Extreme Arctic cyclone in August 2016

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Abstract

An extremely strong Arctic cyclone (AC) developed in August 2016. The AC exhibited a minimum sea level pressure (SLP) of 967.2 hPa and covered the entire Pacific sector of the Arctic Ocean on 16 August. At this time, the AC was comparable to the strong AC observed in August 2012, in terms of horizontal extent, position, and intensity as measured by SLP. Two processes contributed to the explosive development of the AC: growth due to baroclinic instability, similar to extratropical cyclones, during the early phase of the development stage, and later nonlinear development via the merging of upper warm cores. The AC was maintained for more than 1 month through multiple mergings with cyclones both generated in the Arctic and migrating northward from lower latitudes, as a result of the high cyclone activity in summer 2016.

Keywords: Arctic cyclone; warm core; baroclinic instability; merging

1. Introduction

An extremely strong Arctic cyclone (AC) developed over the Arctic on 16 August 2016, spanning the Pacific sector of the Arctic Ocean. Cyclones were quite active over the Arctic in general in the summer of 2016. Many cyclones migrated into the Arctic, and these cyclones maintained the AC for a prolonged period.

The AC that is known as ‘The Great Arctic Cyclone of August 2012’ is well analyzed as a remarkable summer AC (Simmonds and Rudeva, 2012). They showed that this AC had the lowest central pressure and largest size of any summer AC from 1979 to 2012. Zhang et al. (2004) showed that, in general, summer ACs have longer lifetimes, are more numerous, and are weaker than those in winter. On the other hand, Simmonds et al. (2008) found a greater number of cyclones in winter than in summer, as a result of ‘open depression’ systems (Murray and Simmonds, 1991). Most cyclones in the Arctic during summer are generated over the Arctic Ocean, and most of the remainder is generated over the northern Eurasian continent (Brüummer et al., 2000; Serreze and Barrett, 2008). In the context of these previous studies, the intensification of AC in August 2016 (AC16) was unusual in summer.

ACs can impact the wider Arctic climate system through fields, such as seawater temperature (Inoue and Hori, 2011). It has been reported that the AC in August 2012 (AC12) contributed greatly to the record-low sea-ice extent of that summer (Parkinson and Comiso, 2013; Zhang et al. 2013) and influenced biological activities in Arctic Ocean (Zhang et al., 2014).

ACs have warm (cold) core at upper (lower) level and barotropic vorticity in the troposphere (Tanaka et al., 2012). Previous studies showed that the baroclinicity over the Arctic frontal zone was one of the main factors for generation and intensification of ACs (e.g. Serreze and Barrett, 2008). Recently, Crawford and Serreze (2016) indicated that the baroclinicity affected only on an intensification of ACs. The coupling with lower and upper cyclones was also important for the development of ACs (Simmonds and Rudeva, 2012, 2014).

This study investigates the features and mechanisms behind the development of the AC16.

2. Data and methods

ERA-Interim (Dee et al., 2011) data were used in this analysis. Specifically, we used temperature (T), geopotential height, horizontal wind (V = (u, v)), relative vorticity, and sea level pressure (SLP) at 6-hourly intervals, and surface sensible and latent heat fluxes at 12-hourly intervals. The sensible and latent heat fluxes were converted from 12-hourly accumulated values to 12-hourly average rates. The horizontal resolution of all variables was 1.25° × 1.25°.

The method developed by Aizawa and Tanaka (2016) was used to identify cyclone centers at each timestep. The method uses an SLP field interpolated from a regular longitude–latitude grid to an equal-distance grid centered on the North Pole. The equal-distance grid used in this study has 200 grid points in the x and y directions with a spacing of 40 km. The SLP at each grid point is then compared with the SLP averaged over all grid points between 500 and 550 km from the target grid point. If the SLP at the target grid point is lower than the area-averaged SLP, the grid point is regarded as a candidate for a cyclone center. The horizontal resolution of ERA-Interim did not affect the cyclone center detection substantially. Cyclone tracks were then formed based on the nearest-neighbor method.

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(Serreze, 1995), except in the cases of merging and splitting cyclones, which were tracked manually. The radius of ACs was calculated based on outermost closed SLP contour with 1 hPa intervals including single cyclone center.

The magnitude of the temperature gradient at 850 hPa, and the Eady growth rate (EGR) (Simmonds and Lim, 2009) at 700 hPa were also used, in order to identify fronts and measure baroclinicity. They were calculated as follows:

$$ |\nabla T| = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2} $$

$$ \text{EGR} = 0.3098 \frac{|f| \frac{\partial V}{\partial z}}{N} $$
where $f$ is the Coriolis parameter; $x$, $y$, and $z$ are the longitudinal, latitudinal, and vertical coordinates, respectively; and $N$ is the Brunt–Väisälä frequency. The vertical derivatives in EGR were calculated using centered finite differences at the 750 and 650 hPa levels. The heat budget was also calculated as follows:

$$\frac{\partial \theta'}{\partial t} = \frac{\partial (u \theta')}{\partial x} + \frac{\partial (v \theta')}{\partial y} + \frac{\partial (\omega \theta')}{\partial p} + F'$$

where $\theta$ is the potential temperature, $\omega$ is the vertical $p$-velocity, $p$ is the pressure, and $F$ is the diabatic heating evaluated as the residual. The prime indicates an anomaly from the 6-hourly climatology.

In some studies, the term ‘AC’ was applied to both cyclones coming from mid-latitude to the Arctic and those generated over the Arctic. In this study, the cyclones having upper warm core in the upper troposphere were called ‘AC’ according to Tanaka et al. (2012). The cyclones coming from mid-latitude were called ‘cyclone.’ The term ‘merging’ was used based on the definition of Hanley and Caballero (2012). However, the cyclone center detection in this study can identify open depression systems. Therefore, ‘merging’ in this study includes the following case: A cyclone center exists as an open depression system within 1000 km of the other cyclone center at a timestep and then these two SLP minima merge into a single SLP minimum at the next timestep. Most mergings in this study were accompanied by a vorticity merging.

3. Results

The AC16 began with a merging of two cyclones from the Barents Sea and the northeast Siberia (orange in Figure 1(a)) over the Laptev Sea on 4 August (orange star). The AC16 wandered over the Arctic Ocean for 8.5 days (brown in Figure 1(b)). After that, the AC16 merged with a cyclone from the North Atlantic (yellow) on 13 August. Meanwhile, a cyclone formed over the Scandinavian Peninsula (red). This cyclone developed rapidly, and its central pressure dropped by ~30 hPa during 13–15 August (red in Figure 1(h)). The cyclone merged with the AC16 at 1200 UTC on 15 August, and the lowest minimum central pressure of 967.2 hPa was recorded at 0000 UTC on 16 August (Figure 1(c)). As seen from the SLP, the whole Pacific sector of the Arctic Ocean was covered by the AC. The AC16 was quite similar to the AC12 in terms of the SLP values measured, horizontal extent, and position. The central pressure of the AC12 was 964.1 hPa. The radius and the center for the AC16 (AC12) were ~1028 km (~1035 km) and at 187.60°E, 84.56°N (188.53°E, 82.73°N), respectively.

During the time period 19–22 August, the AC16 merged with cyclones that originated over northeast Siberia (purple cross in Figure 1(d)) and the Scandinavian Peninsula (dark blue cross). After these mergings, the AC16 exhibited a minimum pressure of 972.3 hPa and covered the Laptev, Kara, and Arctic oceans (Figure 1(d)). At 1200 UTC on 28 August, the AC16 (dark blue in Figure 1(e)) and cyclones moving from the Atlantic (light blue) and from the Sea of Okhotsk (dark green) formed a huge multicenter cyclone that covered the whole Arctic Ocean. After the merging with the cyclone on 29 August (light blue cross in Figure 1(f)), the resulting AC16 center (light blue) orbited the remaining cyclone center (dark green) according to the Fujiwhara effect (Fujiwhara, 1923). The AC16 (light blue) merged with the cyclone from the North Atlantic (light green cross in Figure 1(g)) on 1 September. The merged AC16 wandered for 15.5 days and dissipated on 16 September over the Canadian Arctic Archipelago. The AC was thus maintained for more than 1 month through repeated cyclone mergings.

The structure of each cyclone was changed after merging with the AC16. The temperature anomalies from 6-hourly climatology (1981–2010) were near-zero or negative at the formation stage of the cyclones (Figure 2(b)). Each cyclone had an upper-level warm core of ~6 K during its mature stage. The change from cold to warm core is considered to mark the change from an extratropical cyclone to an AC (Aizawa and Tanaka, 2016).

In particular, the fourth cyclone (red) had a weak warm core of 1 K and a strong cold core of ~8 K at 250 and 850 hPa, respectively, in its formation stage. As the cyclone developed on 13 August, the cold core at the lower level weakened to near-zero. These suggest that the shift in position from a highly stable environment to the climatological environment contributed to the beginning of the cyclone’s development. The warm core at the upper level strengthened during the early phase of the rapid development stage from 1200 UTC on 13 August to 1800 UTC on 14 August. The cold core at the lower level also strengthened at this time. From Figures 3(d)–(f) and Figures 4(c)–(f), the warm and cold cores accompanied by the cyclone developed on the rear of the center. Although both cores continued to develop during the later phase of the development stage, the warm core reached its peak value, 6 K, faster than the cold core.

The relative vorticity also strengthened at upper and lower levels during its development and mature stages (Figures 2(d) and (e)). These also indicated that the AC16 has barotropic vorticity. The vorticity at 850 hPa represents that the vorticity accompanied by a cyclone was as high as that accompanied by the AC16 when the cyclone merged with the AC16. The horizontal structure of the vorticity merging is shown in Figures 3(a)–(c). The maximum relative vorticity at 850 hPa for AC16 (3.04 × 10⁻³ s⁻¹) was also very similar to that for AC12 (3.05 × 10⁻³ s⁻¹).

The cyclone featured relatively large surface heat fluxes, especially latent heat flux, on 11 and 12 August (Figure 2f). These large fluxes occurred when the cyclone was located over the Scandinavian Peninsula. LeDrew (1984) indicated that the surface enthalpy flux contributed only for cyclones over the Laptev Sea in end of fall significantly and for cyclone in summer insignificantly. These surface heat fluxes seem insignificant.
Figure 2. (a) As in Figure 1(h). (b–f) Cyclone temperature anomalies at (b) 250 hPa and (c) 850 hPa, defined as departures from 6-hourly climatology, relative vorticity at (d) 300 hPa and (e) 850 hPa, and (f) surface sensible (solid lines) and latent (dashed lines) heat fluxes, averaged over a circle of radius 1000 km centered at the cyclone center. Colors and symbols are as in Figure 1.
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for the development of the AC16, since values were at most 100 W m$^{-2}$ and were comparable to monthly mean value in August (Serreze and Barry, 2014).

On 13 August, the AC16 (yellow in Figure 1(c)) did not have any remarkable frontal structure in its mature stage (Figure 3(d)). The cyclone over Novaya Zemlya (red in Figure 1(c)) possessed cold and warm fronts. On 14 August, the Novaya Zemlya cyclone had moved northeastward to the Kara Sea (Figure 3(e)). The cyclone’s fronts formed a T-bone structure, indicating that the cyclone had reached its mature stage. The surrounding environment of the cyclone was unstable on 13 August (Figure 3(g)). The unstable area expanded into the northern part of the cyclone (Figure 3(h)), corresponding to the direction of motion of the cyclone. On the other hand, EGR around the AC16 was small on August 13 and 14 (Figures 3(g) and (h)). Therefore, the cyclone over the northern coast of Eurasia developed via baroclinic instability, as do extratropical cyclones, during the early phase of its rapid development. After the merging of the cyclone and the AC16 on 16 August, the fronts became separated from the AC16 center (Figure 3(f)) and the strong instability disappeared (Figure 3(i)). The results suggest that baroclinicity was not the primary energy source in the later phase of the rapid development stage of the AC.

Figure 4(a) shows that a polar vortex with a warm core was located over the Arctic Ocean on 11 August and was connected to the AC16 (brown in Figure 1(b)). Deep and shallow troughs extended over the Scandinavian Peninsula and the Kara Sea, respectively. Cyclones (yellow and red in Figure 1) were located to the east of these troughs. The deep trough moved eastward; accordingly, the surface cyclone (red) also traveled

![Figure 3](image-url)
eastward to the Kara Sea on 14 August. The cyclone center was located east of the trough, suggesting that the cyclone was developing in the same manner as extratropical cyclones in their formation stage. The trough and surface cyclone then traveled farther eastward, and the cyclone gradually progressed to its mature stage. In contrast, although the AC16 merged with the cyclone that was accompanied by the shallow trough on 13 August (Figure 4(c)), the AC16 remained over the Arctic Ocean from 11 to 14 August (Figure 4(d)). From 14 to 16 August, the warm core in the polar vortex merged with the warm core in the trough over the Kara Sea (Figure 4(e)). The merger resulted in the warm core strengthening and expanding over the AC16, marking the later phase of the rapid development stage. The AC16 center and the upper vortex exhibited a barotropic structure on 16 August (Figure 4(f)).

For the development of the upper-level warm core accompanied by the cyclone (red in Figure 1(c)), the horizontal flux convergence (dotted line in Figure 5(b)) was a dominant component during the whole period. The horizontal component was relatively small for the generation of the cyclone before 1200 UTC on 11 August. The sum of the horizontal and the vertical components (solid line in Figure 5(b)) was \(~0.8\) K \((6\text{ h})^{-1}\) at 1800 UTC on 11 August, for the beginning of the cyclone’s development. The sum first peaked at 1800 UTC on 13 August with \(~1.9\) K \((6\text{ h})^{-1}\), corresponding to the early phase of the rapid development stage (Figure 5(a)). The peak indicates that the warm core in the upper trough caught up with the surface cyclone (Figures 4(d) and (e)). A second peak appeared on 15 August, corresponding to the later phase of the rapid development stage (Figure 5(a)). The second peak indicates that the warm cores are merging (Figure 4(e)). Although the sum during the second peak is weaker than that during the first peak, the heat budget at upper levels also indicates that two processes have contributed to the development of the warm core over the cyclone, and as a result, the cyclone has developed to an extreme AC. The upper warm core was mainly maintained by the horizontal flux convergence after 17 August. Although the eddy component of the vertical flux convergence was small, the background component of that was \(~0.4\) K \((6\text{ h})^{-1}\). It indicates that an upper warm core accompanied by ACs was maintained by both merging of two cyclones and the background downward flow.

4. Summary and conclusions

In this study, the features and mechanisms behind the development of the extreme AC of August 2016 were investigated. The AC16 occurred over the Laptev Sea on 4 August and was maintained for more than 1 month.
through repeated mergings with other cyclones. The AC16 recorded a minimum SLP of 967.2 hPa and covered the entire Pacific sector of the Arctic Ocean. In addition, the AC16 experienced two notable periods of development after its initial development.

On 15 August, the AC16 merged with a cyclone that originated to the west of the trough over the Scandinavian Peninsula on 11 August. The combined cyclone moved along the northern coast of Eurasia and developed rapidly from 13 to 16 August, with a decrease in central pressure of ≈30 hPa. The extreme development of the cyclone occurred via two processes: a baroclinic process, as occurs in extratropical cyclones, in the early phase of the development stage (from 13 to 14 August), and a nonlinear process caused by the merging of the upper-level warm cores in the later phase of the development stage (on 15 August). Simmonds and Rudeva (2012) concluded that not only baroclinicity but also the establishment of a connection with the tropopause polar vortex were important to the development of the AC12. Both processes were also seen during the rapid development of the AC16. Furthermore, our results confirm that a merging of warm cores accelerates the development of the AC16.

The lifetime of the AC16 was much longer than that of the AC12 due to multiple merging events. The merging process is essential to ACs, and it may correspond to the connection between an upper polar vortex and a surface vortex. However, when the cyclones were as strong as the AC16, two vortices were merged with in some cases (purple cross in Figure 1(d)) and not in the other cases (light blue and dark green in Figure 1(f)). Thus, it is suggested that the occurrence of merging for ACs is not determined by only length scale or strength of cyclones. In this study, we focused only on the cyclone with the lowest minimum SLP; however, many other interesting events occurred during the lifetime of the AC. The mechanisms of merging and the AC in terms of atmosphere–ocean–sea-ice interactions were also interesting.

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