**4. Features and processes influencing the forecast skill of a selected strong low-skill AC**

*a. Overview and objectives*

In this chapter, hypothesis 5 is addressed. Hypothesis 5 states that forecast errors in TPVs, baroclinic zones, and WCBs, and forecast errors in TPV–AC interactions, baroclinic processes, and latent heating, contribute to forecast errors in strong low-skill ACs during low-skill periods. Hypothesis 5 is addressed by analyzing and comparing ensemble forecasts of a strong low-skill AC that occurred during 13–19 August 2016 (i.e., AC16), which is a representative member of the strong low-skill ACs during low-skill periods from section 3c(1). AC16 tracks east-northeastward north of Eurasia during 13–19 August in ERA5 (Fig. 4.1a). AC16 quickly intensifies during 13–15 August, reaching a peak intensity of 968.5 hPa at 0000 UTC 16 August in ERA5 (Fig. 4.1b).

*b. Data and methods*

ERA5 is utilized to perform a synoptic-dynamic analysis of AC16 and to identify features and processes influencing the evolution of AC16. Forecasts from the 51-member ECMWF EPS that are extracted from The Observing System Research and Predictability Experiment (THORPEX) Interactive Grand Global Ensemble (TIGGE) (Bougeault et al. 2010) and download at 0.5° horizontal resolution are utilized to examine the forecast skill of the intensity and position of AC16. Ensemble forecasts of the intensity and position of AC16 from the ECMWF EPS initialized at 0000 UTC 10 August and verifying at 0000 UTC 15 August (120 h) are focused on, as the corresponding ensemble forecasts of the intensity of AC16 in the GEFS reforecast dataset version 2 were determined in section 2b(4) to be characterized by low forecast skill.

AC16 is tracked in the ensemble forecasts by utilizing the objective SLP-based cyclone tracking algorithm developed by Crawford et al. (2020). The cyclone matching procedure described in section 2b(4) is used to find the matching forecast AC track corresponding to AC16 in each ensemble forecast. If no matching forecast AC track is identified in an ensemble forecast, AC16 is manually identified and tracked in the ensemble forecast. The intensity error and position error of AC16 is calculated for each ensemble forecast at 0000 UTC 15 August (120 h). The intensity error of AC16 is calculated as the absolute difference in minimum SLP between AC16 in the ensemble forecast and AC16 in ERA5. The position error of AC16 is calculated as the great circle distance between the location of minimum SLP of AC16 in the ensemble forecast and the location of minimum SLP of AC16 in ERA5. Figure 4.2 shows the position and intensity of AC16 at 0000 UTC 15 August (120 h) in ERA5 and the ensemble forecasts. The ensemble forecasts show that there is large uncertainty in the position and intensity of AC16 at 0000 UTC 15 August (120 h) (Fig. 4.2). Intensity errors among the ensemble forecasts range from 0.2 to 29.0 hPa and position errors among the ensemble forecasts range from 83 to 1306 km. Ensembles with a more accurate intensity forecast of AC16 tend to have a more accurate position forecast of AC16 (Fig. 4.2). The correlation coefficient (r) between intensity error and position error is 0.72, indicating that intensity error and position error correlate fairly well with each other.

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

, (5)

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).

A forecast metric *J* that is representative of both intensity error and position error of AC16 is determined. Average SLP within a circle surrounding the ERA5 position of AC16 at 0000 UTC 15 August (120 h) is used as a proxy for intensity error and position error of AC16, with lower average SLP within the circle anticipated to correspond with smaller intensity error and smaller position error of AC16. Circles with radii of 100–1200 km, every 100 km, are tested. A radius of 700 km is found to be optimal for correlating average SLP within the circle with intensity error and with position error. The correlation coefficient (r) between average SLP within the 700-km circle and intensity error at 0000 UTC 15 August (120 h) (circle shown in Fig. 4.2) is 0.76, which is the highest value of all radii tested. The correlation coefficient (r) habetween average SLP within the 700-km circle and position error at 0000 UTC 15 August (120 h) is 0.87, which is the second highest value of all radii tested. Therefore, average SLP within the 700-km circle at 0000 UTC 15 August (120 h) is utilized as the forecast metric, which is hereafter referred to as *J*AC.

In addition to utilizing the ESA technique, the most-accurate and least-accurate ensemble forecasts of AC16 are identified and compared to understand how features and processes influencing AC16 evolve differently between these respective categories of forecasts. The most-accurate and least-accurate ensemble forecasts of AC16 are determined by adopting the methodology used by Lamberson et al. (2016) to identify the most-accurate ensemble forecasts of a strong midlatitude cyclone. The ensemble forecasts initialized at 0000 UTC 10 August are utilized. At each forecast time from 1200 UTC 13 August (84 h) through 0000 UTC 16 August (144 h), every 12 h, the intensity error and position error of AC16 for each ensemble forecast is calculated as described earlier. The intensity errors and position errors are then averaged over time for each ensemble forecast. The ensemble forecasts are ranked 1 to 51 for average intensity error and for average position error. The intensity error ranks and position error ranks are then added together. The 10 ensemble forecasts with the lowest combined intensity and position error ranks are considered the most-accurate ensemble forecasts, and the 10 ensemble forecasts with the highest combined intensity and position error ranks are considered the least-accurate ensemble forecasts.

The tracks of AC16 for the most-accurate ensemble forecasts are located farther to the northwest and closer to the track of AC16 for ERA5 compared to the tracks of AC16 for the least-accurate ensemble forecasts (Fig. 4.3a). The intensity time series of AC16 for the most-accurate ensemble forecasts more closely resemble the intensity time series of AC16 for ERA5 compared to the intensity time series of AC16 for the least-accurate ensemble forecasts (Fig. 4.3b). At 0000 UTC 15 August, there are large differences in the intensity of AC16 between the most-accurate and least-accurate ensemble forecasts, with minimum SLP values of AC16 ranging from 968 to 981 hPa for the most-accurate ensemble forecasts and from only 989 to 1002 hPa for the least-accurate ensemble forecasts (Fig. 4.3b).

*c. Results*

1) ERA5 synoptic-dynamic overview

At 1200 UTC 13 August, shortly after AC16 forms, AC16 is positioned in a region of strong lower-to-midtropospheric baroclinicity, between a thickness trough and ridge and beneath a strong upper-tropospheric jet streak (Fig. 4.4a). By 0000 UTC 14 August, the strong upper-tropospheric jet streak splits into dual upper-tropospheric jet streaks (Fig. 4.4b), with AC16 suggested to be intensifying in a region of upper-tropospheric jet coupling. During 0000 UTC 14–0000 UTC 15 August, the thickness trough and ridge amplify, 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. 4.4b–d). Regions of strong lower-to-midtropospheric baroclinicity extending east and south from AC16 during 1200 UTC 13–0000 UTC 15 August (Figs. 4.4a–d) are indicative of warm and cold frontal zones, respectively, associated with AC16. During 1200 UTC 15–0000 UTC 16 August, AC16 reaches peak intensity and lower-to-midtropospheric baroclinicity decreases near the center of AC16 (Figs. 4.4e,f), suggesting that AC16 becomes occluded. Figures 4.4a–d suggest that baroclinic processes play an important role in the development and intensification of AC16, which is in agreement with the findings of Yamagami et al. (2017).

Figures 4.5a–d show that AC16 intensifies downstream of an upper-tropospheric PV maximum that gradually approaches AC16 during 1200 UTC 13–0000 UTC 15 August. The upper-tropospheric PV maximum is indicative of a TPV that interacts with AC16. There is also a second upper-tropospheric PV maximum indicative of a TPV located to the northeast of AC16 over the Arctic during 1200 UTC 13–1200 UTC 14 August (Figs. 4.5a–c). At 0000 UTC 14 August, there is an establishment of enhanced upper-tropospheric PV gradients between an amplifying upper-tropospheric ridge downstream of AC16 and the TPV northeast of AC16 (Fig. 4.5b), and between the aforementioned upper-tropospheric ridge and the TPV upstream of AC16 (Fig. 4.5b). The establishment of the enhanced upper-tropospheric PV gradients likely contributes to the formation of the dual upper-tropospheric jet streaks at 0000 UTC 14 August (Fig. 4.4b). There is a decrease in the vertical tilt between the upstream TPV and AC16 during 1200 UTC 13–0000 UTC 15 August (Figs. 4.5a–d) as AC16 intensifies, which is similarly shown by QG theory for midlatitude cyclones (e.g., Martin 2006, section 8.8). The upstream TPV becomes vertically superposed with AC16 during 1200 UTC 15–0000 UTC 16 August (Figs. 4.5e,f) as AC16 reaches peak intensity, suggesting that AC16 becomes equivalent barotropic in structure. Yamagami et al. (2017) similarly show that a TPV upstream of AC16 gradually approaches AC16 and becomes vertically superposed with AC16. The upstream TPV likely plays an important role in the development and intensification of AC16.

Figures 4.5a–d also show that there are regions of lower-to-midtropospheric ascent and upper-tropospheric divergence in the vicinity of AC16 during 1200 UTC 13–0000 UTC 15 August. Furthermore, there is a “starburst” irrotational wind pattern during 1200 UTC 13–0000 UTC 15 August (Figs. 4.5a–d), which is especially well-defined at 0000 UTC 14 August (Fig. 4.5b). The “starburst” irrotational wind pattern may be a signature of latent heating. Figure 4.6a indicates that there is an IVT corridor southeast of AC16 at 1200 UTC 13 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 southeast and east of AC16 (Fig. 4.6a). By 0000 UTC 14 August, the IVT corridor strengthens east of AC16 and IMFC increases markedly northeast of AC16 (Fig. 4.6b). The region of IMFC indicative of latent heating northeast of AC16 at 0000 UTC 14 August (Fig. 4.6b) coincides with well-defined regions of lower-to-midtropospheric accent and upper-tropospheric divergence (Fig. 4.5b), and with the well-defined “starburst” irrotational wind pattern (Fig. 4.5b), at this time. The latent heating likely contributes to the development and intensification of AC16. The IVT corridor and associated regions of IMFC persist and gradually weaken during 1200 UTC 14–0000 UTC 16 August (Figs. 4.6c–f).

The development and intensification of AC16 appear to be influenced by a TPV, TPV–AC interactions, baroclinic processes, an IVT corridor, and latent heating. The sensitivity of the forecast skill of the intensity and position 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 and position of AC16.

2) ESA results

In this section, the sensitivity of *J*AC to selected dynamic and thermodynamic quantities are presented. All sensitivity values are multiplied by −1, such that positive sensitivity values indicate that increasing the value of the quantity correlates with a decrease in *J*AC. Since *J*AC is correlated with intensity error and position error of AC16 at 0000 UTC 15 August (120 h), lower values of *J*AC correspond with a more accurate prediction of the intensity and position of AC16 at 0000 UTC 15 August (120 h). Negative values of sensitivity indicate that decreasing the value of the quantity correlates with a decrease in *J*AC and thus correlates with a more accurate prediction of the intensity and position of AC16 at 0000 UTC 15 August (120 h). Refer to Fig. 1.2 for a map of geographic features that are discussed throughout the rest of the chapter.

The sensitivity of the prediction of AC16 to upper-tropospheric features is first determined by examining the sensitivity of *J*AC to upper-tropospheric PV. During 0000 UTC 10–1200 UTC 11 August (0–36 h), a region of negative sensitivity of *J*AC to upper-tropospheric PV propagates southeastward from just northeast of Iceland 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 (Figs. 4.7a–d). The region of negative sensitivity of *J*AC to upper-tropospheric PV suggests that shifting R1 slightly farther east during 0000 UTC 10–1200 UTC 11 August (0–36 h) correlates with a more accurate prediction of AC16.

At 0000 UTC 12 August (48 h), the region of negative sensitivity of *J*AC to upper-tropospheric PV persists between R1 and T1 over northern Europe (Fig. 4.8a). Also at 0000 UTC 12 August (48 h), a region of positive sensitivity of *J*AC to upper-tropospheric PV becomes established over portions of Scandinavia and northwestern Russia, within and on the eastern side of T1 (Fig. 4.8a). By 1200 UTC 12 August (60 h), the aforementioned regions of negative and positive sensitivity of *J*AC to upper-tropospheric PV grow in size and magnitude (Fig. 4.8b). The aforementioned region of positive sensitivity of *J*AC to upper-tropospheric PV during 0000–1200 UTC 12 August (48–60 h) suggests that a slightly stronger and slightly more amplified T1 over Scandinavia and northwestern Russia during this period correlate with a more accurate prediction of AC16. Embedded within T1 is the TPV that was discussed in section 4c(1) as being located upstream of AC16. A slightly stronger T1 is likely associated with a slightly stronger TPV. A new region of negative sensitivity of *J*AC to upper-tropospheric PV becomes established at 1200 UTC 12 August (60 h) near the crest of an upper-tropospheric ridge (R2) located downstream of T1 (Fig. 4.8b). The new region of negative sensitivity of *J*AC to upper-tropospheric PV suggests that a slightly more amplified R2 at 1200 UTC 12 August (60 h) correlates with a more accurate prediction of AC16.

During 0000 UTC 13–1200 UTC 14 August (72–108 h), the aforementioned region of positive sensitivity of *J*AC to upper-tropospheric PV increases in size and becomes relatively large in magnitude within and on southeastern side of T1, which propagates east-northeastward from Scandinavia (Figs. 4.8c–f). Also during 0000 UTC 13–1200 UTC 14 August (72–108 h), the region of negative sensitivity of *J*AC to upper-tropospheric PV at the crest of R2 grows in size and magnitude as R2 amplifies (Figs. 4.8c–f). The aforementioned regions of positive and negative sensitivity of *J*AC to upper-tropospheric PV during 0000 UTC 13–1200 UTC 14 Aug (72–108 h) suggest that a farther southeastward positioned and more amplified T1, and a more amplified R2, correlate with a more accurate prediction of AC16.

Since upper-tropospheric features can have a large influence on surface features, the sensitivity of *J*AC to SLP will now be examined. During 0000–1200 UTC 12 Aug (48–60 h), a region of negative sensitivity of *J*AC to SLP increases quickly in magnitude over Scandinavia and northwestern Russia, in a broad region of relatively low SLP (Figs. 4.9a,b). The region of negative sensitivity of *J*AC to SLP increases in magnitude and size during 0000 UTC 13–1200 UTC 14 August (72–108 h) in a region of low SLP that corresponds to AC16 (Figs. 4.9c–f). The region of negative sensitivity of *J*AC to SLP during 0000 UTC 13–1200 UTC 14 August (72–108 h) (Figs. 4.9c–f) is positioned between the regions of positive and negative sensitivity of *J*AC to upper-tropospheric PV associated with T1 and R2, respectively, during this period (Figs. 4.8c–f). The sensitivity patterns in Figs. 4.8c–f and Figs. 4.9c–f suggest that a more amplified T1 and R2 is correlated with lower SLP in between T1 and R2, and thus correlated with a stronger AC16, during 0000 UTC 13–1200 UTC 14 August (72–108 h). A stronger AC16 during 0000 UTC 13–1200 UTC 14 August (72–108 h) correlates with a more accurate prediction of AC16.

As discussed in section 4c(1), latent heating likely contributes to the development and intensification of AC16. The sensitivity of *J*AC to 850-hPa specific humidity and to lower-tropospheric IMFC indicative of latent heating will now be examined. At 0000 UTC 13 August (84 h), there is a small region of positive sensitivity of *J*AC to 850-hPa specific humidity over and near Novaya Zemlya, at the northwestern flank of a moisture corridor extending from western Russia into the Kara Sea (Fig. 4.10a). There is also a region of lower-tropospheric IMFC indicative of latent heating at the northern flank of this moisture corridor (Fig. 4.11a), with a small region of positive sensitivity of *J*AC to lower-tropospheric IMFC over and near Novaya Zemlya (Fig. 4.11a). During 1200 UTC 13–1200 UTC 14 August (84–108 h), the moisture corridor shifts northeastward (Figs. 4.10b–d), and the region of positive sensitivity of *J*AC to 850-hPa specific humidity increases in size and magnitude at the northwestern flank of the moisture corridor (Figs. 4.10b–d). The region of positive sensitivity of *J*AC to lower-tropospheric IMFC concomitantly increases in size and magnitude at the northwestern flank of a region of lower-to-midtropospheric IMFC indicative of latent heating during 1200 UTC 13–1200 UTC 14 August (84–108 h) (Figs. 4.11b­–d).

The aforementioned region of positive sensitivity of *J*AC to 850-hPa specific humidity during 0000 UTC 13­–1200 UTC 14 August (72–108 h) (Figs. 4.10a–d) suggests that a northwestward shift of the moisture corridor during this period correlates with a more accurate prediction of AC16. The aforementioned region of positive sensitivity of *J*AC to lower-tropospheric IMFC during 0000 UTC 13­–1200 UTC 14 August (72–108 h) (Figs. 4.11a–d) suggests that a corresponding northwestward shift in the region of latent heating during this period correlates with a more accurate prediction of AC16. It is unclear from Figs. 4.10a–d and Figs. 4.11a–d as to whether an increase in the amount of moisture in the moisture corridor and an increase in the magnitude of latent heating, respectively, correlate with a more accurate prediction of AC16. The position of the moisture corridor and the position of the region of latent heating may matter more to the predictability of AC16 than the amount of moisture in the moisture corridor and the magnitude of latent heating.

The ESA suggests that the evolution of T1 and an embedded TPV upstream of AC16 has important implications of the evolution of AC16. Relatively small differences in the strength and amplitude of T1, and in the strength of the embedded TPV, during 0000–1200 UTC 12 August (48–60 h) may be associated with increasingly large differences in the amplitude of the downstream upper-tropospheric flow and in the evolution of AC16 during 0000 UTC 13–1200 UTC 14 August (72–108 h). The ESA suggests that a slightly more eastward shifted R1 building into western Eurasia during 0000 UTC 10–0000 UTC 12 August (0–48 h) may be associated with a slightly more amplified and slightly stronger T1, and a slightly stronger embedded TPV, over Scandinavia and northwestern Russia during 0000–1200 UTC 12 August (48–60 h). The small changes in T1 and the embedded TPV during 0000–1200 UTC 12 August (48–60 h) may be associated with greater development of AC16 and greater downstream upper-tropospheric flow amplification by 0000 UTC 13 August (72 h). There then may be a positive feedback between the development of AC16 and the amplification of the downstream upper-tropospheric flow during 0000 UTC 13–1200 UTC 14 August (72–108 h), with an increasingly stronger AC16 being associated with an increasingly amplified downstream upper-tropospheric flow during this period. A stronger AC16 during 0000 UTC 13–1200 UTC 14 August (72–108 h) may be associated with a stronger lower-tropospheric circulation, which may be associated with a northwestward shift in the moisture corridor and region of latent heating in the vicinity of AC16.

The ESA suggests that forecasts errors in T1 and the embedded TPV, and forecast errors in other upper-tropospheric features, contribute to forecast errors in AC16. Yamagami et al. (2018a) and Johnson and Wang (2021) also show that forecast errors in TPVs and other upper-tropospheric features can contribute to forecast errors in ACs. Yamagami et al. (2018a) show via a composite comparison between most-accurate and least-accurate ensemble forecasts of AC12 that accurate prediction of AC12 depends on accurate prediction of TPVs, an upper-tropospheric trough, and an upper-tropospheric ridge, in the vicinity of AC12. Johnson and Wang (2021) find that track error and intensity error of an AC occurring during July 2018 are sensitive to the position and intensity of TPVs, and to the amplitude of a midtropospheric ridge downstream of the AC. Johnson and Wang (2021) also find that intensity error of the AC occurring during July 2018 is sensitive to midtropospheric moisture within a moisture corridor associated with the AC. In the present study, the predictability of AC16 may be more sensitive to the position of the moisture corridor influencing AC16 than to the amount of moisture within the moisture corridor influencing AC16.

Past studies of midlatitude cyclones have similarly shown that forecast errors in the intensity and position of midlatitude cyclones can be linked to forecast errors in upper-tropospheric features like 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 as structures resembling wave-packets. The propagation of coherent regions of sensitivity of *J*AC to upper-tropospheric PV from the North Atlantic, across Eurasia, and into the Arctic during 0000 UTC 10–1200 UTC 14 August (Figs. 4.7a–d and Figs. 4.8a–f) suggest that upper-tropospheric forecast errors influencing the forecast skill of AC16 may similarly propagate as structures resembling wave-packets. The aforementioned suggested propagation of upper-tropospheric forecast errors in Figs. 4.7a–d and Figs. 4.8a–f suggests that upper-tropospheric forecast errors influencing the forecast skill of ACs like AC16 may originate well upstream of the ACs.

3) Comparison between most-accurate and least-accurate ensemble forecasts

Composites of selected dynamic and thermodynamic quantities are constructed for the most-accurate and least-accurate ensemble forecasts for AC16 (forecasts shown in Figs. 4.3a,b) to compare the evolution of features and processes influencing AC16 between these respective categories of forecasts and to expand upon the ESA results. There is variability in the positions of AC16 among the most-accurate ensemble forecasts and among the least-accurate ensemble forecasts (Fig. 4.3b), such that composite smoothing occurs. Therefore, selected dynamic and thermodynamic quantities that are representative of features and processes influencing AC16 are area-averaged within a 1000-km radius from the center of AC16 for each forecast in order to compare these quantities between the most-accurate and least-accurate ensemble forecasts without needing to account for composite smoothing. A bootstrap resampling without replacement test following the second procedure described in section 2b(5) is used to determine whether there are statistically significant differences in the area-averaged quantities between the most-accurate and least-accurate ensemble forecasts.

The influence of baroclinic processes on the development and intensification of AC16 for the most-accurate and least-accurate ensemble forecasts is first examined. At 0000 UTC 13 August (72 h), an area of low SLP corresponding to AC16 is found over the Barents Sea within a region of strong lower-to-midtropospheric baroclinicity and beneath a strong upper-tropospheric jet streak in both the most-accurate ensemble forecasts (Fig. 4.12a) and least-accurate ensemble forecasts (Fig. 4.12b). The strength of lower-to-midtropospheric baroclinicity appears to be comparable between the most-accurate ensemble forecasts (Fig. 4.12a) and least-accurate ensemble forecasts (Fig. 4.12b). However, the area of low SLP corresponding to AC16 is stronger and found between a more amplified thickness trough and ridge in the most-accurate ensemble forecasts (Fig. 4.12a) compared to in the least-accurate ensemble forecasts (Fig. 4.12b).

At 0000 UTC 14 August (96 h), the area of low SLP corresponding to AC16 intensifies quickly between an amplifying thickness trough and ridge in the most-accurate ensemble forecasts (Fig. 4.12c). Furthermore, the strong upper-tropospheric jet streak at 0000 UTC 13 August (72 h) (Fig. 4.12a) appears to evolve into dual upper-tropospheric jet streaks by 0000 UTC 14 August (96 h) (Fig. 4.12c) in the most-accurate ensemble forecasts, with AC16 suggested to intensify in a region of upper-tropospheric jet coupling. The formation of the dual upper-tropospheric jet streaks is likely related to the reconfiguration of the region of strong lower-to-midtropospheric baroclinicity in the vicinity of AC16 during 0000 UTC 13–0000 UTC 14 August (72–96 h) (Figs. 4.12a,c), which likely occurs partly in response to lower-to-midtropospheric thermal advection in the vicinity of AC16. There is no coherent area of low SLP corresponding to AC16 at 0000 UTC 14 August (96 h) in the least-accurate ensemble forecasts (Fig. 4.12d), which is partially due to composite smoothing. Furthermore, there is only a low-amplitude thickness trough and ridge over and near northern Eurasia, and a flat upper-tropospheric jet streak over and near the northern Eurasian coast, in the least-accurate ensemble forecasts at 0000 UTC 14 August (96 h) (Fig. 4.12d).

A more amplified thickness trough in the most-accurate ensemble forecasts (Fig. 4.12c) compared to in the least-accurate ensemble forecasts (Fig. 4.12d) may be associated with greater thermal vorticity, such that there may be greater advection of thermal vorticity by the thermal wind over AC16 in the most-accurate ensemble forecasts. Greater advection of thermal vorticity by the thermal wind may contribute to the greater development and intensification of AC16 in the most-accurate ensemble forecasts. At 0000 UTC 15 August (120 h), the area of low SLP corresponding to AC16 is found in the poleward exit region of a cyclonically curved upper-tropospheric jet streak in the most-accurate ensemble forecasts (Fig. 4.12e), and there continues to be no coherent area of low SLP corresponding to AC16 in the least-accurate ensemble forecasts (Fig. 4.12f).

The ESA suggested that a more amplified upper-tropospheric flow is correlated with a more accurate prediction of AC16. At 0000 UTC 13 August (72 h), there is clearly a more amplified T1 and R2 over northwestern Eurasia and the adjacent Arctic in the most-accurate ensemble forecasts (Fig. 4.13a) compared to in the least-accurate ensemble forecasts (Fig. 4.13b). Furthermore, T1 is characterized by higher values of upper-tropospheric PV in the most-accurate ensemble forecasts (Fig. 4.13a) compared to in the least-accurate ensemble forecasts (Fig. 4.13b), suggesting that there may be a stronger TPV embedded in T1 in the most-accurate ensemble forecasts. Between the more amplified T1 and R2 is a region of much stronger upper-tropospheric divergence and irrotational outflow in the most-accurate ensemble forecasts (Fig. 4.13a) compared to in the least-accurate ensemble forecasts (Fig. 4.13b). The much stronger upper-tropospheric divergence and irrotational outflow likely contribute to the greater development and intensification of AC16 in the most-accurate ensemble forecasts.

By 0000 UTC 14 August (96 h), R2 amplifies over Eurasia and the adjacent Arctic in the most-accurate ensemble forecasts (Fig. 4.13c), but is fairly flat over Eurasia in the least-accurate ensemble forecasts (Fig. 4.13d). There continues to be a region of much stronger upper-tropospheric divergence and irrotational outflow in the most-accurate ensemble forecasts (Fig. 4.13c) compared to in the least-accurate ensemble forecasts (Fig. 4.13d). By 0000 UTC 15 August (120 h), R2 remains more amplified in the most-accurate ensemble forecasts (Fig. 4.13e) compared to in the least-accurate ensemble forecasts (Fig. 4.13f).

The stronger upper-tropospheric irrotational outflow in the most-accurate ensemble forecasts may suggest that there is greater latent heating in the most-accurate ensemble forecasts. At 0000 UTC 13 August (72 h), there is a lower-tropospheric IVT corridor over western Russia that is of comparable magnitude between the most-accurate ensemble forecasts (Fig. 4.14a) and least-accurate ensemble forecasts (Fig. 4.14b). However, the lower-tropospheric IVT corridor is more poleward directed in the most-accurate ensemble forecasts (Fig. 4.14a) compared to in the least-accurate ensemble forecasts (Fig. 4.14b). There is also greater lower-tropospheric IMFC indicative of greater latent heating over and near Novaya Zemlya, near the developing AC16, in the most-accurate ensemble forecasts (Fig. 4.14a) compared to in the least-accurate ensemble forecasts (Fig. 4.14b). The greater lower-tropospheric IMFC over and near Novaya Zemlya in the most-accurate ensemble forecasts likely relates to the stronger lower-tropospheric IVT over and near Novaya Zemlya in the most-accurate ensemble forecasts (Fig. 4.14a) compared to in the least-accurate ensemble forecasts (Fig. 4.14b). The greater lower-tropospheric IMFC over and near Novaya Zemlya in the most-accurate ensemble forecasts may also relate to greater upper-tropospheric dynamical forcing that is likely associated with the suggested stronger TPV embedded in T1 in the most-accurate ensemble forecasts (Fig. 4.13a) compared to in the least-accurate ensemble forecasts (Fig. 4.13b).

By 0000 UTC 14 August (96 h), there is a stronger and more northwestward positioned corridor of IVT, and a region of larger lower-tropospheric IMFC indicative of greater latent heating, in the most-accurate ensemble forecasts (Fig. 4.14c) compared to in the least-accurate ensemble forecasts (Fig. 4.14d). By 0000 UTC 15 August (120 h), the lower-tropospheric IVT corridor and associated regions of lower-tropospheric IMFC weaken considerably in both the most-accurate ensemble forecasts (Fig. 4.14e) and least-accurate ensemble forecasts (Fig. 4.14f).

Figure 4.15a shows that the mean value of area-averaged lower-to-midtropospheric Eady growth rate at 0000 UTC 14 August (96 h) is larger for the most-accurate ensemble forecasts (0.85 day−1) compared to the least-accurate ensemble forecasts (0.81 day−1), but that the difference between these mean values is not statistically significant. Therefore, AC16 intensifies in regions of comparable lower-to-midtropospheric Eady growth rates in the most-accurate and least-accurate ensemble forecasts. The comparable lower-to-midtropospheric Eady growth rates are likely related to the comparable strength of lower-to-midtropospheric baroclinicity between the most-accurate ensemble forecasts (Fig. 4.12c) and least-accurate ensemble forecasts (Fig. 4.12d) over and near the northern Eurasian coast at 0000 UTC 14 August (96 h). Figure 4.15b indicates that the mean value of area-averaged upper-tropospheric PV at 0000 UTC 14 August (96 h) is statistically significantly larger for the most-accurate ensemble forecasts (8.6 PVU) compared to the least-accurate ensemble forecasts (8.0 PVU). Similarly, Fig. 4.15c indicates that the mean value of area-averaged 500-hPa relative vorticity at 0000 UTC 14 August (96 h) is statistically significantly larger for the most-accurate ensemble forecasts (6.0 × 10−5 s−1) compared to the least-accurate ensemble forecasts (5.0 × 10−5 s−1). The statistically significantly larger area-averaged upper-tropospheric PV and statistically significantly larger area-averaged 500-hPa relative vorticity for the most-accurate ensemble forecasts suggest that the TPV embedded in T1 is stronger for the most-accurate ensemble forecasts. A stronger TPV embedded in T1 in the most-accurate ensemble forecasts may be associated with larger TPV–AC interactions that support the greater intensification of AC16 in the most-accurate ensemble forecasts.

Figure 4.15d shows that the mean value of area-averaged 300-hPa irrotational wind magnitude at 0000 UTC 14 August (96 h) is statistically significantly larger for the most-accurate ensemble forecasts (3.0 m s−1) compared to the least-accurate ensemble forecasts (2.3 m s−1). The mean value of area-averaged lower-tropospheric IVT at 0000 UTC 14 August (96 h) is also statistically significantly larger for the most-accurate ensemble forecasts (97 kg m−1 s−1) compared to the least-accurate ensemble forecasts (84 kg m−1 s−1) (Fig. 4.15e). The statistically significantly larger area-averaged 300-hPa irrotational wind magnitude and statistically significantly larger area-averaged lower-tropospheric IVT for the most-accurate ensemble forecasts suggest that there may be statistically significantly greater latent heating for the most-accurate ensemble forecasts. However, the mean value of area-averaged lower-tropospheric IMFC at 0000 UTC 14 August (96 h) is only slightly larger for the most-accurate ensemble forecasts (465 W m−2) compared to the least-accurate ensemble forecasts (433 W m−2), suggesting that latent heating is comparable between the most-accurate and least-accurate ensemble forecasts.

Therefore, there are mixed signals as to whether there are statistically significant differences in latent heating between the most-accurate and least-accurate ensemble forecasts.

It is possible that area-averaged IVT may be larger for the most-accurate ensemble forecasts due to there possibly being a more widespread region of relatively high values of IVT in the vicinity of AC16 in the most-accurate ensemble forecasts. It is possible that the maximum magnitude of IVT may be comparable between the most-accurate and least-accurate ensemble forecasts. The maximum value of IVT within a 1000-km radius from the center of AC16 for each of the most-accurate and least-accurate ensemble forecasts is determined at 0000 UTC 14 August (96 h). The mean maximum value of IVT is only slightly larger for the most-accurate ensemble forecasts (322 kg m−1 s−1) compared to the least-accurate ensemble forecasts (304 kg m−1 s−1) (not shown), and the difference between the mean values are not statistically significant. The IVT corridor being of comparable maximum magnitude between the most-accurate and least-accurate ensemble forecasts may help explain the comparable lower-tropospheric IMFC between the most-accurate and least-accurate ensemble forecasts. It is possible that the differences in upper-tropospheric irrotational wind magnitude between the most-accurate and least-accurate ensemble forecasts may relate more to the differences in upper-tropospheric flow amplitude between these respective categories of forecasts than to differences in latent heating between these respective categories of forecasts.

The foregoing analyses of the most-accurate and least-accurate ensemble forecasts suggest that an important distinction between these respective categories of forecasts is the amplitude and strength of T1, and the strength of an embedded TPV, upstream of AC16, which is consistent with the ESA results. There appears to be comparable lower-to-midtropospheric baroclinicity and comparable lower-to-midtropospheric Eady growth rates in the vicinity of AC16 between the most-accurate and least-accurate ensemble forecasts. However, the more amplified and stronger T1, and stronger embedded TPV, appear to contribute to greater baroclinic growth of AC16, and to greater downstream upper-tropospheric flow amplification, in the most-accurate ensemble forecasts compared to in the least-accurate ensemble forecasts. The more amplified and stronger T1, and stronger embedded TPV, and a correspondingly more intense AC16, may interact with the region of strong lower-to-midtropospheric baroclinicity in the vicinity of AC16 to a greater extent in the most-accurate ensemble forecasts. There are concomitantly large differences in the amplitude and position of the thickness trough and ridge in the vicinity of AC16 between the most-accurate and least-accurate ensemble forecasts, suggesting that there are large differences in the positions of warm and cold frontal zones associated with AC16 between these respective categories of forecasts. A stronger TPV contributing to a more intense AC16 is consistent with the findings of a sensitivity experiment by Tao et al. (2017b), which shows that decreasing the strength of TPVs influencing the evolution of AC12 contributes to a weaker AC12.

Although there are mixed signals as to whether there is greater latent heating in the vicinity of AC16 in the most-accurate ensemble forecasts, there is clearly a more poleward directed and more northwestward positioned lower-tropospheric IVT corridor, and much stronger upper-tropospheric irrotational outflow, in the vicinity of AC16 in the most-accurate ensemble forecasts. The more intense AC16 in the most-accurate ensemble forecasts is associated with a stronger lower-tropospheric circulation that helps transport moisture farther northwestward in the most-accurate ensemble forecasts. The stronger upper-tropospheric irrotational outflow likely contributes to the greater intensification of AC16 in the most-accurate ensemble forecasts.

*d. Summary*

In this chapter, features and processes influencing the forecast skill of AC16 were determined by conducting an ESA of AC16 and by comparing the most-accurate and least-accurate ensemble forecasts of AC16. The ESA and the comparison of forecasts served as a basis to address hypothesis 5. Hypothesis 5 states that forecast errors in TPVs, baroclinic zones, and WCBs, and forecast errors in TPV–AC interactions, baroclinic processes, and latent heating, contribute to forecast errors in strong low-skill ACs during low-skill periods. A summary of how hypothesis 5 is supported in regards to AC16 is given below.

* The ESA and the comparison of forecasts suggest that a more amplified and stronger T1, and a stronger embedded TPV, upstream of AC16 are associated with greater downstream upper-tropospheric flow amplification, greater intensification of AC16, and a correspondingly more accurate prediction of AC16. Therefore, the hypothesis (part of hypothesis 5) that forecast errors in TPVs contribute to forecast errors in AC16 is supported. It is anticipated that forecast errors in the TPV are associated with forecast errors in TPV–AC interactions that may contribute to forecast errors in AC16.
* The comparison of forecasts suggests that there is comparable lower-to-midtropospheric baroclinicity and comparable lower-to-midtropospheric Eady growth rates in the vicinity of AC16 between the most-accurate and least-accurate ensemble forecasts. However, there appears to be more robust interaction between a more intense AC16 and a region of strong lower-to-midtropospheric baroclinicity in the vicinity of AC16 in the most-accurate ensemble forecasts compared to in the least-accurate ensemble forecasts. Correspondingly, there are large differences in the amplitude and position of a thickness trough and ridge in the vicinity of AC16 between the most-accurate and least-accurate ensemble forecasts, suggesting that there are large differences in the positions of warm and cold frontal zones associated with AC16 between the most-accurate and least-accurate ensemble forecasts. Thus, there is support for the hypothesis (part of hypothesis 5) that forecasts errors in baroclinic zones and baroclinic processes contribute to forecast errors in AC16.
* Both the location and magnitude of dynamical forcing associated with T1 and the embedded TPV likely matter for the development and intensification of AC16. The more amplified and stronger T1, and the stronger embedded TPV, in the most-accurate ensemble forecasts are likely associated with greater dynamical forcing that contributes to the greater development and intensification of AC16 in the most-accurate ensemble forecasts. The more amplified and stronger T1, and the stronger embedded TPV, are likely better positioned with respect to AC16 and the region of strong lower-to-midtropospheric baroclinicity in the vicinity of AC16 to contribute to the greater development and intensification of AC16 in the most-accurate ensemble forecasts.
* The ESA and the comparison of forecasts suggest that a northwestward shift in a moisture corridor and region of latent heating in the vicinity of AC16 is associated with a more accurate prediction of AC16. There are mixed signals as to whether greater latent heating is associated with a more accurate prediction of AC16. Thus, the extent to which the hypothesis (part of hypothesis 5) that forecast errors in WCBs and latent heating contribute to forecast errors in AC16 is supported is unclear.