Ice lollies: An ice particle generated in supercooled conveyor belts

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Abstract On 21 January 2009, a maturing low-pressure weather system approached the UK along with several associated frontal systems. As part of the Aerosol Properties, Processes And Influences (Aerosol Properties, Processes And Influences) project, an observational research flight took place in southern England, sampling the leading warm front of this system. During the flight, a distinctive hydrometeor type was repeatedly observed which has not been widely reported in previous studies. We refer to the hydrometeors as “drizzle-rimmed columnar ice” or “ice lollies” for short due to their characteristic shape. We discuss the processes that led to their formation using in situ and remote sensing data.

1. Introduction

Remote sensing and in situ observations have made a significant contribution to the study of cloud microphysical processes. Locatelli and Hobbs [1987] provided a detailed analysis of the structure of a warm front using radar and radiosonde data, identifying the typical patterns in temperature, wind, and precipitation, including the existence of nonuniform rainbands. Browning and Roberts [1994] further developed the understanding of frontal cyclones using model output and satellite images and discussed the dynamical factors leading to the formation of various cloud features.

Dearden et al. [2016] used the WRF numerical model to simulate two summer cyclones to gain an understanding of sensitivities to ice microphysics, including the role of primary versus secondary ice formation. Primary ice formation describes the nucleation of new ice particles via homogeneous freezing of liquid droplets at cold temperatures (< −37°C [Koop et al., 2000]) or via heterogeneous processes involving ice nuclei [Vali et al., 2015]. Secondary ice formation processes, often referred to as “ice multiplication processes,” increase the number of ice particles in clouds by fragmenting existing ice particles in various ways, such as freezing and shattering of water drops [Johnson and Hallett, 1968; Pruppacher and Schluamp, 1975; Lawson et al., 2015], rime splintering [Mossop and Hallett, 1974] fragmentation following ice crystal collisions [Hobbs and Farber, 1972; Vardiman, 1978], and fragmentation of ice due to evaporation and melting [Knight, 1979]. Dearden et al. [2016] found that in deep frontal systems, precipitation was dominated by primary ice production mechanisms, and that secondary processes had no significant impact.

In contrast to this modeling study, observations presented in Crosier et al. [2011, 2014] and Lloyd et al. [2014] showed that secondary ice processes can dominate ice crystal formation in a wide variety of frontal clouds. These studies implicate the Hallett-Mossop (H-M) process [Mossop and Hallett, 1974], which is thought to be active in the temperature region −3°C and −8°C, as being the source of the secondary ice particles—manifesting as abnormally large numbers of pristine columnar ice crystals at relatively warm temperatures. The leading theory describing the H-M process is presented by Choularton et al. [1980], which suggests that supercooled droplets with a diameter of >24 μm explosively freeze when they come into contact with pre-rimed ice particles. The explosive freezing is thought to occur as a result of the formation and subsequent fracturing of an ice crust which forms on the surface of the particle—the subsurface water freezes after the crust forms which imparts stress on the crust, resulting in fracturing. The fracturing of the surface crust is thought to be responsible for the generation of small splinters of ice which typically grow into observable columnar ice particles due to the temperature at which the whole process operates. As the H-M process requires large liquid water droplets, the process is most active in convective regions where large droplets can be generated. Predicting the formation of convective features on appropriate scales may impose a limit on the ability of numerical models to assess the importance of the H-M process, in addition to fundamental uncertainties associated with the H-M process itself.
In this paper, we present observations of a warm front which is sampled extensively. We present particle imagery showing a distinctive type of ice particle which was repeatedly observed in the warm frontal cloud. This ice particle has never been observed in significant concentrations before. We discuss the microphysical and dynamical processes which lead to the formation of these ice particles through the use of in situ aircraft observations and radar data.

2. Instrumentation and Data

Measurements of cloud microphysical properties were collected on 21 January 2009 between 15:00 UTC and 20:30 UTC as part of the APPRAISE-Clouds (Aerosol Properties, Processes And InfluenceS on the Earth’s climate) project. On this day a low-pressure system approached the British Isles from the west. The system consisted of multiple frontal boundaries, with multiple rainbands affecting the country, especially in the SW regions of England and Wales. The rainbands consisted of mixed-phase clouds with some embedded convective elements. Observations were collected during the passage of the leading warm front.

In situ measurements were collected on board the UK Facility for Airborne Atmospheric Measurement (FAAM) BAe-146 aircraft, while remote-sensing measurements were obtained from the Chilbolton Facility for Atmospheric and Radio Research (CFARR, located in Southern England; 51.15°N, 1.44°W). The BAe-146 aircraft obtained in situ observations along an azimuth of approximately 255° relative to the CFARR radar site, at horizontal distances ranging from 0 km (overpassing CFARR) to 100 km. The Chilbolton Advanced Meteorological Radar (CAMRa) system continuously scanned along the same 255° azimuth, leading to colocated in situ and radar observations of the frontal cloud. The CAMRa is a dual-polarization Doppler radar operating at 3 GHz, with no significant attenuation issues in a range less than 100 km. It has a large 25 m antenna providing high-resolution data (0.28° beam width, 0.3 km in range) [Goddard et al., 1994]. The CAMRa provides information on the microphysical properties of clouds: reflectivity factor (Z_R) is proportional to the square of the total hydrometeor mass [Doviak et al., 1979; Brown and Wood, 2007]; differential reflectivity (Z_Diff) provides information on the shape of hydrometeors with larger values for oblate and horizontally oriented 2-D planar particles, and low values for quasi-spherical particles [Straka et al., 2000; Wolde and Vail, 2001; Kennedy and Rutledge, 2011; Andrić et al., 2013; Bechini et al., 2013; Kumjian, 2013; Schuur et al., 2014; Moisseev et al., 2015; Schrom et al., 2015; Schrom and Kumjian, 2016]; Doppler velocity provides dynamical information by characterizing the velocity of the hydrometeors along the axis of the radar beam [Brown and Wood, 2007].

The BAe-146 aircraft was equipped with a suite of microphysical probes to measure a wide range of hydrometeors [see Crosier et al., 2014, and references therein]. To summarize the key instrumentation, a CDP (Cloud Droplet Probe) Mie scattering probe was used to measure the number and size of cloud droplets [Lance et al., 2010]; 2DS (Two-Dimensional Stereo), CIP-15, and CIP-100 (Cloud Imaging Probe) Optical Array Probes (OAP) were used to provide shadow imagery of particles from 10–1280, 15–960, and 100–6200 μm, respectively [Krollenberg, 1970; Lawson et al., 2006]; and ambient temperature was measured on a Rosemount inlet.

Liquid water content (LWC) was estimated from the CDP cloud droplet number size distributions. Number size distributions for larger particles were calculated from the OAP data according to [Goddard et al., 1994]. The hydrometeors in question appear to be a combination of single columnar pristine ice crystals (needle or column) with a single drizzle-sized water droplet (typically 300 μm

3. Ice-Lolly Formation

During the collection of in situ data on 21 January 2009, a significant number of the hydrometeors observed exhibited a characteristic shape not widely seen in any previous studies with the exception of one isolated example reported by Korolev et al. [2004]. The hydrometeors in question appear to be a combination of single columnar pristine ice crystals (needle or column) with a single drizzle-sized water droplet (typically 300 μm
diameter). We call these hydrometeors “drizzle-rimed columnar ice” or “ice lollies” due to their similarities in shape. Example images of ice lollies from the 2DS probe are shown in Figure 1c. Labeling and understanding different hydrometeor types give insight into processes active in the cloud system. In our specific case the ice lollies demonstrate interactions between warm rain, primary ice, and secondary ice processes. In sections 3.1, 3.2, and 3.3, we discuss the source of the liquid water droplets, the source of the pristine columnar ice, and the formation of ice lollies, respectively.

3.1. Liquid Water in the Warm Conveyor Belt

On 21 January 2009, a warm conveyor belt (WCB) [Browning and Roberts, 1994] passed over the southwest regions of the UK, lifting warm moist air from the Atlantic Ocean which led to widespread cloud formation. The WCB is well depicted by the radar Doppler velocity parameter in Figure 2b as a slanted region of high velocities (~ 20 m s\(^{-1}\)). Near the radar, the WCB is located close to the surface (~1.5 km altitude), whereas further away to the southwest the WCB is located at higher altitudes (~3 km altitude). The aircraft flew through the WCB (Figure 2b, from left to the right) and surrounding regions, and the data from one pass through the WCB at \(T = -5^\circ\text{C}\) are shown in Figure 2a, with the associated aircraft flight track highlighted in Figure 2b. In the core of the WCB, which the aircraft passed through between 65 and 80 km from the radar, significant mass concentrations of liquid water were observed (>0.15 g m\(^{-3}\)), while relatively little ice mass was observed (generally <0.025 g m\(^{-3}\)). As the aircraft exited the core of the WCB and sampled below the overlying elements of the WCB (30–65 km from the radar), the mass concentration of liquid water reduced greatly (<0.01 g m\(^{-3}\)) and the mass concentration of ice increased, occasionally exceeding 0.05 g m\(^{-3}\). Hence, it seems that the WCB was feeding the cloud system with water vapor and directly led to the formation and growth of the water droplets. During the same measurement period, water droplets with diameters <12 μm and >24 μm were observed with average number concentrations of 0.13 cm\(^{-3}\) and 1.99 cm\(^{-3}\), respectively (with peak number concentrations of 0.27 and 4.94 cm\(^{-3}\), respectively). According to current understanding, the existence of those specific sizes of water drops is a key ingredient for the ice column formation via the H-M process, and so for the ice-lolly formation as will be discussed in section 3.3.

3.2. The Origin of the Pristine Columnar Ice

Particle imagery shows that pristine planar ice crystals were present near cloud top (~4 km, ~ -12.5°C) (Figure 3a). Average ice particle number concentration and size in this region are ~2 L\(^{-1}\) and ~670 μm, respectively. This observed crystal habit is consistent with the expected habit based on the ambient temperature [Kobayashi, 1961]. These crystals are formed via heterogeneous processes due to the relatively modest cloud top temperatures [Rogers and Yau, 1989]. The radar can identify regions of cloud with significant concentrations of planar ice crystals, as these types of particle have strong differential reflectivity signals (\(Z_{\text{DR}} > 2 \text{ dB}\)) due to their relatively two-dimensional structure [Seliga and Bringi, 1978; Ryzhkov and Zrnic, 1998; Kennedy and Rutledge, 2011; Andrić et al., 2013; Moisseev et al., 2015]. \(Z_{\text{DR}}\) features were frequently observed near cloud top which is consistent with ice being formed in convective generating cells near...
cloud echo top [Kumjian et al., 2014]. The association of planar ice crystals with high values of $Z_{DR}$ was found to be valid near cloud top based on aircraft observations. An example of a similar $Z_{DR}$ feature at cloud top can be seen in Figure 2d. Below the high $Z_{DR}$ cloud tops, slanted zero $Z_{DR}$ (typically between $-0.5$ and $0.5$ dBZ) zones were observed. Within these zones more aged/processed ice particles, such as rimed/aggregated ice crystals, were observed in variable concentrations between 1 and 10 L$^{-1}$ and variable average sizes between 300 μm (for rimed) and 800 μm (for aggregates). Some pristine ice crystal high $Z_{DR}$ regions near cloud top appear to be transported to these zones and are observed in a more processed stated (rimed and/or aggregated) as shown in some of the imagery in Figures 3b and 3c.

Observations at lower levels ($T \sim -6.2^\circ C$, altitude $\sim 2.3$ km), which represent more aged/processed ice particles relative to the young/pristine particle observed near cloud top, were observed in similar number concentrations ($\sim 9$ L$^{-1}$) and size (337 μm). These observations were collected in a region of low $Z_{DR}$, with particle imagery (Figure 3d) supporting the concept of increased processing via riming and aggregation particles precipitate down toward the surface.

At the same altitude and temperature (approximately $-6^\circ C$), large numbers of pristine columnar ice particles were observed in mixed phase regions, where large amounts of liquid water were observed. Imageries of these pristine columnar ice particles and the individual water droplets (shown as single pixels due to the coarse resolution of the probes) are shown in Figure 3e. Further east (Figure 2a) at the same altitude, the average ice crystal number concentration is significantly enhanced relative to regions above the WCB with no liquid water, with a mean value of 20.7 L$^{-1}$ (peak values up to 37.8 L$^{-1}$) at 50–70 km and 8.9 L$^{-1}$ (peak values up to 14.1 L$^{-1}$) at 31–43 km range. In these regions mixed-ice columns, ice lollies, and rimed crystals were

**Figure 2.** (a) LWC, IWC, and ice number concentration; (b) Doppler velocity (dashed line for $-20$ m s$^{-1}$); (c) reflectivity factor ($Z_{RH}$); and (d) differential reflectivity ($Z_{DR}$). Figures 2b–2d refer to the period between 19:16:12 and 19:17:42 UTC at an azimuth of 255°, pointing roughly WSW. In Figure 2b negative Doppler velocity values indicate flow toward the radar. The gray scale line shows the aircraft track between 19:11:26 and 19:17:42 (black for the starting position and white for the final position). Figure 2a corresponds to the aircraft path of Figure 2b, which is from right to left.
Figure 3. (a) Pristine crystals and snowflakes from high ZDR regions near cloud top (T = −12.5°C, altitude = 4 km), (b) rimed and aggregated ice crystals from low ZDR regions below cloud tops (T = −7.5°C, altitude = 2.5-3 km), (c) rimed crystals from low ZDR regions below cloud tops (T = −7°C, altitude = 2.6 km), (d) aged rimed ice crystals from low ZDR regions close to ice-lolly regions (T = −6.2°C, altitude = 2.3), (e) ice columns and liquid droplets (T = −5°C), and (f) ice lollies observed at midlevels (T = −5°C, 2 km altitude). The red square includes some examples of the ice lollies with side planes (see explanation in the text) imaged by the 2DS. The horizontal dimension of each strip of images is equal to 1.28 mm. In Figures 3b–3d CIP-100 strip dimension is equal to 6.4 mm.
observed in the imagery. The increased number concentrations and relatively small and pristine nature of the observed columnar ice suggest that a multiplication mechanism has been active. As mentioned in section 3.1, the drop size distribution is suitable for the H-M rime splintering mechanism to operate, as both <12 \( \mu m \) and >24 \( \mu m \) droplets (required for the splinter production) were present at within the relatively narrow temperature regime where the H-M process is active [Mossop and Hallett, 1974; Mossop, 1976; Choularton et al., 1978, 1980]. This interaction would result in the large number of pristine columnar ice crystals observed.

To summarize, it appears that pristine columnar ice particles are formed as a result of the H-M process. The H-M process is facilitated by the presence of ice particles which form in generating cells near cloud tops and by liquid water which is formed in the core of the WCB.

### 3.3. The Formation of Ice Lollies and Their Polarimetric Radar Properties

As mentioned in sections 3.1 and 3.2, columnar ice crystals were produced by ice multiplication processes and they were detected within a mixed-phase region, which consisted of ice columns and water droplets. Here we try to demonstrate that the collision between these water drops and ice columns, and thus the formation of ice lollies (Figure 1a), was possible. In general, the columnar part of ice lollies was >250 \( \mu m \) (up to 1400 \( \mu m \)), while the attached supercooled droplet diameter was >100 \( \mu m \) (up to 700 \( \mu m \)). According to Böhm [1992, 1994], such particles would collide with efficiencies >70%. In addition, the ratio between supercooled droplet and ice column terminal velocities [Mitchell, 1996] for the observed range of sizes was mostly >1, which also supports particle collisions. It should be highlighted that ice columns (for Reynolds number \( \leq 50 \), thus laminar flow) fall with their long \((c)\) axis perpendicular to their fall direction, which explains why the spherical part was in the middle of some ice lollies (Figure 1c) [Jayaweera and Mason, 1965].

An alternative mechanism, as suggested by Korolev et al. [2004], would be for the long columnar component of an ice lolly being as a result of depositional growth on a frozen water droplet. However, depositional growth on a frozen droplet at these temperatures would hypothetically result in something resembling a bullet rosette and not a frozen droplet with a single protrusion which is what we observe. Also, evidence for the “drizzle riming” mechanism which we propose is strongly supported by the occurrence of large numbers of pristine columnar ice particles in the vicinity of ice lollies.

The 2DS probe imaged many ice lollies (Figure 3f) during the scanning period of the radar images (Figures 2b–2d), only a small number of which are shown. In this paragraph we present some polarimetric characteristics of the ice lollies. When the aircraft flew through a high \( Z_H \) region (\( Z_H > 15 \text{dBZ} \)) (Figure 2c), low ice-lolly concentrations were measured (~0.4 L\(^{-1}\)). However, as the aircraft was flying toward a region of moderate \( Z_H \) (7–15 dBZ), larger concentrations were observed (~3.8 L\(^{-1}\)). Typically, ice lollies were found in regions with \( Z_{DR} \) values between 0.3 and 1.6 dB (Figure 2d). The elongated shape of the ice lollies can justify such values, as shown later in the text. However, regions of 0.3 dB are present due to the existence of less oblate particles (such as large aggregates or quasi-spherical heavily rimed crystals/graupeels), which were probably dominating both \( Z_H \) and \( Z_{DR} \) signals. Using the discrete dipole approximation (public-domain code DDSCAT) [Draine and Flatau, 1994] for particles consisted of a column and a sphere (this ice lollies) in various observed size combinations, we calculated the theoretical \( Z_{DR} \) of ice-lolly particles. Ice lollies could lead to \( Z_{DR} \) ranging between 0.2 and 3.2 dB depending on their specific geometry. In particular, ice-lolly \( Z_{DR} \) seems to be dependent primarily on the ratio between the column width and the drop diameter and, secondarily, on the ratio of column length to column width. In our observations the ratio of column width to drop diameter (CWDD) ranged from 0.2 to 0.75, with a typical value of ~0.4. The ratio of column length to width ranged between 2.5 and 10, with a typical value of ~5. For ice lollies with relatively large droplets frozen onto relatively small columns, with CWDD = 0.2, \( Z_{DR} \) values range from 0.2 dB to 0.5 dB, with longer columns generating the larger \( Z_{DR} \) values. For the case of relatively small droplets frozen onto relatively large columns, with CWDD = 0.75, \( Z_{DR} \) values are significantly higher and range from 2 dB to 3.2 dB, again with the longest columns generating the largest values. Theoretical \( Z_{DR} \) values for the most typically observed shape of horizontally oriented ice lolly are between 1.5 and 2.2 dB. Jayaweera and Mason [1966] showed that columns (diameter = 160 \( \mu m \)) capped by hexagonal plates (e.g., diameter ≤ 300 \( \mu m \)) fall horizontally aligned if the column length is >1000 \( \mu m \). Otherwise, these particle types fall vertically. Capped columns have the most similar geometry to an ice lolly, and so are likely to behave in a similar manner. However, there is uncertainty in fall orientation due to lack of data.
In general, ice lollies were found above the melting layer and in the vicinity of the WCB (in or below it), where temperatures were between 0 and $-6^\circ$C. Nevertheless, some deformed and melted ice lollies were observed between 0 and $2^\circ$C (Figure 1c). It is worth noting that both columnar and spherical parts of ice lollies became thicker as the temperature increased, probably due to growth from vapor diffusion.

The growth of the columnar part of the ice lolly appears to be more complicated in some cases. In general, needles and columns can be produced at the same temperatures (~$-5^\circ$C), but in different supersaturation conditions [Kobayashi, 1961; Magono and Lee, 1966; Bailey and Hallett, 2009]. However, some ice lollies were observed with some side planes (growing from the spherical part of some ice lollies) facing away from the attached column (examples are depicted in Figure 3c, red squares) at temperatures between $-4$ and $-6^\circ$C. We speculate that as the frozen droplet breaks due to H-M process or shattering due to freezing, the surface at the breakage point (where the side planes were developed on the frozen drop) becomes roughened. Then, these protrusions grow into needles/spikes due to diffusion (Figure 1b). Broadly, ice multiplication can potentially occur during the formation of an ice lolly as explained above. However, these particular ice lollies could be a visual evidence of ice multiplication occurrence.

### 4. Conclusion

On 21 January 2009, a maturing low-pressure system over North Atlantic moved toward the British Isles. A warm front associated with the depression passed over the British Isles and was sampled intensively and consisted of large regions of mixed-phase clouds. In these clouds, we observed a hydrometeor type, ice lollies, for the first time in significant concentrations, which form due to a variety of microphysical processes. Ice lollies were also observed in significant concentration during BAE146 flight on 23 September 2016 within a warm conveyor belt system. However, the data were collected over the northeast Atlantic Ocean, with no supporting radar coverage, which complicates in situ data interpretation. Aside from these two cases, ice lollies have not been seen on other research flights. Thus, future missions in warm conveyor belts spanning the H-M zone would provide insight into the importance of ice-lolly formation. The microphysical processes that led to the ice-lolly formation are described and summarized, as in Figure 4, as follows:

1. Widespread supercooled cloud was formed by a large-scale WCB circulation.
2. Planar ice crystals and snowflakes were formed via heterogeneous processes near cloud top and fell through the core of the WCB with significant amounts of supercooled liquid water.
3. Riming occurring in the WCB led to large numbers of columnar ice particles in the H-M secondary ice production zone.
4. Ice lollies were formed due to the collision of water drops with columnar crystals within the H-M region and were observed at temperatures between $-6$ and $0^\circ$C.
5. Some ice lollies appear to exhibit some side planes facing away from the attached column. This could be a visual evidence of ice multiplication occurrence.

6. The freezing of supercooled water is involved in the formation of ice lollies. Also, ice lollies can act as rimers enhancing ice multiplication mechanisms, removing further liquid water from the clouds. These processes can impact on cloud lifetime and precipitation formation.

7. Ice lollies in isolation demonstrate high \( Z_{DR} \) due to their elongated shape. Ice lollies were observed in significant concentrations within regions with \( Z_{DR} \) ranging between 0.3 and 1.6 dB, albeit not in complete isolation from other hydrometeor types. Such values could also be representative of ice lollies and were confirmed by calculations using the discrete dipole approximation.

8. Some ice lollies were also still found in areas where quasi-spherical graupels/heavily rimed crystals or water drops were the dominant hydrometeor type. In these areas, \( Z_{DR} \) tends to be much lower (−0 dB).

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