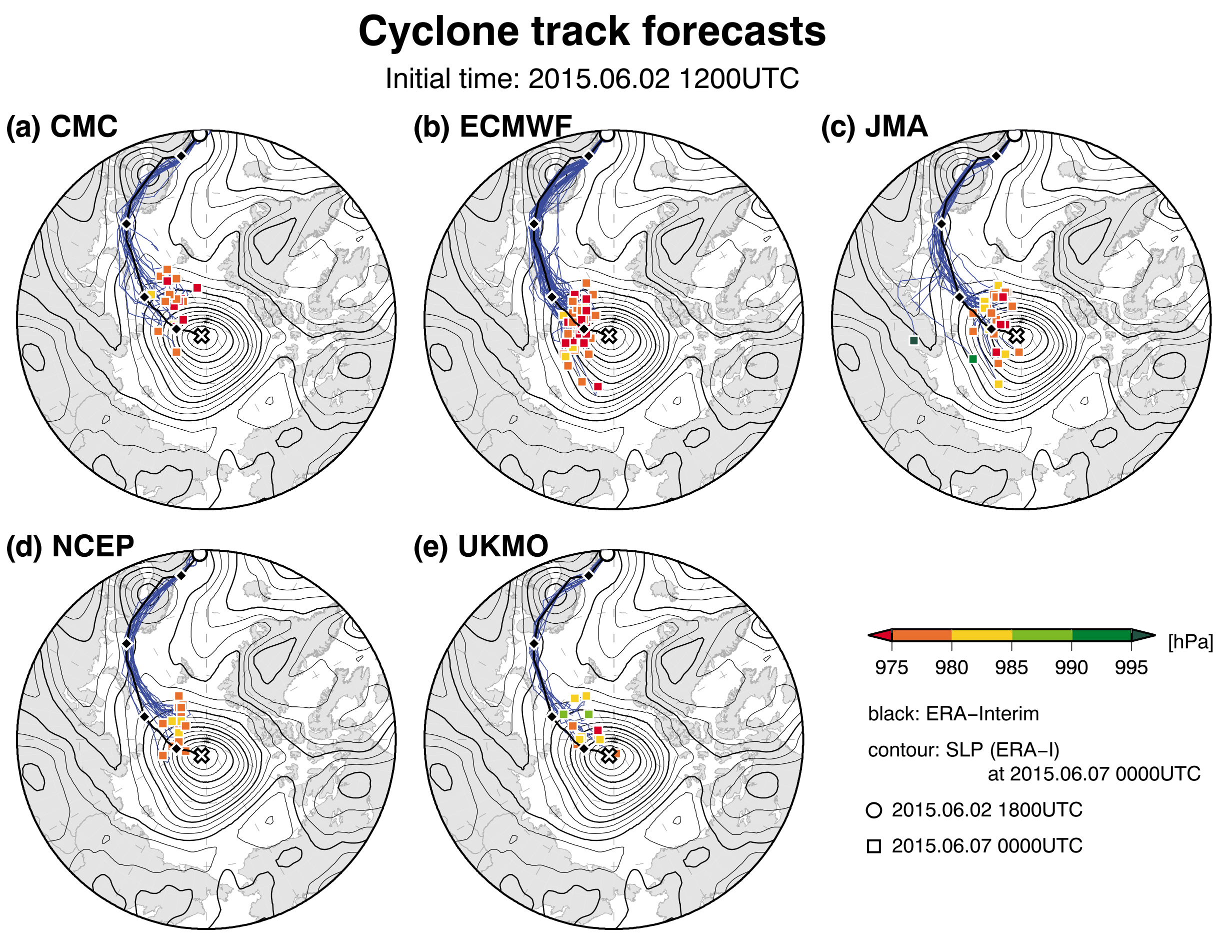

Figure 3. An example of cyclone track ensemble forecasts for (a) the Canadian Meteorological Centre (CMC), (b) the European Centre for Medium-Range Weather Forecasts (ECMWF), (c) the Japan Meteorological Agency (JMA), (d) the National Centers for Environmental Prediction (NCEP), and (e) the UK Met Office (UKMO) initialized at 1200 UTC on 2 June 2015. The white circles indicate the initial position of the AC. Black and blue lines indicate the analyzed (ECMWF Reanalysis [ERA]-Interim) and predicted cyclone tracks, respectively. Black rhombuses on the analyzed track indicate the central position at 0000 UTC on each day. Colored squares indicate the predicted central pressures and positions at 0000 UTC on 7 June 2015. The contour shows the analyzed SLP at 0000 UTC on 7 June 2015, with a contour interval every 3 hPa (the central position is given by a white cross).

the AC was over Novaya Zemlya. Except for several JMA members, the predicted ACs were located further south compared with the observed position at 0000 UTC on 7 June. The majority of the CMC and ECMWF members predicted central pressures <980 hPa. These results suggest that for the 4.5-day forecast of the AC (1) most members accurately predicted the existence of the AC (Figure S1h), (2) CMC and ECMWF showed a better skill in predicting the central pressure than the other centers (Figure S2h), and (3) all centers showed a similar forecast skill for the central position (Figure S3h).

3.4. Existence Probability for the Extraordinary ACs

The existence probability of ACs is primarily related to the forecast performance for the generation (but also maintenance) of the ACs (Figure 4a). For 10 extraordinary ACs, ECMWF exhibited the highest probability at lead times of 2.5–6.5 days, with probabilities of ~0.77 and ~1.0 on average, at lead times of 6.5 and 2.5 days, respectively. Both CMC and NCEP were the second-best performing centers at lead times of 4.5–6.5 days. The probability differences between ECMWF and these two centers were ~0.10 and ~0.05 at lead times of 6.5 and 4.5 days, respectively. Overall, JMA and UKMO showed the lowest probability at equivalent lead times, and their differences from ECMWF were ~0.18 and ~0.08 at lead times of 6.5 and 4.5 days, respectively. Thus, ECMWF showed 1- to 1.5-day advantage in predicting AC generation and maintenance at these lead times, compared with the other centers (i.e., the probability for ECMWF at a lead time of 6.5 days was similar to the probability for the other centers at lead times of 5.0–5.5 days). At lead times of 2.5–3.5 days, JMA and

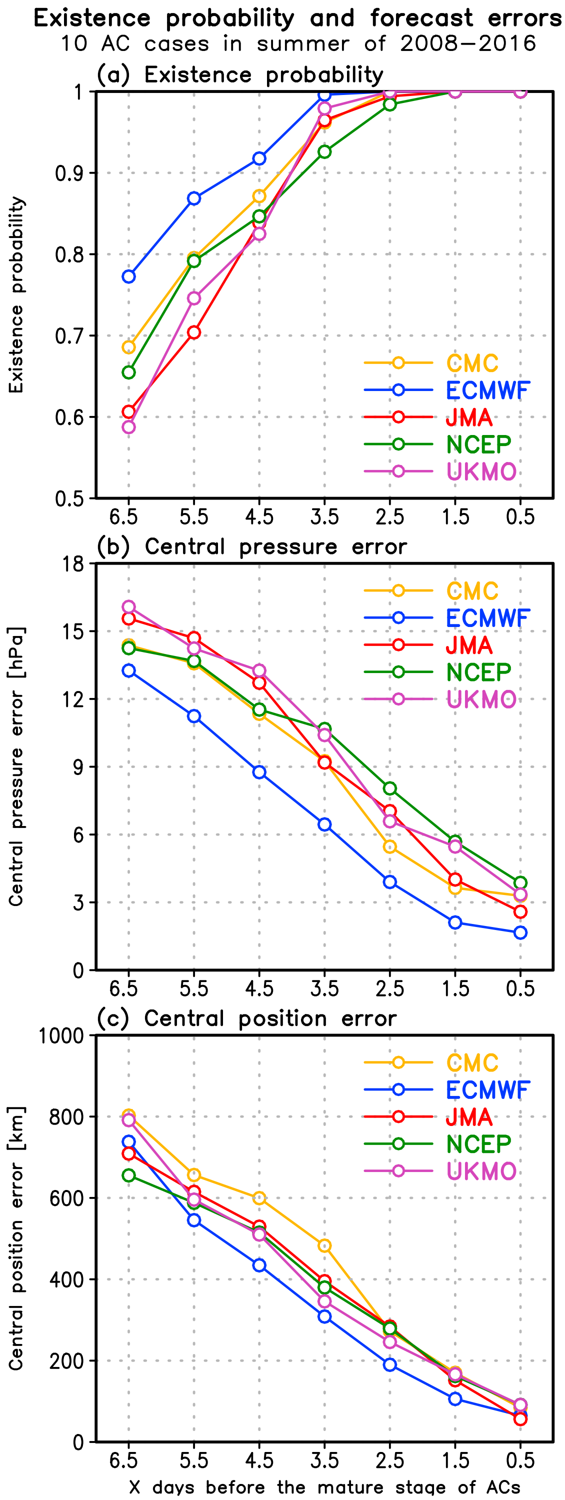

Figure 4. Average (a) existence probability, (b) central pressure error, and (c) central position error for the mature stages of 10 extraordinary Arctic cyclones (ACs) in summer of 2008–2016, predicted by the Canadian Meteorological Centre (CMC; yellow), the European Centre for Medium-Range Weather Forecasts (ECMWF; blue), the Japan Meteorological Agency (JMA; red), the National Centers for Environmental Prediction (NCEP; green), and the UK Met Office (UKMO; purple), as a function of forecast lead time. The forecasts were verified against ECMWF Reanalysis (ERA)-Interim.

UKMO displayed vast improvement whereby probabilities were >0.95, similar to ECMWF and CMC. Although NCEP showed the lowest existence probabilities of 0.93–0.98 at these lead times, all centers had a probability of 1.0 at lead times of ≤1.5 days.

The existence probability varied for each AC (Figure S1). For example, the probability for the AC in June 2015 (Figure S1h) was ~1.0 at almost all lead times for all NWP centers. The probability was also higher for the ACs in July 2013 (except at a lead time of 7 days, Figure S1f) and August 2016 (Figure S1j) than for all remaining ACs. Conversely, the existence probability of ~0.3 for the AC in August 2013 (Figure S1g) at lead times of 4.5–6.5 days was the lowest out of the 10 ACs but significantly improved at a lead time of 3.5 days. In this AC event, the generation of the AC over the Eurasian continent was difficult to predict at lead times ≥4.5 days. For these 10 events, the long-lived ACs are likely to show the high existence probability, especially in its developing stage.

3.5. Forecast Skills of Central Pressure and Position for the Extraordinary ACs

On average, ECMWF exhibited the highest forecast skill in predicting central pressures at all lead times (Figure 4b). The central pressure errors were 13.3 and 1.7 hPa at lead times of 6.5 and 0.5 days, respectively. Overall, ECMWF had 1- to 1.5-day advantage compared with the other centers, in addition to the existence probability. Further, ECMWF outperformed the other NWP centers for most AC events in terms of predicting central pressures (Figure S2). At lead times of 4.5–6.5 days (Figure 4b), CMC and NCEP were the second-best performing centers. The differences in central pressure errors between ECMWF and these two centers were 1.0 and 2.8 hPa at lead times of 6.5 and 4.5 days, respectively. For these lead times, JMA and UKMO exhibited the lowest performance, and their differences from ECMWF were 2.5 and 4.3 hPa at lead times of 6.5 and 4.5 days, respectively. CMC was also the second-best performing center at lead times of 1.5–3.5 days, whereas NCEP had the lowest forecast skill at these shorter lead times. The performance of JMA improved considerably at lead times ≤3.5 days, and its central pressure errors were similar to those for CMC at lead times of 3.5 and 1.5 days. Interestingly, JMA had the second lowest central pressure error of 2.6 hPa at a lead time of 0.5 days. For individual ACs (Figure S2), the forecast skill for the AC in August 2012 was particularly low compared with the other ACs (Figure S2e). In this AC event, the development of an upper-level warm core resulting from a merging cyclone was difficult to predict (Yamagami et al., 2018). In contrast, the central pressure errors for the ACs in July 2013 (Figure S2f) and 2016 (Figure S2i) were lower than those for the other ACs.

For predictions of the central position (Figure 4c), the average errors in the 6.5-day forecasts were 650–800 km for all NWP centers. These average position errors were somewhat similar to the radius of the ACs (Table S2), suggesting that all NWP centers failed to predict the positions of the ACs at this lead time. At lead times of 1.5–5.5 days, ECMWF showed the highest performance in predicting the central position and a 1-day advantage compared with the other centers. The difference in the average errors between ECMWF and the other centers was ~100 km. At lead times of 3.5–5.5 days, the average position error was larger for CMC than for the other centers. However, the CMC forecast improved significantly at a lead time of 2.5 days and the error was similar to that for JMA, NCEP, and UKMO at lead times of 1.5–2.5 days. At a lead time of 0.5 days, all NWP centers exhibited average errors <100 km. The central position errors for individual ACs (Figure S3) showed that the AC in June 2015 (Figure S3h) had the largest error of all the ACs. Conversely, the errors for the ACs in July 2013 (Figure S3f) and 2016 (Figure S3i) were lower than those for the remaining ACs. In these ACs, the position of an upper-level polar vortex was predicted well compared with the other ACs. On average, a large ensemble spread of geopotential height at 300 hPa appeared around the polar vortex at their mature stage, implying that main difference between members is the position of the predicted upper-level polar vortex. Unlike the central pressure predictions, the best performing center was dependent on the AC event, particularly at lead times of 4.5–6.5 days.

The average central position error for ECMWF at a lead time of 4.5 days was reduced to less than half of the mean observed radius (469.1 km) for the 10 ACs, with the average pressure error of 8.8 hPa. In addition, JMA, NCEP, and UKMO had average position errors <496.1 km at a lead time of 3.5 days and their average central pressure errors were 9.2, 10.7, and 10.4 hPa, respectively. Predictions of CMC had an average central position error <496.1 km at a lead time of 2.5 days, with average central pressure error of 5.5 hPa. The skill difference between ECMWF and JMA suggests that the impact of ensemble size on the forecast skill is little. Given that the model resolution has little impact on forecast skill over the Arctic and representation of extraordinary cyclones (Bauer et al., 2016; Jung et al., 2006) and that the ECMWF analysis is the closest to the mean analysis for all the NWP centers (Park et al., 2008; Wei et al., 2010), the higher quality of the ECMWF control analysis, rather than its higher model resolution and larger ensemble size, might be a main contributor to its higher forecast skill regarding ACs.

4. Concluding Remarks

In this study, the forecast skill for 10 extraordinary ACs in summer (June–August) during 2008–2016 is assessed at medium-range timescales using five leading operational ensemble forecasts.

Larger forecast uncertainties are expected over the Arctic than the lower latitudes, predominantly because of the analysis uncertainties due to the sparse network of observations. The central pressure and position of the individual mature AC from analyses of each NWP center are largely similar to those in ERA-Interim. The average differences in the central pressure and position for the 10 ACs between each center's analysis and ERA-Interim are less than 0.5 hPa and 37.6 km, respectively.

Overall, ECMWF exhibits 1- to 1.5-day advantage in predicting the existence, central pressure, and central position of the ACs, compared with the other centers. The second-best performing center was dependent on the forecast lead time and the AC event. The average central position error for ECMWF (CMC) decreased to ≤469.1 km, which is half of the average radius for the 10 ACs, at a lead time of 4.5 (2.5) days, and its average central pressure error was 8.8 (5.5) hPa. Further, JMA, NCEP, and UKMO had an average position error ≤469.1 km at a lead time of 3.5 days, and their average central pressure errors were 9.2, 10.7, and 10.4 hPa, respectively. The results suggest that the operational ensemble prediction systems generally predict the position of the ACs within 469.1 km at 2.5–4.5 days before the mature stage, with a central pressure error of 5.5–10.7 hPa. A higher quality of the control analysis, rather than a higher model resolution and a larger ensemble size, can lead to a higher forecast skill of extraordinary ACs.

The mean forecast skill for the extraordinary ACs is lower than that for midlatitude cyclones in the Northern Hemisphere (Froude, 2010) yet similar to that in the Southern Hemisphere (Froude, 2011). The sparse network of observations over both the Arctic and Southern Hemisphere (Jung et al., 2016) and the consequential analysis uncertainties in initial conditions (Inoue et al., 2015; Jung & Matsueda, 2016) are presumably one of the reasons for the similarity in forecast skills. However, mechanisms associated with the development and maintenance of ACs during summer, especially a coupling between upper- and lower-level vorticities, also contribute to lower predictability (Yamagami et al., 2018; Yamazaki et al., 2015). Therefore, more detailed analyses are needed of individual ACs to better understand the causes of this low forecast skill. Further, the best performing center in predicting the central position is dependent on the AC event, as well as other severe events (Matsueda & Nakazawa, 2015). This suggests that an estimate of uncertainties in the central position forecast using a multicenter grand ensemble approach is useful for shipping activities on the Northern Sea Route and aircraft activities on the Polar Route.

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