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

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1. **Introduction**
	1. Define Arctic cyclones (ACs) (e.g., Serreze 1995; Crawford and Serreze 2016), and discuss potential hazards associated with ACs (e.g., Zhang et al. 2013; Thomson and Rogers 2014).
	2. Discuss that there has been a recent increase in studies that examine features and processes influencing the evolution of ACs from a case study perspective (e.g., Simmonds and Rudeva 2012; Tao et al. 2017a,b; Qian et al. 2023) and from a composite perspective (e.g., Clancy et al. 2022; Vessey et al. 2022).
	3. Discuss that tropopause polar vortices (TPVs) (e.g., Cavallo and Hakim 2010; Tao et al. 2017a,b; Yamagami et al. 2017) and baroclinic processes (e.g., Tao et al. 2017a,b; Yamagami et al. 2017) have been shown to influence the evolution of ACs.
	4. Discuss that 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.
	5. Discuss that a strong AC that occurred during August 2016, hereafter referred to as AC16, is a notable example of an AC in the literature for which TPVs, baroclinic processes, and latent heating have been shown to influence the evolution of ACs (e.g., Yamagami et al. 2017; Ban et al. 2023; Qian et al. 2023).
	6. Discuss that forecast errors related to upper-tropospheric features (e.g., Langland et al. 2002; Lamberson et al. 2016), forecast errors related to baroclinic processes (e.g., Sanders 1986; Zhu and Thorpe 2006), and forecast errors related to latent heating (e.g., Zhang et al. 2003, 2007) have been shown to contribute to forecast errors in midlatitude cyclones.
	7. Discuss that 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 ACs.
	8. Discuss that the forecast skill of ACs has been shown to be sensitive to the position an intensity of TPVs (e.g., Yamazaki et al. 2015; Yamagami et al. 2018; Johnson and Wang 2021) and the strength of tropospheric baroclinicity (e.g., Tao et al. 2017b).
	9. Discuss that the ensemble sensitivity analysis (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 ACs (e.g., Johnson and Wang 2021).
	10. Discuss that Biernat et al. (2023) identified ACs that are characterized by low forecast skill of intensity and that occur during periods of low forecast skill of the synoptic-scale flow over that Arctic, and that Biernat et al. (2023) referred to these ACs as low-skill ACs during low-skill periods.
	11. Discuss that Biernat et al. (2023) find that low-skill ACs during low-skill periods tend to be located in regions of relatively large lower-tropospheric baroclinicity, lower-to-midtropospheric Eady growth rate (EGR), and latent heating.
	12. Discuss that 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.
	13. Indicate that strong low-skill ACs are of interest because these ACs may pose large challenges to human activities in the Arctic that may be impacted by potential hazardous weather conditions associated with these ACs.
	14. Indicate that to address the objective of the present study, AC-centered composites of strong low-skill ACs are constructed, and a synoptic-dynamic analysis and ESA of a selected strong low-skill AC are conducted.
	15. Indicate that the selected strong low-skill AC is AC16.
2. **Data and methods**
3. *AC-Centered Composites of Strong Low-skill ACs*
	1. Discuss that the strong low-skill ACs defined in section 1 are identified as 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.
	2. Discuss that the tracks of the strong low-skill ACs in Biernat et al. (2023) are based on 6-h SLP data from the ERA-Interim at 1° horizontal grid spacing.
	3. Discuss that the strong low-skill ACs are now tracked using 6-h SLP data from ERA5 at 0.25° horizontal grid spacing and discuss how the tracking is done.
	4. Use Fig. 1 to discuss the tracks of the strong low-skill ACs and use Table 1 to discuss the lowest SLP attained by the strong low-skill ACs within the Arctic.
	5. Discuss that 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).
	6. Discuss that lag times of tlow−48 h to tlow+12 h, every 12 h, are focused on to examine the evolution of the strong low-skill ACs when these ACs intensify and reach peak intensity.
	7. Discuss the AC-centered compositing procedure, which involves shifting, rotating, and reprojecting ERA5 grids of selected dynamic and thermodynamic quantities such that the center of each strong low-skill AC (i.e., location of minimum SLP) is positioned at the mean latitude and mean longitude of the strong low-skill ACs at each lag time.
4. *Analysis of AC16*
	1. Discuss that features and processes influencing the evolution and forecast skill of the intensity of a strong low-skill AC that occurred during 12–22 August 2016, i.e., AC16, are examined.
	2. Discuss the track (Fig. 2a) and intensity time series (Fig. 2b) of AC16.
	3. Discuss that ERA5 is utilized to identify features and processes influencing the evolution of AC16.
	4. Discuss that the 51-member ECMWF Ensemble Prediction System (EPS) at 0.5° horizontal grid spacing is utilized to examine features and processes influencing the forecast skill of the intensity of AC16.
	5. Discuss that ensemble forecasts initialized at 0000 UTC 10 August 2016 and verifying at 0000 UTC 15 August 2016 (120 h) are utilized as the corresponding ensemble forecasts from the 11-member GEFS reforecast dataset version 2 were identified in Biernat et al. (2023, section 3a) as low-skill forecasts of the synoptic-scale flow over the Arctic.
	6. Discuss that the intensity and position of AC16 is manually identified in each ensemble forecast at 0000 UTC 15 August 2016 (120 h).
	7. Use Fig. 3 to show that there is large uncertainty in the intensity of AC16 at 0000 UTC 15 August 2016 (120 h).
	8. Discuss that the ESA technique (e.g., Torn and Hakim 2008) is utilized to examine the sensitivity of the forecast skill of the intensity of AC16 to selected dynamic and thermodynamic quantities at earlier forecast lead times.
	9. Discuss the equation utilized in the ESA technique to determine the sensitivity of a forecast metric of interest to a model state variable at an earlier lead time.
	10. Indicate that sensitivity is determined to be statistically significant at the 95% confidence level by following the methodology of Torn and Hakim (2008).
	11. Discuss that the forecast metric chosen, hereafter referred to as *JAC*, is the minimum SLP of AC16 in the ensemble forecasts at 0000 UTC 15 August 2016 (120 h), as this metric is a proxy for the intensity error of AC16.
	12. Indicate that Johnson and Wang (2021) conduct an ESA of an AC occurring during July 2018 and similarly use minimum SLP as a metric for the intensity error of the AC.
5. **Results**
6. *AC-Centered Composites of Strong Low-skill ACs*
	1. Discuss that the composite AC is located in a region of strong lower-to-midtropospheric baroclinicity between a thickness trough and ridge at tlow−48 h (Fig. 4a).
	2. Discuss that 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), suggesting that the composite AC is in a favorable region for intensification.
	3. Discuss that between tlow−48 h and tlow−12 h, the two jet streaks evolve into a cyclonically curved jet streak between the thickness trough and ridge (Figs. 4a–d), with the composite AC continuing to be in a region of strong lower-to-midtropospheric baroclinicity (Figs. 4a–d).
	4. Discuss that 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).
	5. Summarize from Figs. 4a–d and Figs. 5a–d that baroclinic processes likely play an important role in the intensification of the strong low-skill ACs.
	6. Discuss that lower-to-midtropospheric baroclinicity weakens considerably in the vicinity of the composite AC duringtlow through tlow+12 h as the composite AC reaches peak intensity and begins to weaken (Figs. 4e,f).
	7. Discuss that 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 strong low-skill ACs become occluded and equivalent barotropic in structure.
	8. Discuss that the composite AC is positioned downstream of an upper-tropospheric potential vorticity (PV) maximum at tlow−48 h (Figs. 6a) and discuss that the PV maximum is likely a signature of TPVs.
	9. Discuss that the PV maximum 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.
	10. Discuss that the upper-tropospheric PV maximum becomes positioned over the composite AC at tlow and tlow+12 h (Figs. 6e,f), suggesting that the strong low-skill ACs become equivalent barotropic in structure.
	11. Discuss that there is a well-defined integrated water vapor transport (IVT) corridor that gradually wraps cyclonically from the southern to northern flank of the composite AC during tlow−48 h through tlow−12 h (Figs. 7a–d), and a well-defined region of integrated horizontal moisture flux convergence (IMFC) in the vicinity of the composite AC during tlow−48 h through tlow−12 h (Figs. 7a–d).
	12. Discuss that the IVT corridor may be a manifestation of warm conveyor belts and/or atmospheric rivers associated with the strong low-skill ACs.
	13. State that the region of IMFC implies that latent heating is occurring in the vicinity of the strong low-skill ACs and that the latent heating is likely contributing to the intensification of the strong low-skill ACs.
	14. State that regions of lower-to-midtropospheric ascent, upper-tropospheric divergence, and upper-tropospheric irrotational outflow in the vicinity of the composite AC during tlow−48 h through tlow−12 h (Figs. 6a–d) are likely signatures of the latent heating.
	15. Indicate that the magnitudes of IVT and IMFC decrease substantially as the composite AC reaches peak intensity and begins to weaken during tlow through tlow+12 h (Figs. 7e,f).
	16. Compare the results of the composites in the present subsection with the results of previous studies that have examined features and processes influencing the evolution of ACs (e.g., Tao et al. 2017a,b; Yamagami et al. 2017; Vessey et al. 2022).
7. *ERA5 Synoptic-Dynamic Overview of AC16*
	1. Discuss that 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 upper-tropospheric jet coupling associated with dual upper-tropospheric jet streaks (Fig. 8a).
	2. Discuss that 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).
	3. Discuss that 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.
	4. Discuss that 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.
	5. Discuss that 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).
	6. Discuss that the TPV becomes positioned over AC16 as AC16 reaches peak intensity and shortly afterward during 0000–1200 UTC 16 August (Figs. 10e,f), suggesting that AC16 becomes equivalent barotropic in structure.
	7. Discuss how regions of lower-to-midtropospheric ascent, upper-tropospheric divergence, and upper-tropospheric irrotational outflow (Fig. 10a), and regions of strong IMFC associated with a strong IVT corridor (Fig. 11a), at 0000 UTC 14 August are indicative of latent heating occurring in the vicinity of AC16.
	8. Discuss that the IVT corridor and associated regions of IMFC persist and gradually weaken during 1200 UTC 14–1200 UTC 16 August (Figs. 11b–f).
	9. Summarize that the evolution of AC16 appears to be influenced by a TPV, TPV–
	AC interactions, baroclinic processes, and latent heating.
	10. Discuss how Yamagami et al. (2017), Ban et al. (2023), and Qian et al. (2023) also show that baroclinic processes and TPVs influence the evolution of AC16, and how Qian et al. (2023) show that latent heating influences the evolution of AC16.
8. *ESA of AC16*
	1. Indicate that the sensitivity of *JAC* (defined in section 2b) to selected dynamic and thermodynamic quantities is presented in this section.
	2. Indicate that 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*.
	3. Indicate that since *JAC* is defined as the minimum SLP of AC16 at 0000 UTC 15 August (120 h), lower values of *JAC* are associated with stronger AC16, and a correspondingly more accurate intensity prediction of AC16, at 0000 UTC 15 August (120 h).
	4. Accordingly, a more accurate intensity prediction 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.
	5. State that the sensitivity of *JAC* to upper-tropospheric PV is first examined to determine the sensitivity of the intensity prediction of AC16 to upper-tropospheric features.
	6. Discuss that 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) and an upper-tropospheric trough (T1) during 1200 UTC 10–1200 UTC 11 August (12–36 h) (Figs. 12b–d).
	7. Discuss that the region of negative sensitivity of *JAC* to upper-tropospheric PV during 1200 UTC 10–1200 UTC 11 August (12–36 h) suggests that shifting R1 slightly farther east during this period is associated with a more accurate intensity prediction of AC16.
	8. Discuss that 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).
	9. Indicate that embedded within T1 is the TPV located upstream of AC16 that was discussed in section 3c.
	10. Discuss that 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).
	11. Indicate that AC16 develops and intensifies between T1 and R2.
	12. Discuss that 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, are associated with a more accurate intensity prediction of AC16.
	13. Discuss that the sensitivity of *JAC* to 1000–500-hPa thickness is next examined to determine the sensitivity of the intensity prediction of AC16 to the thermal structure of the lower-to-middle troposphere.
	14. Discuss that 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), and that this region of negative sensitivity persists and grows in size during 1200 UTC 13–1200 UTC 14 August (84–108 h) (Figs. 14b–d).
	15. Discuss that there is a region of positive sensitivity of *JAC* to 1000–500-hPa thickness that increases in magnitude and size 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).
	16. Indicate that AC16 intensifies between the thickness trough and ridge.
	17. Discuss that the aforementioned regions of negative and positive sensitivity of *JAC* to 1000–500-hPa thickness suggest that a more amplified thickness trough and a more amplified thickness ridge are associated with a more intense AC16 and hence a more accurate intensity prediction of AC16.
	18. Last discuss the sensitivity of *JAC* to lower-tropospheric IMFC to determine the sensitivity of the intensity prediction of AC16 to latent heating.
	19. Discuss that there is small region positive sensitivity of *JAC* to lower-tropospheric IMFC northeast of Scandinavia at 0000 UTC 13 August (72 h) (Fig. 15a) that increases in magnitude and size over the northwestern flank of a region of lower-tropospheric IMFC associated with AC16 during 1200 UTC 13–1200 UTC 14 August (84–108 h) (Figs. 15­b–d).
	20. Discuss that the region of positive sensitivity of *JAC* to lower-tropospheric IMFC suggests that that a northwestward shift in the region of latent heating associated with AC16 during this period is associated with a more accurate intensity prediction of AC16.
	21. Compare the results in the present subsection with the results of previous studies that have examined features and processes influencing the forecast skill of ACs (e.g., Yamazaki et al. 2015; Yamagami et al. 2018; Johnson and Wang 2021).
9. **Summary and Conclusions**
	1. State that 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.
	2. State the composite analysis for the strong low-skill ACs suggests that these ACs are associated with a well-defined IVT corridor and well-defined region of IMFC that implies latent heating.
	3. State that the composite analysis for the strong low-skill ACs suggests that TPVs, TPV–AC interactions, baroclinic processes, and latent heating likely support the intensification of these ACs.
	4. State that 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.
	5. State that the synoptic-dynamic analysis of AC16 indicates that a TPV, TPV–AC interactions, baroclinic processes, and latent heating appear to influence the evolution of AC16.
	6. State that 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.
	7. State that the ESA of AC16 suggests that the forecast skill of the intensity of AC16 is also sensitive to the amplitude of 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.
	8. Speculate that 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.
	9. Speculate that 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.
	10. Speculate that a more amplified thickness trough and ridge 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.
	11. Discuss that 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 across strong low-skill ACs.

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