**Features and Processes Influencing the Evolution and Forecast Skill of Strong Low-skill Arctic Cyclones**

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ABSTRACT

Strong Arctic cyclones (ACs) characterized by low forecast skill of intensity, hereafter referred to as strong low-skill ACs, may pose challenges to human activities in the Arctic. The purpose of this study is to increase understanding of features and processes influencing the evolution and forecast skill of the intensity of strong low-skill ACs. Features and processes influencing the evolution of strong low-skill ACs are examined by constructing AC-centered composites for strong low-skill ACs and by conducting a synoptic-dynamic analysis of a representative strong low-skill AC that occurred during August 2016, hereafter referred to as AC16. Features and processes influencing the forecast skill of the intensity of strong low-skill ACs are examined by utilizing the ensemble-based sensitivity analysis (ESA) technique for AC16. The composite analysis for the strong low-skill ACs and the synoptic-dynamic analysis of AC16 suggest that tropopause polar vortices (TPVs), TPV–AC interactions, baroclinic processes, and latent heating influence the evolution of the strong low-skill ACs and AC16. The ESA suggests that the forecast skill of the intensity of AC16 is sensitive to the amplitude of an upper-tropospheric trough, and the strength of an embedded TPV, upstream of AC16, and the amplitude of an upper-tropospheric ridge downstream of AC16. The ESA also suggests that the forecast skill of the intensity of AC16 is sensitive to the amplitude of a 1000–500-hPa thickness trough and of a 1000–500-hPa thickness ridge in the vicinity of AC16, and the position of a region of latent heating associated with AC16.

1. Introduction

As defined in Biernat et al. (2023, section 1), ACs are extratropical cyclones that originate within the Arctic or move into the Arctic from lower latitudes (e.g., Serreze 1995; Zhang et al. 2004; Serreze and Barret 2008; Crawford and Serreze 2016). ACs can be associated with strong surface winds and high waves (e.g., Zhang et al. 2013; Thomson and Roger 2014), which may pose hazards to human activities in the Arctic, such as shipping (e.g., Eguíluz et al. 2016) and tourism (e.g., Hall and Saarinen 2010). There has been recent increased interest in examining features and processes that influence the evolution of ACs from a case study perspective (e.g., Simmonds and Rudeva 2012; Tao et al. 2017a,b; Ban et al. 2023; Qian et al. 2023) and from a composite perspective (e.g., Clancy et al. 2022; Vessey et al. 2022; Yang et al. 2024). TPVs, which are coherent tropopause-based cyclonic vortices (e.g., Cavallo and Hakim 2010), have been shown to influence the evolution of ACs (e.g., Simmonds and Rudeva 2012; Tao et al. 2017a,b; Yamagami et al. 2017; Gray et al. 2021; Ban et al. 2023; Qian et al. 2023). Baroclinic processes have also been shown to influence the evolution of ACs (e.g., Aizawa et al. 2014; Tao et al. 2017a,b; Yamagami et al. 2017; Ban et al. 2023; Croad et al. 2023; Qian et al. 2023). In addition, ACs can be associated with intrusions of warm, moist air into the Arctic (e.g., Fearon et al. 2021), which may influence the evolution of ACs through latent heating. A strong AC that occurred during August 2016, hereafter referred to as AC16, is a notable example of an AC for which TPVs, baroclinic processes, and latent heating have been shown to influence the evolution of ACs (Yamagami et al. 2017; Ban et al. 2023; Qian et al. 2023).

Forecast errors related to upper-tropospheric features (e.g., Langland et al. 2002; Chang et al. 2013; Lamberson et al. 2016), baroclinic processes (e.g., Sanders 1986; Zhu and Thorpe 2006; Zheng et al. 2013), and latent heating (e.g., Zhang et al. 2003, 2007) have been shown to contribute to forecast errors in midlatitude cyclones. Although there have been numerous studies that have examined features and processes influencing the forecast skill of midlatitude cyclones, there have been relatively few studies that have examined features and processes influencing the forecast skill of the intensity and position ACs (e.g., Tao et al. 2017b; Yamagami et al. 2018; Capute and Torn 2021; Johnson and Wang 2021). Forecasts of the intensity and position of ACs have been shown to be sensitive to the position and strength of TPVs and other upper-tropospheric features (e.g., Yamazaki et al. 2015; Yamagami et al. 2018; Johnson and Wang 2021; Ban et al. 2023) and the strength of tropospheric baroclinicity (e.g., Tao et al. 2017b). Observing system experiments by Yamazaki et al. (2015) and Johnson and Wang (2021) show that the denial of radiosonde observations located in the vicinity of TPVs linked to the development of a strong AC that occurred during August 2012, hereafter referred to as AC12, and an AC that occurred during July 2018, respectively, degrade the forecasts of the ACs.

The ESA technique (e.g., Torn and Hakim 2008) is a useful method to help determine features and processes that may influence the forecast skill of cyclones. The ESA technique can be used to determine the sensitivity of a forecast metric of interest (e.g., cyclone intensity) at a given forecast lead time to selected dynamic and thermodynamic quantities (e.g., lower-tropospheric temperature) at earlier forecast lead times (e.g., Torn and Hakim 2008). The ESA technique has been applied to midlatitude cyclones (e.g., Chang et al. 2013; Zheng et al. 2013) and to ACs (e.g., Johnson and Wang 2021). Johnson and Wang (2021) conducted an ESA of the AC that occurred during July 2018 and find that track and intensity errors of the AC are sensitive to the structure of a large-scale Rossby wave, the strength of TPVs, and the structure of the lower-tropospheric thermal field.

Biernat et al. (2023) identified ACs characterized by low forecast skill of intensity during periods of low forecast skill of the synoptic-scale flow over that Arctic during the summers (June–August) of 2007–2017. They referred to these ACs as low-skill ACs during low-skill periods. They found that low-skill ACs during low-skill periods tend to be located in regions of relatively strong lower-tropospheric baroclinicity, relatively large lower-to-midtropospheric Eady growth rate (EGR) (Hoskins and Valdes 1990), and relatively large latent heating. The objective of the present study is to improve understanding of features and processes influencing the evolution and forecast skill of the intensity of strong low-skill ACs during low-skill periods, hereafter referred to as strong low-skill ACs. Strong low-skill ACs are of interest because these ACs may pose challenges to human activities in the Arctic and these activities may be adversely impacted by hazardous weather conditions associated with these ACs. To address the objective of the present study, AC-centered composites for the strong low-skill ACs are constructed, and a synoptic-dynamic analysis and an ESA of AC16, which is a representative strong low-skill AC, are conducted. The remainder of this paper is organized as follows. Section 2 presents the data and methods used to construct the AC-centered composites for the strong low-skill ACs, and to conduct the synoptic-dynamic analysis and ESA of AC16. Section 3 presents the results of the AC-centered composites for the strong low-skill ACs, and the results of the synoptic-dynamic analysis and ESA of AC16. Section 4 summarizes the results of the paper.

2. Data and methods

a. AC-centered composites for strong low-skill ACs

The strong low-skill ACs defined in section 1 comprise the top 25% strongest low-skill ACs during low-skill periods from Biernat et al. (2023) based on the lowest sea level pressure (SLP) attained by these ACs when located within the Arctic (> 70°N) during low-skill periods. The tracks of the strong low-skill ACs in Biernat et al. (2023) were constructed using an objective SLP-based cyclone tracking algorithm developed by Crawford et al. (2021) and using 6-h SLP data from the ERA-Interim (Dee et al. 2011) at 1° horizontal grid spacing. The strong low-skill ACs are now tracked using 6-h SLP data from the ERA5 dataset (Hersbach et al. 2020, 2023a) at 0.25° horizontal grid spacing. To track each AC in ERA5, the location of minimum SLP within a 200-km radius of each track point of the corresponding ERA-Interim track is identified in ERA5. The resulting ERA5 track for each AC is then manually analyzed to ensure it properly follows the location of minimum SLP of the AC. No changes to the ERA5 tracks were needed after conducting the manual analysis of the ERA5 tracks. There is a total of 13 strong low-skill ACs. Table 1 shows that the lowest SLP attained within the Arctic for all 13 strong low-skill ACs is in the range of 962–982 hPa. Two notable strong low-skill ACs are AC12, which occurred during 3–10 August 2012 and attained a lowest SLP of 962.5 hPa within the Arctic (Table 1), and AC16, which occurred during 12–22 August 2016 and attained a lowest SLP of 968.3 hPa within the Arctic (Table 1). The majority of the strong low-skill ACs track east-northeastward while intensifying over the seas adjacent to Eurasia or over the central Arctic Ocean (Fig. 1).

Features and processes influencing the evolution of the strong low-skill ACs are examined by constructing AC-centered composites for the ACs at various lag times relative to the time of lowest SLP attained by the ACs within the Arctic (tlow). Lag times of tlow−48 h to tlow+12 h, every 12 h, are considered to examine the evolution of the ACs when the ACs intensify and reach peak intensity. For each lag time, the mean latitude and mean longitude of the ACs are determined. ERA5 grids of selected dynamic and thermodynamic quantities at 0.25° horizontal resolution (Hersbach et al. 2020, 2023a, 2023b) are shifted and rotated such that the center of each AC (i.e., location of minimum SLP) is positioned at the mean latitude and mean longitude of the ACs.

Since ERA5 data are on latitude–longitude grids, the area of grid cells over the Arctic varies. In order to shift ERA5 grids while preserving area, each ERA5 grid is projected onto a 25-km polar Equal-Area Scalable Earth 2.0 (EASE2) grid (Brodzik et al. 2012) by utilizing a portion of the cyclone tracking algorithm developed by Crawford et al. (2021) that projects latitude–longitude grids onto EASE2 grids. The EASE2 grid uses a polar Lambert azimuthal equal-area projection centered at 90°N, 0°E (Brodzik et al. 2012). Each ERA5 latitude–longitude grid is first rotated such that the AC center is located at 0°E, which lies along the y-axis of the EASE2 grid, before being projected onto the EASE2 grid. Doing this rotation allows both the AC center and North Pole to lie along the y-axis of the EASE2 grid such that the y-axis corresponds to the meridional direction with respect to the AC center. Each EASE2 grid is then shifted north or south along the y-axis, such that the AC center is located at the grid point closest to the mean latitude of the ACs. Each shifted EASE2 grid is then projected back onto a 0.25° latitude–longitude grid and lastly rotated such that the AC center is located at the mean longitude of the ACs. The resulting grids are then composited for each lag time. Throughout section 3a, geography will be shown on composite maps for reference. Since the ACs form over various locations, the geography is not representative of all ACs. The influence of land–sea boundaries, ice–sea boundaries, and topographic features on the evolution of the ACs will thus not be discussed, given that the locations of these boundaries and topographic features vary among the ACs.

b. Analysis of AC16

The ERA5 dataset is utilized to perform a synoptic-dynamic analysis of AC16 in order to identify features and processes influencing the evolution of AC16. As mentioned in section 2a, AC16 is a strong low-skill AC that occurs during 12–22 August 2016. AC16 tracks east-northeastward north of Eurasia during 12–15 August, performs a cyclonic loop over the Arctic Ocean during 15–18 August, and then tracks generally eastward over the Arctic Ocean during 18–22 August in ERA5 (Fig. 2a). AC16 rapidly intensifies during 12–15 August, reaching a peak intensity of 968.3 hPa at 0000 UTC 16 August in ERA5 (Fig. 2b). AC16 weakens until 1200 UTC 19 August and then appears to strengthen as it mergers with another AC (not shown) during 1200 UTC–1800 UTC 19 August (Fig. 2b). AC16 then weakens after 1800 UTC 19 August (Fig. 2b).

Ensemble forecasts from the 51-member ECMWF ensemble prediction system (EPS) that are extracted from The Observing System Research and Predictability Experiment (THORPEX) Interactive Grand Global Ensemble (TIGGE) (Bougeault et al. 2010) at 0.5° horizontal grid spacing are utilized to examine features and processes influencing the forecast skill of the intensity of AC16. Ensemble forecasts from the ECMWF EPS initialized at 0000 UTC 10 August and verifying at 0000 UTC 15 August (120 h) are utilized. The aforementioned ensemble forecasts from the ECMWF EPS are utilized because ensemble forecasts initialized at 0000 UTC 10 August and verifying at 0000 UTC 15 August (120 h) from the 11-member GEFS reforecast dataset version 2 (Hamill et al. 2013) were identified in Biernat et al. (2023) as low-skill forecasts of the synoptic-scale flow over the Arctic. The intensity and position of AC16 is manually identified in each ensemble forecast at 0000 UTC 15 August (120 h). Figure 3 shows the intensity and position of AC16 at 0000 UTC 15 August (120 h) in ERA5 and the ensemble forecasts. Figure 3 shows that there is large uncertainty in the intensity of AC16 at 0000 UTC 15 August (120 h), with the ensemble forecasts of minimum SLP at this time ranging between 968.7 hPa and 995.6 hPa. The large uncertainty in the intensity of AC16 at 0000 UTC 15 August (120 h) facilitates examining features and processes influencing the forecast skill of the intensity of AC16.

The ESA technique (e.g., Torn and Hakim 2008) is utilized to examine the sensitivity of the forecast skill of the intensity of AC16 at 0000 UTC 15 August (120 h) to selected dynamic and thermodynamic quantities at earlier forecast lead times. The sensitivity of a forecast metric of interest *J* to a model state variable *xi* at an earlier forecast lead time for an ensemble of size *M* is calculated via

, (1)

where **J** denotes the 1 × *M* ensemble estimate of the forecast metric, **x***i* denotes the 1 × *M* ensemble estimate of the *i*th model state variable, cov denotes the covariance, and var denotes the variance (e.g., Torn and Hakim 2008). The values of *xi* are normalized by the ensemble standard deviation of *xi* following Torn and Romine (2015), such that all sensitivities have units of the forecast metric per standard deviation of the model state variable. This normalization allows various model state variables characterized by different units and different intrinsic variability to be quantitatively compared (e.g., Torn and Romine 2015). Sensitivity is determined to be statistically significant at the 95% confidence level by following the methodology of Torn and Hakim (2008, section 3). This methodology consists of determining if the absolute value of *∂J/∂xi* is greater than its 95% confidence interval. The forecast metric chosen, hereafter referred to as *JAC*, is the minimum SLP of AC16 in the ensemble forecasts at 0000 UTC 15 August (120 h), as this metric is a proxy for the intensity error of AC16. Johnson and Wang (2021) conducted an ESA of an AC occurring during July 2018 and similarly used minimum SLP as a metric for the intensity error of the AC.

3. Results

a. AC-centered composites for strong low-skill ACs

The role of baroclinic processes in the evolution of the strong low-skill ACs is first examined. Figure 4a shows that the composite AC is located in a region of strong lower-to-midtropospheric baroclinicity between a thickness through and ridge at tlow−48 h. Corresponding to the region of strong lower-to-midtropospheric baroclinicity are dual upper-tropospheric jet streaks located to the southwest and northeast of the composite AC (Fig. 4a), which suggest that the composite AC may be located in a region of lateral jet coupling, a favorable region for cyclone intensification (e.g., Uccellini and Kocin 1987). Tao et al. (2017b) similarly indicate that AC12, which is one of the strong low-skill ACs, is located between two upper-tropospheric jet streaks during a portion of the intensification phase of AC12, with one upper-tropospheric jet streak located to the southwest of AC12 and another upper-tropospheric jet streak located to the northeast of AC12.

Between tlow−36 h and tlow−12 h, the two jet streaks evolve into a cyclonically curved jet streak between the thickness trough and ridge (Figs. 4b–d), with the composite AC continuing to be located in a region of strong lower-to-midtropospheric baroclinicity (Figs. 4b–d). At tlow−12 h, the composite AC is located in the poleward exit region of the cyclonically curved jet streak (Fig. 4d), a favorable region for continued intensification of the composite AC. Tao et al. (2017b) similarly show that the two upper-tropospheric jet streaks influencing AC12 evolve into a cyclonically curved upper-tropospheric jet streak, with AC12 becoming positioned in the poleward exit region of the cyclonically curved upper-tropospheric jet streak. There are regions of relatively large lower-to-midtropospheric EGR in the vicinity of the composite AC during tlow−48 h through tlow−12 h (Figs. 5a–d) that are associated with the region of strong lower-to-midtropospheric baroclinicity (Figs. 4a–d) [readers interested in documentation for the calculation of lower-to-midtropospheric EGR are referred Biernat et al. (2023, section 2c)]. Figures 4a–d and Figs. 5a–d suggest that baroclinic processes likely play an important role in the intensification of the strong low-skill ACs. Previous studies have also shown the importance of baroclinic processes in the intensification of AC12 (Simmonds and Rudeva 2012; Yamazaki et al. 2015; Tao et al. 2017b) and AC16 (Yamagami et al. 2017; Ban et al. 2023; Qian et al. 2023), which are two of the strong low-skill ACs. Simmonds and Rudeva (2012) similarly show that there is relatively large EGR at 500-hPa in the vicinity of AC12, and Yamagami et al. (2017) similarly show that there is relatively large EGR at 700-hPa in the vicinity of AC16, as these ACs intensify.

At tlow and tlow+12 h, lower-to-midtropospheric baroclinicity weakens in the vicinity of the composite AC as the composite AC reaches peak intensity and begins to weaken (Figs. 4e,f). The warm sector of the composite AC (Figs. 4e,f) and regions of relatively large lower-to-midtropospheric EGR (Figs. 5e,f) become increasingly separated from the composite AC center duringtlow through tlow+12 h, suggesting that the strong low-skill ACs become occluded. Simmonds and Rudeva (2012) similarly show that there is a decrease in EGR at 500-hPa in the vicinity of AC12, and Yamagami et al. (2017) similarly show that there is a decrease in EGR at 700-hPa in the vicinity of AC16, around the time these ACs reach peak intensity.

TPVs have been shown to play an important role in the evolution of ACs (e.g., Simmonds and Rudeva 2012; Tao et al. 2017a,b; Gray et al. 2021; Ban et al. 2023). The role of TPVs in the evolution of the strong low-skill ACs is now examined. Figure 6a shows that there is an upper-tropospheric potential vorticity (PV) maximum upstream of the composite AC at tlow−48 h. Figs. 6a also shows that there is another upper-tropospheric PV maximum northeast of the composite AC at tlow−48 h. The upper-tropospheric PV maxima are likely signature of TPVs, given that TPVs are characterized by a cyclonic PV anomaly and are common features in the Arctic (e.g., Cavallo and Hakim 2010). Relatively large upper-tropospheric PV gradients are found between an upper-tropospheric ridge downstream of the composite AC and the PV maxima upstream of the composite AC, and between the aforementioned upper-tropospheric ridge and the PV maximum northeast of the composite AC, at tlow−48 h (Fig. 6a). The relatively large upper-tropospheric PV gradients are consistent with the dual upper-tropospheric jet streaks in the vicinity of the composite AC at tlow−48 h (Fig. 4a) that support the intensification of the strong low-skill ACs via baroclinic processes. The upper-tropospheric PV maximum upstream of the composite AC gradually approaches the composite AC during tlow−48 h through tlow−12 h (Figs. 6a–d), suggesting that there is interaction between TPVs and the strong low-skill ACs. Tao et al. (2017b) similarly show that a TPV interacting with AC12 approaches AC12 while AC12 intensifies.

The upper-tropospheric PV maximum upstream of the composite AC becomes positioned over the composite AC at tlow and tlow+12 h (Figs. 6e,f), suggesting that TPVs become vertically superposed with the strong low-skill ACs. Previous studies similarly show that TPVs become vertically superposed with ACs while the ACs intensify and reach peak intensity (e.g., Aizawa et al. 2014; Aizawa and Tanaka 2016; Tao et al. 2017a,b; Yamagami et al. 2017; Ban et al. 2023; Qian et al. 2023). The vertical superposition of the TPVs and strong low-skill ACs suggest the strong low-skill ACs are becoming more equivalent barotropic in structure. In addition, a 1000–500-hPa thickness minimum becomes closer to the center of the composite AC duringtlow through tlow+12 h (Figs. 5e,f), further suggesting that the strong low-skill ACs are becoming more equivalent barotropic in structure. Several previous studies describes ACs as becoming equivalent barotropic or barotropic in structure at or around the time the ACs reach peak intensity (e.g., Tao et al. 2017a,b; Yamagami et al. 2017; Ban et al. 2023). Vessey et al. (2022) conclude from a composite analysis of the 100 strongest ACs during the summers of 1979–2020 using ERA5 that ACs transition from having a baroclinic structure to an axi-symmetric cold-core structure throughout the troposphere, with a lowered troposphere above the ACs, around the time the ACs reach peak intensity. The transition of the composite AC from being located in a region of strong lower-to-midtropospheric baroclinicity (Figs. 4a–d) downstream of the upstream upper-tropospheric PV maximum (Figs. 6a–d) during tlow−48 h through tlow−12 h to being located closer to the 1000–500-hPa minimum (Figs. 4e,f) and beneath the upper-tropospheric PV maximum (Figs. 6e,f) during tlow through tlow+12 h may similarly suggest a transition of the strong low-skill ACs from having a baroclinic structure to a more axi-symmetric cold-core structure throughout the troposphere.

The role of latent heating in the evolution of the strong low-skill ACs is lastly examined. Figures 6a–d show that there are regions of lower-to-midtropospheric ascent, upper-tropospheric divergence, and upper-tropospheric irrotational outflow in the immediate vicinity of the composite AC during tlow−48 h through tlow−12 h. The regions of lower-to-midtropospheric ascent, upper-tropospheric divergence, and upper-tropospheric irrotational outflow during tlow−48 h through tlow−12 h (Figs. 6a–d) are also found in the suggested region of lateral jet coupling at tlow−48 h (Fig. 4a), and in and near the poleward exit region of a cyclonically curved upper-tropospheric jet streak during tlow−36 h through tlow−12 h (Figs. 4b–d). A well-defined integrated water vapor transport (IVT) corridor also gradually wraps cyclonically from the southern to the northeastern flank of the composite AC during tlow−48 h through tlow−12 h (Figs. 7a–d). The IVT corridor may be a manifestation of warm conveyor belts (WCBs) and/or atmospheric rivers associated with the strong low-skill ACs. There is an abrupt decrease in IVT just northeast of the composite AC center during tlow−48 h through tlow−12 h (Figs. 7a–d) that corresponds to a well-defined region of integrated horizontal moisture flux convergence (IMFC) (Figs. 7a–d). As discussed in Biernat et al. (2023, section 2c), positive values of IMFC are used as a proxy for latent heating (e.g., Torn and Hakim 2015). The well-defined region of IMFC during tlow−48 h through tlow−12 h (Figs. 7a–d) thus implies that latent heating is occurring in the vicinity of the strong low-skill ACs and is likely contributing to the intensification of the strong low-skill ACs. The regions of lower-to-midtropospheric ascent, upper-tropospheric divergence, and upper-tropospheric irrotational outflow during tlow−48 h through tlow−12 h (Figs. 6a–d) are likely signatures of the latent heating. During tlow through tlow+12 h, the IVT corridor wraps around the composite AC (Figs. 7e,f), with the magnitudes of IVT and IMFC decreasing substantially (Figs. 7e,f) as the composite AC reaches peak intensity and begins to weaken.

The composite analysis for the strong low-skill ACs suggests that these ACs interact with TPVs in a region of strong lower-to-midtropospheric baroclinicity and relatively large lower-to-midtropospheric EGR, and that these ACs are associated with a well-defined IVT corridor and a well-defined region of IMFC that implies latent heating. The composite analysis for the strong low-skill ACs suggests that TPVs, TPV–AC interactions, baroclinic processes, and latent heating influence the evolution of these ACs. The rest of the present study will focus on examining features and processes influencing the evolution and forecast skill of the intensity of AC16, which is a representative strong low-skill AC.

b. ERA5 synoptic-dynamic analysis of AC16

The role of baroclinic processes in the evolution of AC16 is first examined. At 0000 UTC 14 August, AC16 intensifies in a region of strong lower-to-midtropospheric baroclinicity between a thickness trough and ridge, and in an apparent region of lateral jet coupling associated with dual upper-tropospheric jet streaks (Fig. 8a). During 1200 UTC 14–1200 UTC 15 August, the dual upper-tropospheric jet streaks gradually evolve into a cyclonically curved upper-tropospheric jet streak, and AC16 continues to intensify in a region of strong lower-to-midtropospheric baroclinicity (Figs. 8b–d). There are regions of strong lower-to-midtropospheric EGR (Figs. 9a–d) associated with the region of strong lower-to-midtropospheric baroclinicity (Figs. 8a–d) during 0000 UTC 14–1200 UTC 15 August. Figures 8a–d and Figs. 9a–d suggest that baroclinic processes play an important role in the intensification of AC16, which is in agreement with the findings of Yamagami et al. (2017), Ban et al. (2023), and Qian et al. (2023). Lower-to-midtropospheric baroclinicity (Figs. 8e,f) and lower-to-midtropospheric EGR (Figs. 9e,f) decrease near the center of AC16 as AC16 reaches peak intensity and shortly afterward, suggesting that AC16 becomes occluded.

The role of TPVs in the evolution of AC16 is next examined. There is an upper-tropospheric PV maximum corresponding to a TPV upstream of AC16 that gradually approaches AC16 as AC16 intensifies during 0000 UTC 14–1200 UTC 15 August (Figs. 10a–d), suggesting that there is interaction between the TPV and AC16. There is also a second upper-tropospheric PV maximum corresponding to a TPV located to the northeast of AC16 over the Arctic during 0000 UTC 14–1200 UTC 14 August (Figs. 10a,b). Relatively large upper-tropospheric PV gradients are found between an upper-tropospheric ridge downstream of AC16 and the TPV upstream of AC16, and between the aforementioned upper-tropospheric ridge and the TPV northeast of AC16, during 0000 UTC 14–1200 UTC 14 August (Figs. 10a,b). The relatively large upper-tropospheric PV gradients are consistent with the upper-tropospheric jet streaks in the vicinity of AC16 during 0000 UTC 14–1200 UTC 14 August (Fig. 8a,b) that support the intensification of AC16 via baroclinic processes. The existence of multiple TPVs in the vicinity of AC16 is consistent with the results of Yamagami et al. (2017), Ban et al. (2023), and Qian et al. (2023). Qian et al. (2023) show through the pressure tendency equation that warm air advection related to the TPVs contributes to the intensification of AC16. The TPV upstream of AC16 becomes positioned over AC16 as AC16 reaches peak intensity and shortly afterward during 0000–1200 UTC 16 August (Figs. 10e,f), suggesting that the TPV becomes vertically superposed with AC16 and that AC16 is possibly becoming equivalent barotropic in structure. Still, AC16 is not positioned over a thickness minimum during 0000–1200 UTC 16 August (Figs. 8e,f), which argues against a fully equivalent barotropic structure. Yamagami et al. (2017), Ban et al. (2023), and Qian et al. (2023) similarly show that the TPV upstream of AC16 gradually approaches AC16 and becomes vertically superposed with AC16.

The role of latent heating in the evolution of AC16 is lastly examined. Figure 11a indicates that there is an IVT corridor extending from southern to the northeastern flank of AC16 at 0000 UTC 14 August. The IVT corridor may be a manifestation of a WCB associated with AC16. Associated with the IVT corridor are regions of IMFC indicative of latent heating in the vicinity of AC16 at 0000 UTC 14 August (Fig. 11a). A region of relatively strong IMFC northeast of AC16 at 0000 UTC 14 August (Fig. 11a) coincides with well-defined regions of lower-to-midtropospheric accent, upper-tropospheric divergence, and upper-tropospheric irrotational outflow at this time (Fig. 10a). The well-defined regions of lower-to-midtropospheric accent, upper-tropospheric divergence, and upper-tropospheric irrotational outflow at 0000 UTC 14 August (Fig. 10a) are likely signatures of the latent heating. The latent heating likely contributes to the intensification of AC16. Qian et al. (2023) show through the pressure tendency equation that lower-to-midtropospheric diabatic heating, which they state is probably related to latent heating, contributes to the intensification of AC16. The IVT corridor and associated regions of IMFC persist and gradually weaken during 1200 UTC 14–1200 UTC 16 August (Figs. 11b–f). Regions of lower-to-midtropospheric ascent, upper-tropospheric divergence, and upper-tropospheric irrotational outflow also persist and gradually weaken during 1200 UTC 14–1200 UTC 16 August (Figs. 10b–f).

Consistent with the results of the composite analysis for the strong low-skill ACs in section 3a, and consistent with the results of Yamagami et al. (2017), Ban et al. (2023), and Qian et al. (2023), the synoptic-dynamic analysis of AC16 indicates that TPVs, TPV–AC interactions, baroclinic processes, and latent heating appear to influence the evolution of AC16. The sensitivity of the forecast skill of the intensity of AC16 to selected dynamic and thermodynamic quantities will next be examined to help determine what features and processes may influence the forecast skill of the intensity of AC16.

c. ESA of AC16

The sensitivity of JAC, which was defined in section 2b, to selected dynamic and thermodynamic quantities is examined in the present subsection. Sensitivity values are multiplied by −1, such that positive sensitivity values indicate that increasing the value of the quantity is associated with a decrease in JAC and negative sensitivity values indicate that decreasing the value of the quantity is associated with a decrease in JAC. Since JAC was defined in section 2b as the minimum SLP of AC16 at 0000 UTC 15 August (120 h), lower values of JAC are associated with a stronger AC16, and a correspondingly more accurate intensity forecast of AC16, at 0000 UTC 15 August (120 h). Accordingly, a stronger AC16, and a correspondingly more accurate intensity forecast of AC16, at 0000 UTC 15 August (120 h) is associated with increasing the value of the quantity for positive sensitivity values and with decreasing the value of the quantity for negative sensitivity values.

The sensitivity of JAC to upper-tropospheric PV is first examined to determine the sensitivity of the intensity forecast of AC16 to upper-tropospheric features. There is a small region of negative sensitivity of JAC to upper-tropospheric PV just north of Iceland at 0000 UTC 10 August (0 h) (Fig. 12a) that grows in size and propagates southeastward to southwestern Scandinavia between an upper-tropospheric ridge (R1) over the North Atlantic and an upper-tropospheric trough (T1) over the Norwegian Sea and western Eurasia during 1200 UTC 10–1200 UTC 11 August (12–36 h) (Figs. 12b–d). A decrease in upper-tropospheric PV in the region of negative sensitivity of JAC to upper-tropospheric PV during 1200 UTC 10–1200 UTC 11 August (12–36 h) suggests a slight eastward shift in R1 during this period. The region of negative sensitivity of JAC to upper-tropospheric PV during 1200 UTC 10–1200 UTC 11 August (12–36 h) suggests that a slight eastward shift in R1 during this period is associated with a stronger AC16, and a correspondingly more accurate intensity forecast of AC16, at 0000 UTC 15 August (120 h).

A region of positive sensitivity of JAC to upper-tropospheric PV becomes established within and on the southeastern side of T1 during 0000–1200 UTC 12 August (48–60 h) (Figs. 13a,b), grows in size and magnitude during 0000–1200 UTC 13 August (72–84 h) (Figs. 13c,d), and persists during 0000–1200 UTC 14 August (96–108 h) (Figs. 13e,f). Embedded within T1 is the TPV located upstream of AC16 that was discussed in section 3b. A region of negative sensitivity of JAC to upper-tropospheric PV becomes established near the crest of an upper-tropospheric ridge (R2) located downstream of T1 during 0000 UTC 12–0000 UTC 13 August (48–72 h) (Figs. 13a–c), and grows in size and magnitude during 1200 UTC 13–1200 UTC 14 August (84–108 h) as R2 amplifies (Figs. 13d–f). AC16 develops and intensifies between T1 and R2. The aforementioned regions of positive and negative sensitivity of JAC to upper-tropospheric PV during 0000 UTC 12–1200 UTC 14 August (48–108 h) suggest that a more amplified T1, and a stronger embedded TPV, and a more amplified R2 during this period are associated with a stronger AC16, and a correspondingly more accurate intensity forecast of AC16, at 0000 UTC 15 August (120 h).

The sensitivity of JAC to 1000–500-hPa thickness is next examined to determine the sensitivity of the intensity forecast of AC16 to the thermal structure of the lower-to-middle troposphere. There is a region of negative sensitivity of JAC to 1000–500-hPa thickness near the base of a thermal trough over Scandinavia at 0000 UTC 13 August (72 h) (Fig. 14a). The region of negative sensitivity of JAC to 1000–500-hPa thickness persists and grows in size during 1200 UTC 13–1200 UTC 14 August (84–108 h) (Figs. 14b–d). There is a region of positive sensitivity of JAC to 1000–500-hPa thickness that increases in size and magnitude near the crest of a thermal ridge located downstream of the thermal trough during 0000 UTC 13–1200 UTC 14 August (72–108 h) (Figs. 14a–d). AC16 intensifies between the thickness trough and ridge. The aforementioned regions of negative and positive sensitivity of JAC to 1000–500-hPa thickness during 0000 UTC 13–1200 UTC 14 August (72–108 h) suggest that a more amplified thickness trough and a more amplified thickness ridge during this period are associated with a stronger AC16, and a correspondingly more accurate intensity forecast of AC16, at 0000 UTC 15 August (120 h).

The sensitivity of JAC to lower-tropospheric IMFC is lastly examined to determine the sensitivity of the intensity forecast of AC16 to latent heating. At 0000 UTC 13 August (72 h), there is region of lower-tropospheric IMFC associated with AC16 on the northern flank of a moisture corridor extending from western Russia into the Kara Sea (Fig. 15a). The region of lower-tropospheric IMFC associated with AC16 and the moisture corridor move eastward along the north coast of Russia during 1200 UTC 13–1200 UTC 14 August (Figs. 15b–d). There is small region of positive sensitivity of JAC to lower-tropospheric IMFC northeast of Scandinavia at 0000 UTC 13 August (72 h) (Fig. 15a) that increases in size and magnitude over the northwestern flank of the region of lower-tropospheric IMFC associated with AC16 during 1200 UTC 13–1200 UTC 14 August (84–108 h) (Figs. 15b–d). The region of positive sensitivity of JAC to lower-tropospheric IMFC during 1200 UTC 13–1200 UTC 14 August (84–108 h) suggests that a northwestward shift in the region of latent heating associated with AC16 during this period is associated with a stronger AC16, and a correspondingly more accurate intensity forecast of AC16, at 0000 UTC 15 August (120 h).

Based on the ESA of AC16, the following speculations are made. A slight eastward shift in R1 building into western Eurasia may be associated with a more amplified T1, and a stronger embedded TPV, upstream of AC16. A more amplified T1, and a stronger embedded TPV, upstream of AC16 may be associated with greater intensification of AC16 and greater downstream amplification of R2. A stronger AC16 may be associated with a stronger lower-to-midtropospheric circulation that contributes to a more amplified thickness trough upstream of AC16, a more amplified thickness ridge downstream of AC16, and to a northwestward shift of a region of latent heating associated with AC16. Based on Sutcliffe development theory, cyclogenesis is favored between a thickness trough and ridge, in response to the advection of thermal vorticity by the thermal wind (e.g., Carlson 1998, section 8.1). It is hypothesized that a more amplified thickness trough upstream of AC16 and a more amplified thickness ridge downstream of AC16 may be associated with greater advection of thermal vorticity by the thermal wind between the thickness trough and ridge that contributes to greater intensification of AC16.

It is speculated from the ESA of AC16 that accurate forecasts of upper-tropospheric features, including T1, and the embedded TPV, and R1, are important for an accurate forecast of the intensity of AC16. Ban et al. (2023) show in their study of AC16 that a more accurate simulation of upper-level atmospheric fields likely contributes to a more accurate forecast of the intensity and position of AC16. Yamagami et al. (2018) show that accurate forecasts of TPVs, an upper-tropospheric trough, and an upper-tropospheric ridge in the vicinity of AC12 are important for accurate forecasts of the intensity and position of AC12. Previous studies of midlatitude cyclones have shown that forecast errors in the intensity and position of midlatitude cyclones can be linked to forecast errors in upper-tropospheric features, such as upper-tropospheric troughs and ridges (e.g., Sanders 1986, 1992; Kuo and Reed 1988; Sanders et al. 2000; Langland et al. 2002; Chang et al. 2013; Zheng et al. 2013; Lamberson et al. 2016). Furthermore, previous studies including Langland et al. (2002), Chang et al. (2013), and Lamberson et al. (2016) show that upper-tropospheric forecast errors influencing the forecast skill of midlatitude cyclones can propagate downstream as structures resembling wave packets. The propagation of coherent regions of sensitivity of JAC to upper-tropospheric PV from the North Atlantic, across Eurasia, and into the Arctic during 0000 UTC 10–1200 UTC 14 August (Figs. 12a–d and Figs. 13a–f) suggests that upper-tropospheric forecast errors influencing the forecast skill of the intensity of AC16 may similarly propagate downstream as structures resembling wave packets.

4. Summary

There has been a recent increase in studies aimed to better understand features and processes influencing the evolution of ACs (e.g., Tao et al. 2017a,b; Yamagami et al. 2017; Gray et al. 2021; Vessey et al. 2022; Ban et al. 2023; Qian et al. 2023; Yang et al. 2024). There have been relatively few studies that have examined features and processes influencing the forecast skill of ACs (e.g., Tao et al. 2017b; Yamagami et al. 2018; Capute and Torn 2021; Johnson and Wang 2021). The present study provides insights into features and processes influencing the evolution and forecast skill of the intensity of strong low-skill ACs.

The composite analysis for the strong low-skill ACs suggests that these ACs intensify as they interact with TPVs in a region of strong lower-to-midtropospheric baroclinicity and relatively large lower-to-midtropospheric EGR, and that the TPVs become vertically superposed with these ACs as these ACs reach peak intensity. The composite analysis for the strong low-skill ACs also suggests that these ACs are associated with a well-defined IVT corridor and a well-defined region of IMFC that implies latent heating as these ACs intensify. The composite analysis for the strong low-skill ACs suggests that TPVs, TPV–AC interactions, baroclinic processes, and latent heating influence the evolution of these ACs. Previous studies have similarly indicated the importance of TPVs and TPV–AC interactions (e.g., Aizawa and Tanaka 2016; Tao et al. 2017a,b; Yamagami et al. 2017; Gray et al. 2021; Ban et al. 2023), baroclinic processes (e.g., Tao et al. 2017a,b; Ban et al. 2023; Croad et al. 2023; Qian et al. 2023), and latent heating (e.g., Qian et al. 2023) in influencing the evolution of ACs. Forecast errors related to TPVs, TPV–AC interactions, baroclinic processes, and latent heating may contribute to the low forecast skill of the intensity of the strong low-skill ACs.

The synoptic-dynamic analysis of AC16, which is one of the strong low-skill ACs, indicates that TPVs, TPV–AC interactions, baroclinic processes, and latent heating appear to influence the evolution of AC16, which is consistent with the results of the composite analysis for the strong low-skill ACs and consistent with the results of Yamagami et al. (2017), Ban et al. (2023), and Qian et al. (2023). The ESA of AC16 suggests that the forecast skill of the intensity of AC16 is sensitive to the amplitude of an upper-tropospheric trough (T1), and to the strength of an embedded TPV, upstream of AC16, and to the amplitude of an upper-tropospheric ridge (R2) downstream of AC16. The ESA of AC16 also suggests that the forecast skill of the intensity of AC16 is sensitive to the amplitude of a thickness trough upstream of AC16, the amplitude of a thickness ridge downstream of AC16, and to the position of a region of latent heating associated with AC16. Previous studies indicate that accurate forecasts of upper-tropospheric features, including TPVs, troughs, and ridges, are important for an accurate forecast of the intensity and position of ACs (e.g., Yamazaki et al. 2015; Yamagami et al. 2018a, Johnson and Wang 2021; Ban et al. 2023). It is speculated from the ESA of AC16 that accurate forecasts of upper-tropospheric features are important for an accurate forecast of the intensity of AC16. A limitation of the present study is that the ESA is conducted for one strong low-skill AC and should be conducted for multiple strong low-skill ACs to determine the variability in the sensitivity of the forecast skill of the intensity of strong low-skill ACs to selected dynamic and thermodynamic quantities for strong low-skill ACs.

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Data availability statement.

The ERA5 data were obtained from the Copernicus Climate Change Service Climate Data Store (<https://doi.org/10.24381/cds.adbb2d47> and <https://doi.org/10.24381/cds.bd0915c6>). The ECMWF EPS data were obtained from the TIGGE data retrieval portal at ECMWF (<https://apps.ecmwf.int/datasets/data/tigge>).

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*Table and Figure Captions*

Table 1. Dates and lowest SLP attained within the Arctic (hPa) for the strong low-skill ACs.

Fig. 1. Red lines indicate tracks of the strong low-skill ACs, every 6 h, yellow circles indicate locations of the ACs at genesis, and cyan circles indicate locations of the ACs at tlow (i.e., time of lowest SLP attained by the ACs within the Arctic).

Fig. 2. (a) Track (red line) and (b) minimum SLP (red line) of AC16 during 1800 UTC 12–0600 UTC 22 August 2016, every 6 h. Cyan dots in (a) indicate 0000 UTC positions of AC16.

Fig. 3. Positions of AC16 for the ensemble forecasts (colored dots; *N* = 51) at 0000 UTC 15 August 2016 (120 h). Dots are colored and sized by minimum SLP (hPa) at 0000 UTC 15 August 2016 (120 h) according to the legend. The position of AC16 for ERA5 at 0000 UTC 15 August 2016 is given by the “X” within the black circle. The corresponding minimum SLP of AC16 for ERA5 is 972.8 hPa. Black contours denote SLP (hPa) from ERA5 at 0000 UTC 15 August 2016.

Fig. 4. AC-centered composites for the strong low-skill ACs of 300-hPa wind speed (m s−1; shading), 1000–500-hPa thickness (dam; dashed red and blue contours), and SLP (hPa; black contours) at (a) tlow−48 h, (b) tlow−36 h, (c) tlow−24 h, (d) tlow−12 h, (e) tlow, and (f) tlow+12 h. The green dot shows the location of the composite AC.

Fig. 5. AC-centered composites for the strong low-skill ACs of 850–600-hPa EGR (day−1; shading) and SLP (hPa; black contours) at (a) tlow−48 h, (b) tlow−36 h, (c) tlow−24 h, (d) tlow−12 h, (e) tlow, and (f) tlow+12 h. The cyan dot shows the location of the composite AC.

Fig. 6. AC-centered composites for the strong low-skill ACs of 350–250-hPa divergence area averaged within 200 km of each grid point (10−6 s−1; shading), 350–250-hPa irrotational wind (m s−1; vectors), 350–250-hPa PV (PVU; dark gray contours), and 800–600-hPa ω (only negative values every 1 × 10−3 hPa s−1 are shown; red contours) at (a) tlow−48 h, (b) tlow−36 h, (c) tlow−24 h, (d) tlow−12 h, (e) tlow, and (f) tlow+12 h. The green dot shows the location of the composite AC.

Fig. 7. AC-centered composites for the strong low-skill ACs of 1000–300-hPa IVT (kg m−1 s−1; shading and vectors), 1000–300-hPa IMFC area averaged within 200 km of each grid point (only positive values every 100 W m−2 are shown; blue contours), and 700-hPa geopotential height (dam; black contours) at (a) tlow−48 h, (b) tlow−36 h, (c) tlow−24 h, (d) tlow−12 h, (e) tlow, and (f) tlow+12 h. The cyan dot shows the location of the composite AC.

Fig. 8. ERA5 analyses of 300-hPa wind speed (m s−1; shading), 1000–500-hPa thickness (dam; dashed red and blue contours), and SLP (hPa; black contours) for AC16 at (a) 0000 UTC 14 August (tlow−48 h), (b) 1200 UTC 14 August (tlow−36 h), (c) 0000 UTC 15 August (tlow−24 h), (d) 1200 UTC 15 August (tlow−12 h), (e) 0000 UTC 16 August (tlow), and (f) 1200 UTC 16 August 2016 (tlow+12 h). The green dot shows the location of AC16.

Fig. 9. ERA5 analyses of 850–600-hPa EGR (day−1; shading) and SLP (hPa; black contours) for AC16 at (a) 0000 UTC 14 August (tlow−48 h), (b) 1200 UTC 14 August (tlow−36 h), (c) 0000 UTC 15 August (tlow−24 h), (d) 1200 UTC 15 August (tlow−12 h), (e) 0000 UTC 16 August (tlow), and (f) 1200 UTC 16 August 2016 (tlow+12 h). The cyan dot shows the location of AC16.

Fig. 10. ERA5 analyses of 350–250-hPa divergence area averaged within 200 km of each grid point (10−6 s−1; shading), 350–250-hPa irrotational wind (m s−1; vectors), 350–250-hPa PV (PVU; dark gray contours), and 800–600-hPa ω (only negative values every 2 × 10−3 hPa s−1 are shown; red contours) for AC16 at (a) 0000 UTC 14 August (tlow−48 h), (b) 1200 UTC 14 August (tlow−36 h), (c) 0000 UTC 15 August (tlow−24 h), (d) 1200 UTC 15 August (tlow−12 h), (e) 0000 UTC 16 August (tlow), and (f) 1200 UTC 16 August 2016 (tlow+12 h). The green dot shows the location of AC16.

Fig. 11. ERA5 analyses of 1000–300-hPa IVT (kg m−1 s−1; shading and vectors), 1000–300-hPa IMFC area averaged within 200 km of each grid point (only positive values every 250 W m−2 are shown; blue contours), and 700-hPa geopotential height (dam; black contours) for AC16 at (a) 0000 UTC 14 August (tlow−48 h), (b) 1200 UTC 14 August (tlow−36 h), (c) 0000 UTC 15 August (tlow−24 h), (d) 1200 UTC 15 August (tlow−12 h), (e) 0000 UTC 16 August (tlow), and (f) 1200 UTC 16 August 2016 (tlow+12 h). The cyan dot shows the location of AC16.

Fig. 12. Sensitivity of *JAC* to 250-hPa PV area averaged within 200 km of each grid point (hPa; shading) and ensemble mean 250-hPa PV area averaged within 200 km of each grid point (PVU; dark gray contours) for AC16 at (a) 0000 UTC 10 August (0 h), (b) 1200 UTC 10 August (12 h), (c) 0000 UTC 11 August (24 h), and (d) 1200 UTC 11 August 2016 (36 h). Regions of white stippling enclosed by white contours indicate where sensitivity is statistically significant at the 95% confidence level. Black dot indicates ERA5 position of AC16 at 0000 UTC 15 August 2016. Labels “R1” and “T1” indicate the positions of these respective features, which are defined in the text. Label “Iceland” and arrow in (a) indicate the location of Iceland. Positive values of sensitivity given by warm colors indicate that increasing 250-hPa PV area averaged within 200 km of each grid point is associated with a decrease in *JAC* and thus associated with a more accurate intensity forecast of AC16. Negative values of sensitivity given by cool colors indicate that decreasing 250-hPa PV area averaged within 200 km of each grid point is associated with a decrease in *JAC* and thus associated with a more accurate intensity forecast of AC16.

Fig. 13. As in Fig. 12, but at (a) 0000 UTC 12 August (48 h), (b) 1200 UTC 12 August (60 h), (c) 0000 UTC 13 August (72 h), (d) 1200 UTC 13 August (84 h), (e) 0000 UTC 14 August (96h), and (f) 1200 UTC 14 August 2016 (108 h). Labels “R1”, “R2”, and “T1” indicate the positions of these respective features, which are defined in the text.

Fig. 14. As in Fig. 12, but for sensitivity of *JAC* to 1000–500-hPa thickness (hPa; shading)

and ensemble mean 1000–500-hPa thickness (dam; black contours) for AC16 at (a) 0000 UTC 13 August (72 h), (b) 1200 UTC 13 August (84 h), (c) 0000 UTC 14 August (96 h), and (d) 1200 UTC 14 August 2016 (108 h).

Fig. 15. As in Fig. 12, but for sensitivity of *JAC* to 1000–850-hPa IMFC area averaged within

200 km of each grid point (hPa; shading), ensemble mean 1000–850-hPa IMFC area averaged within 200 km of each grid point [every 80 W m−2; black contours (solid for positive values and dashed for negative values)], and ensemble mean 1000–850-hPa IVT (kg m−1 s−1; vectors) for AC16 at (a) 0000 UTC 13 August (72 h), (b) 1200 UTC 13 August (84 h), (c) 0000 UTC 14 August (96 h), and (d) 1200 UTC 14 August 2016 (108 h).