Exploring the Diabatic Role of Ice Microphysical Processes in Two North Atlantic Summer Cyclones

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(Manuscript received 20 July 2015, in final form 21 December 2015)

ABSTRACT

Numerical simulations are performed with the Weather Research and Forecasting Model to elucidate the diabatic effects of ice phase microphysical processes on the dynamics of two slow-moving summer cyclones that affected the United Kingdom during the summer of 2012. The first case is representative of a typical midlatitude storm for the time of year, while the second case is unusually deep. Sensitivity tests are performed with 5-km horizontal grid spacing and at lead times between 1 and 2 days using three different microphysics schemes, one of which is a new scheme whose development was informed by the latest in situ observations of midlatitude weather systems. The effects of latent heating and cooling associated with deposition growth, sublimation, and melting of ice are assessed in terms of the impact on both the synoptic scale and the frontal scale. The results show that, of these diabatic processes, deposition growth was the most important in both cases, affecting the depth and position of each of the low pressure systems and influencing the spatial distribution of the frontal precipitation. Cooling associated with sublimation and melting also played a role in determining the cyclone depth, but mainly in the more intense cyclone case. The effects of ice crystal habit and secondary ice production are also explored in the simulations, based on insight from in situ observations. However in these two cases, the ability to predict changes in crystal habit did not significantly impact the storm evolution, and the authors found no obvious need to parameterize secondary ice crystal production at the model resolutions considered.

1. Introduction

The effects of latent heat release and uptake due to the phase changes of water are known to play a key role in the development of extratropical cyclones. The earliest work on this topic demonstrated the importance of heating due to condensation (Manabe 1956; Danard 1964), which has since been confirmed by many other studies, most recently Joos and Wernli (2012). The diabatic role of ice processes has also been explored, although arguably to a lesser extent, and primarily using idealized models (e.g., Parker and Thorpe 1995; Marecal and Lemaitre 1995; Barth and Parsons 1996). Perhaps the most thorough exploration to date was conducted by Forbes and Clark (2003), who investigated the sensitivity of rapidly developing winter cyclones to the representation of ice phase processes (specifically deposition and sublimation) within the Met Office Unified Model. They simulated case studies from the Fronts and Atlantic Storm Track Experiment (FASTEX) field campaign and showed that “ice sublimation beneath sloping precipitating frontal updrafts has a significant impact on the development of frontal rain bands.” They also concluded that “the dynamical effects of latent heating due to ice deposition act on both cyclone and frontal scales, whereas the main impact of latent cooling due to ice
sublimation is restricted to the frontal-scale, and has little impact on the overall evolution and surface pressure on the synoptic-scale.” The Forbes and Clark study also highlighted the need to establish the sensitivity of more weakly driven cyclones to the representation of ice phase processes, although to our knowledge no studies have yet followed up on this recommendation. In situ observations, such as those taken during the Diabatic Influences on Mesoscale Structures in Extratropical Cyclones (DIAMET) project (Vaughan et al. 2015) can help to inform and constrain the treatment of ice processes in numerical models to explore this sensitivity.

A summary of the in situ microphysics observations taken during DIAMET are presented in Lloyd et al. (2014). Data from three specific cyclones were examined in detail—two from the winter months and one in summer. In each case, a wide variety of ice crystal habits (shapes) were detected as a function of altitude, with high ice water contents and number concentrations around -5°C due to secondary ice crystal production via rime splintering (Hallett and Mossop 1974). Existing operational models are unable to predict variations in number concentration as they typically use a single prognostic variable to represent the evolution of ice species, namely, the mass mixing ratio. Furthermore they tend to assume invariant mass–size and fall speed–size relationships appropriate only for a specific habit, and so are incapable of representing the range of particle characteristics seen in the observations. Deficiencies associated with this approach have been highlighted by a number of studies (e.g., Woods et al. 2007; Harrington et al. 2013a,b; Sulia et al. 2013; Milbrandt and Morrison 2013).

While Forbes and Clark (2003) explored the diabatic role of ice processes in two rapidly deepening winter cyclones, there is a need to expand the literature on this subject, not just to include a consideration of other winter cases, but also in summer too. Summer cyclones often present more of a challenge to forecasters than winter cyclones; recent examples include the low pressure system from 21 September 2012 spawned by Tropical Storm Nadine, and the remnants of ex-Hurricane Bertha (10 August 2014). Considerable uncertainty was associated with the tracks of these storms at short-range forecast lead times. One possible explanation could be that the lower baroclinicity associated with summer cyclones makes them more sensitive to diabatic processes. The DIAMET microphysics measurements reveal that despite the higher freezing level in summer, significant amounts of ice are present with strong variations in habit as a function of temperature. Dearden et al. (2014) showed that local diabatic heating rates associated with vapor growth of ice crystals can differ by a factor of 2 or more depending on the assumptions made in bulk models concerning the treatment of shape and size. Whether this uncertainty range is large enough to have any significant impact on the dynamics of cyclones in general is currently unknown. Thus, the outstanding question is the following: How complex does a microphysics scheme need to be to adequately represent the diabatic effects of ice phase processes on storm intensity and precipitation structure, and are current operational schemes sufficient for this purpose?

The aim of this paper is to try and address this question by taking advantage of the latest insights from aircraft observations and developments in bulk microphysics modeling. We present numerical simulations of two slow-moving summer cyclones with bent-back frontal structure, both of which occurred during the final DIAMET intensive observation period (IOP). Simulations are performed using different microphysics formulations, including a new scheme that parameterizes the habit evolution of pristine ice crystals as well as the production of secondary ice via rime splintering, to establish the diabatic role of ice processes on storm evolution. We also perform physical sensitivity tests to explore the influence on the simulated frontal dynamics. While it is not our intention to conduct a detailed verification of the model performance, we offer some insight into the response of the model to different levels of microphysical complexity, and discuss the implications for the parameterization of ice processes in operational weather forecast models.

2. Model description

All the numerical simulations presented here were conducted using version 3.4.1 of the Weather Research and Forecasting (WRF) Model. Each simulation was configured with a single domain at 5-km horizontal grid spacing. This resolution is sufficiently high that parameterization of subgrid-scale convection was not required; this was an intentional choice so that all cloud and precipitation in the model would be produced by the grid-scale microphysics scheme. This eliminates the possibility that changes to the microphysics formulation could be obscured by a compensating change in the behavior of the cumulus parameterization, and is thus advantageous when performing sensitivity tests designed to explore the role of specific microphysical processes on the dynamics.1 A 30-s model time step was used in all cases, along with 70 vertical levels. The simulations were initialized using operational

1 In section 5 we briefly discuss the effects of resolution on our results.
analyses from the European Centre for Medium-Range Weather Forecasts (ECMWF) on a 0.25° grid, with boundary conditions updated every 6 hours starting from 0000 UTC.

Three different microphysics schemes are used in this study, the first of which is the newly developed National Taiwan University Tsai–Chen (NTU-TC) scheme. We also perform simulations using the WRF single-moment 3-class microphysics (WSM3) scheme (Hong et al. 2004), and the WRF Ferrier scheme (also known as the Eta microphysics scheme; as documented at http://www.emc.ncep.noaa.gov/mmb/mmbpll/eta12tpb/). Further

**FIG. 1.** (a) Met Office surface analysis chart valid at 1200 UTC 18 Jul 2012 (Crown copyright). The model domain used to simulate this case is represented by the red square. (b) MSG satellite image (visible channel), also valid at 1200 UTC.
details of these schemes and how they compare are given in the next subsection. In all simulations we used the Goddard scheme (Chou and Suarez 1999) to parameterize shortwave and longwave radiation, and the Yonsei University boundary layer scheme (Hu et al. 2010).

Description of microphysics schemes used

The NTU-TC scheme treats six classes of hydrometeor: cloud droplets, rain, pristine ice, snow aggregates, graupel, and hail. The scheme predicts two moments of the particle size distribution (viz., mass mixing ratio and number concentration) for each hydrometeor species, as well as the option of a four-moment treatment of pristine ice. The latter allows the scheme to predict the evolution of ice particle shape and volume, from isometric crystals following nucleation to a representation of columnar or plate regimes depending on the ambient temperature. The prediction of shape in the NTU-TC scheme is based on a treatment of ice crystals as spheroids with a freely evolving aspect ratio as described in Chen and Tsai (2016), and is effectively a bulk parameterization of the adaptive habit scheme of Chen and Lamb (1994a, hereafter CL94a). The adaptive habit approach has hitherto been successfully implemented into bin-resolved cloud models to study ice processes (e.g., Dearden et al. 2012). We exploit this feature of the NTU-TC scheme to examine the impact of using an adaptive habit parameterization in the context of the chosen case studies.

Although not the first bulk scheme based on CL94a to predict the shape evolution of pristine crystals (see Harrington et al. 2013a,b), to our knowledge the NTU-TC scheme is the first multimoment bulk scheme to do so while also permitting conversions to other ice categories. This is particularly useful in the context of the present case studies, where in situ measurements show pristine crystals coexisting alongside aggregates and rimed snow. The NTU-TC scheme avoids the use of an arbitrary threshold size for conversion of pristine ice crystals to snow, and is therefore able to simulate aged columns and platelike crystals such as those that were observed during DIAMET. It is also the only scheme used in this study that represents secondary ice crystal production by rime splintering. Both the secondary ice and adaptive habit parameterizations are enabled by default in the NTU-TC control simulations. Ice nucleation is represented using the parameterization of DeMott et al. (2010), assuming that the number of aerosols greater than 500 nm in diameter is a constant value, equal to $2 \text{cm}^{-3}$ in our simulations. This value was chosen to provide a reasonable agreement with DIAMET observations of ice crystal number concentrations made around $-30^\circ\text{C}$. We also output diagnostics for the instantaneous latent heating and cooling rates ($\text{K h}^{-1}$) arising from the following microphysical processes: condensation, evaporation, deposition, sublimation, riming, freezing, and melting. Further details on the treatment of liquid and ice phase processes in the NTU-TC scheme are provided in the appendix, including a discussion of the differences between Chen and Tsai (2016) and Harrington et al. (2013a, 2013b) regarding the parameterization of crystal shape.

The WSM3 and Ferrier schemes are much simpler in comparison, and are standard microphysics options available for use within existing versions of WRF. These additional schemes were chosen because they are more representative of the level of parameterization used in typical operational models. For instance, WSM3 is a single-moment scheme that predicts the mass mixing ratios for three classes of moisture. In addition to water vapor, a single variable is used to represent cloud condensate, which can be liquid droplets or ice depending on temperature. Similarly a single prognostic variable is used to treat precipitation, using temperature to distinguish rain from snow. The Ferrier scheme is used operationally by the National Centers for Environmental Prediction (NCEP) in the WRF
North American Mesoscale Forecast System (WRF-NAM) model, and is designed with computational efficiency in mind. As such it only treats total condensate as a prognostic variable, and the fractional contribution of cloud water, rain, and ice to total condensate is diagnosed using storage arrays. Comparing results from all three schemes allows us to comment on whether the additional complexity offered by the NTU-TC scheme results in any appreciable impact on the dynamics of the simulations at either the mesoscale or synoptic scale.

3. The DIAMET case studies

The two summer cyclone cases investigated here occurred during the final DIAMET IOP in 2012: one from July (IOP 13) and the other from August (IOP 14); both are described below. Observations of the cyclones were made by the Facility for Airborne Atmospheric Measurements (FAAM) BAe-146 research aircraft—see Vaughan et al. (2015) for details of the aircraft payload and an overview of the DIAMET operations.
The Met Office analysis chart in Fig. 1a reveals the synoptic situation affecting the United Kingdom on 18 July 2012, showing a low pressure system centered over Scotland at 1200 UTC and the associated fronts. The position of the cyclone did not change much during the 6-h period prior to this, with only a small reduction in the cyclone’s central low pressure during this time (1004–1002 hPa). Rainfall radar data (not shown) reveal that the frontal rainband had established itself over central and southern Scotland by 0600 UTC. Between

Fig. 5. (a) Met Office surface analysis chart valid at 1200 UTC 15 Aug 2012 (Crown copyright), with the model domain used to simulate this case represented by the red square. (b) MSG satellite image (visible channel), also valid at 1200 UTC.

### a. DIAMET IOP 13: 18 July 2012

The Met Office analysis chart in Fig. 1a reveals the synoptic situation affecting the United Kingdom on 18 July 2012, showing a low pressure system centered over Scotland at 1200 UTC and the associated fronts.
1200 and 1800 UTC, the system moved slowly eastward over the North Sea as the cyclone continued to deepen gradually to 998 hPa, although the orientation of the occluded front meant that rain continued to affect Scotland for much of this period, leading to flooding in the Edinburgh region. Figure 1b also shows an image from the visible channel of the Meteosat Second Generation (MSG) satellite valid at 1200 UTC, revealing the bent-back nature of the cloud band.

The flight track for this case is shown in Fig. 2. The FAAM aircraft took off from Cranfield, United Kingdom (52.1°N, 0.6°W), at 0745 UTC and subsequently headed north, deploying dropsondes between approximately 0830 and 0900 UTC as it penetrated the cloud band at an altitude of around 9 km. Upon completing the dropsonde leg, the aircraft turned 180° and descended, where it conducted a series of legs at various altitudes back and forth between 55° and 58°N until approximately 1130 UTC. During these legs the microphysics probes revealed a considerable amount of ice was present from around 2.5 km up to almost 10 km (see Fig. 3a). Figure 3b shows the corresponding ambient temperature ranges as a function of altitude, as measured by the aircraft. On this figure we also indicate those regions where supercooled liquid was likely to have been present, as well as the purely glaciated regions of the cloud. The Cloud Droplet Probe (Lance et al. 2010) was not in operation for this particular flight, so we could not use it to identify the presence of supercooled droplets directly. Instead the relative humidity with respect to water was calculated using data from the Buck CR2 hygrometer, along with the saturation mixing ratio calculated from the deiced temperature probe measurements. The results were then used to identify the water-saturated regions. Supercooled droplets were likely to have been present up to a maximum altitude of around 5 km, corresponding to a median temperature of around −13°C. However, at 4 km, the aircraft sampled air below ice saturation, corresponding to a reduction in number concentration at this altitude consistent with sublimating ice crystals. We note that the dropsondes for this case appear to have been deployed into a region where the relative humidity values between 3 and 7 km were consistently below ice saturation, and so the dropsonde humidity profiles are not representative of the ambient conditions in which the ice crystals were later observed to be growing.

Images from the 2D-S cloud microphysics probe (Lawson et al. 2006; see Fig. 4) reveal a wide range of crystal habits were observed in this case. Smaller, more isometric particles were detected around −35°C (Fig. 4a), while larger aggregates and pristine stellar plate crystals dominated around −15°C (Fig. 4b). Around −5°C, high concentrations of columnar crystals were often found (Fig. 4c), which we attribute to the dominance of secondary ice production via rime splintering.

b. DIAMET IOP 14: 15 August 2012

This weather system affected Ireland and parts of the mainland United Kingdom. The 1200 UTC surface chart, along with the corresponding visible satellite image, are shown in Fig. 5a. Between 0000 and 0600 UTC, the low pressure system deepened steadily in the Met Office analysis charts, from 986 to 978 hPa. However, the analyses show that over the next 6 hours, the cyclone maintained this surface pressure and no further intensification occurred, while by 1800 UTC it had started to weaken slightly. IOP 14 has some features in common with IOP 13 (e.g., a distinct bent-back frontal structure and slow-moving rainband). The microphysics measurements for IOP 14, as documented in Lloyd et al. (2014), also exhibit similarities, with a freezing level around 3 km, a similar range of crystal habits throughout the depth of the cloud, and evidence of secondary ice crystal production via rime splintering. However, IOP 14 was unusually deep for the time of year, with a sea level pressure minimum of 978 hPa compared to 998 hPa in the July case. IOP 14 also exhibited a distinct squallline feature, producing generally higher precipitation rates than IOP 13, and a prominent potential vorticity (PV) tower as discussed later in section 4b, an indicator that diabatic processes were very active in this particular cyclone. Indeed, comparison of Fig. 6 with Fig. 3b reveals a slightly deeper mixed-phase layer in IOP 14 relative to IOP 13, indicative of stronger vertical motions and the potential for more latent heat release.
Additional information on this case study, including flight details and vertical soundings from dropsonde measurements, can be found in Lloyd et al. (2014).

4. Modeling results

a. IOP 13

Figure 7 shows plots (valid at 1200 UTC 18 July 2012) of surface precipitation rate, sea level pressure, and the 925-hPa PV field from WRF simulations initialized at 0000 UTC 17 July, using the model domain shown in Fig. 1a. The three simulations provide a reasonable simulation of the general meteorological conditions at this time. In particular the NTU-TC and WSM3 schemes produce very similar results, although the Ferrier scheme has more of a gap between the precipitation over Scotland and the rainband over the North Sea. To shed light on the diabatic role of ice processes in this case, Fig. 8 shows vertical profiles of latent heating and cooling rates produced by the NTU-TC simulation at 1200 UTC, averaged over the area between 51°–58°N and 16°W–10°E. Figure 8a shows the heating profiles for specific microphysical processes, and reveals that deposition heating and sublimation cooling are the dominant ice processes, followed by melting, which produced a localized cooling effect between 2 and 3 km. The heating term due to riming is relatively small in comparison, and the heating from heterogeneous freezing of cloud droplets too small to be visible on the chosen scale. Figure 8b shows the net diabatic heating profile produced by the NTU-TC microphysics at 1200 UTC. Although the effects of condensation and evaporation of liquid drops dominate at lower levels, ice processes still make a nonnegligible contribution to the vertical structure of the heating profile. This raises the following question: What role does the ice phase play in terms
of the synoptic evolution of the cyclone and sea level pressure in these simulations?

To address this question, we performed test simulations with each of the three microphysics schemes such that the heating and cooling terms associated with ice deposition and sublimation were switched off. In each case, ice is still allowed to grow and evaporate via vapor diffusion, but these processes are no longer permitted to feed back onto the temperature field. While we acknowledge that this is unphysical, it is useful as a means of isolating the diabatic effect on the evolution of the cyclone. Results from these test simulations are shown in Fig. 9. First, comparison of Fig. 9 with Fig. 7 reveals clear differences in the spatial distribution of precipitation. The intensity of the rainbands is also generally weaker in the test simulations; this is confirmed by Table 1, which quotes the domain average precipitation rates produced by all three schemes at 3-hourly intervals. Average precipitation rates in the test simulations are typically reduced between 17% and 30% with respect to the control runs. Second, comparison of the low-level PV and sea level pressure fields reveal that the system did not deepen in the test simulations to the same extent as in the control cases, and consequently the PV strip associated with the rainband wrapped up less tightly. This effect can be explained in terms of mass continuity. Sufficient energy is released during deposition growth to strengthen the upper-level divergence, which in turn induces the surface low to deepen further. Without the deposition heating term, the cyclone in the test simulations is unable to reach the same depth as in the control runs. This is further illustrated by the time series plots in Fig. 10, which track the magnitude of the cyclone’s central low pressure within the model domain for each simulation. Figure 10 shows that the impact of switching off deposition heating and sublimation cooling in all three simulations is most evident from 0600 UTC onward, both in terms of the magnitude of the SLP minima and its longitudinal position. The fact that we saw a similar response with each of the three microphysics schemes suggests that our findings concerning the synoptic role of deposition heating are robust. It also implies that the additional complexity of the NTU-TC scheme in terms of its treatment of ice processes is largely inconsequential with regards to synoptic evolution; this idea is explored later in this section.

We also performed test simulations with just the sublimation cooling term disabled. In this case, there was less of an impact on the position of the low pressure center, although it did deepen slightly further than the control run, by an additional 1–2 hPa. A very similar effect was noted when the cooling due to the melting term was disabled. This response can be understood through consideration of Fig. 8a. These cooling processes act to offset some of the diabatic heating due to condensation and deposition in the lower half of the troposphere, and so in their absence there is slightly more heating at lower levels, which in this case leads to a slightly deeper low pressure center. However, when deposition heating and sublimation cooling are both disabled together, the overall effect is to increase surface pressure, as shown in Fig. 10. Thus, from this analysis, we conclude that deposition growth was the dominant ice process.
phase diabatic process in terms of its synoptic-scale effect.

1) DIABATIC EFFECTS ON MESOSCALE DYNAMICS

Previous studies have highlighted the importance of cooling associated with both sublimation and melting in the morphology of frontal rainbands (e.g., Barth and Parsons 1996; Parker and Thorpe 1995; Forbes and Clark 2003), so we now turn our attention to the mesoscale impacts of these processes in the present case study. In order for microphysical processes to modify PV, phase changes of water must occur in regions where the vertical component of the absolute vorticity field is sufficiently high, as demonstrated by Joos and Wernli (2012). When we disabled the cooling terms associated with sublimation and melting in IOP 13, we found that the location and distribution of the frontal precipitation was largely unaffected. To help understand this, Fig. 11 shows cross sections of the $z$ component of absolute vorticity through the warm front from the NTU-TC control simulation, valid at 1200 and 1400 UTC 18 July with instantaneous diabatic heating rates from selected microphysical processes overlaid. Condensation and deposition produce the largest heating rates, consistent with Fig. 8. Both these processes encompass regions where the absolute vorticity is relatively high, thus, it is likely that they were able to play a role in modifying PV and, hence, the dynamics of the advancing warm front. However, the rates of cooling associated with sublimation and melting across the front were relatively small, while also occurring in more localized regions where the absolute vorticity values were closer to zero and, thus, unable to result in significant PV modification at the mesoscale. It is worth mentioning that in these simulations, the frontal rainband was displaced approximately 100 km farther south around 0600 UTC compared to the rainfall radar observations, before progressing northward by 1200 UTC. To investigate whether this discrepancy has any implications for our analysis, we also conducted simulations initialized at

![Fig. 9. As in Fig. 7, but for simulations with deposition heating and sublimation cooling terms switched off in each of the microphysics schemes.](image-url)
1200 UTC 17 July. While the timing of the frontal rainband over Scotland was improved in these simulations, our conclusions regarding the relative diabatic roles of the different microphysical processes remain the same.

2) Sensitivity to Predictive Habit

Given the importance of diabatic heating due to deposition in this case, we now explore the impact of the adaptive habit parameterization in terms of the deposition growth rates and the consequences for the distribution of diabatic heating within the cloud system. To facilitate this, we conducted an additional test with the NTU-TC scheme with the adaptive habit parameterization disabled, thus, reverting to a two-moment treatment of pristine ice assuming constant density spheres.

We first demonstrate that the simulation with adaptive habit is capable of representing realistic variations in pristine crystal shape as a function of temperature. Figure 12 shows cross sections of ice crystal aspect ratio along 28W, which are qualitatively consistent with the observed crystal habits shown in Fig. 4. For instance, the plate regime is evident between −10°C and −20°C, with the crystals keeping their platelike shape as they fall due to the “shape memory” effect described in Chen and Tsai (2016). Columnar crystals dominate between −20°C and −30°C, while pockets of columns are also simulated between 0°C and −10°C. At temperatures below −30°C, the aspect ratios gradually become closer to unity, signaling a transition to more spherical shapes, in agreement with the observations that show more isometric crystals near cloud top (Fig. 4a). Further, these variations in simulated crystal habit are significant enough to result in an appreciable effect on the representation of pristine ice and snow aggregates, relative to the test simulation assuming spherical ice. This is illustrated in Figs. 13 and 14, which show area-averaged vertical profiles of hydrometeor mass and number concentration, respectively, for the time period between 0600 and 1800 UTC 18 July. In terms of mass, the largest impact is seen between 4 and 6 km, where the tendency of the adaptive habit scheme is to increase the mass of pristine ice by up to 70%, and reduce snow aggregate mass by up to 50%. The greatest change in number concentration occurs around 7 km, where the adaptive habit scheme results in a reduction in both pristine ice and snow number concentrations by a factor of 2.

Table 1. Domain-averaged precipitation rates (mm h⁻¹) for simulations of IOP 13, at 3-hourly intervals (in UTC) valid at 18 Jul 2012. The “test” simulations correspond to the experiments with deposition heating and sublimation cooling switched off.

<table>
<thead>
<tr>
<th></th>
<th>0600</th>
<th>0900</th>
<th>1200</th>
<th>1500</th>
<th>1800</th>
</tr>
</thead>
<tbody>
<tr>
<td>NTU-TC control</td>
<td>0.120</td>
<td>0.108</td>
<td>0.118</td>
<td>0.114</td>
<td>0.105</td>
</tr>
<tr>
<td>Ferrier control</td>
<td>0.135</td>
<td>0.117</td>
<td>0.130</td>
<td>0.128</td>
<td>0.111</td>
</tr>
<tr>
<td>WSM3 control</td>
<td>0.14</td>
<td>0.122</td>
<td>0.139</td>
<td>0.142</td>
<td>0.112</td>
</tr>
<tr>
<td>NTU-TC test</td>
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<td>0.085</td>
<td>0.085</td>
<td>0.088</td>
<td>0.087</td>
</tr>
<tr>
<td>Ferrier test</td>
<td>0.117</td>
<td>0.097</td>
<td>0.109</td>
<td>0.117</td>
<td>0.104</td>
</tr>
<tr>
<td>WSM3 test</td>
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<td>0.083</td>
<td>0.095</td>
<td>0.109</td>
<td>0.106</td>
</tr>
</tbody>
</table>

FIG. 10. Time series plots showing the evolution of cyclone central low pressure (hPa) for the simulations of IOP 13 with (a) NTU-TC, (b) WSM3, and (c) Ferrier microphysics. In each plot, the solid thick line represents the control simulation, and the dashed thick line represents the test simulation with deposition heating and sublimation cooling switched off. The numbers labeled at 0000, 0600, 1200, and 1800 UTC (thin dashed lines) indicate the longitudinal position at which the low pressure minima occurred at these times. Numbers in boldface correspond to the control run, and normal typeface numbers to the test simulation.
approximately. These changes are consistent with the increased efficiency of pristine crystal growth under the adaptive habit scheme, resulting in larger and fewer pristine crystals relative to the constant density spheres approach. The consequence of this is that less solid mass is contained within the snow aggregates category. However, in terms of precipitation, the highest mass mixing ratios are associated with the rain and graupel categories, where differences between the two simulations are much smaller. As a result, the adaptive habit parameterization has little impact on the intensity of surface precipitation in this case.

We also evaluated the impact of the adaptive habit parameterization on the distribution of diabatic heating within the model. A vertical cross section along 2°W of the accumulated diabatic heating due to deposition growth between 0600 and 1800 UTC is shown in Fig. 15a, for the simulation with adaptive habit. The difference with respect to the simulation assuming spherical ice is shown in Fig. 15b. There are clearly differences in the spatial distribution of heating between the two simulations (of the order of 6 K over the 12-h period), however, they tend to be associated with a latitudinal displacement of the heating (e.g., around 55.5°N). Indeed, area-averaged profiles of deposition heating, accumulated between 0600 and 1800 UTC (Fig. 15c) confirm that the overall impact on the vertical distribution of diabatic heating is very small, and any change is compensated by an increase in heating from condensation growth of liquid droplets (Fig. 15d). Another test simulation was also performed to explore the sensitivity to the value of the capacitance coefficient used in the deposition growth rate equation for snow aggregates. Based on the findings of Westbrook et al. (2008), we performed an experiment with a capacitance value of 0.25D for snow aggregates (where D is particle size) instead of the default value of 0.5D. However, similar analysis of the vertical profiles of diabatic heating again showed very little response to this change, indicating that at forecast lead times of up to 42 h at least, use of an adaptive crystal habit or a different capacitance did not significantly affect the dynamic evolution of this cyclone.

b. IOP 14

Using the domain shown in Fig. 5a, we performed 42-h simulations initialized from 0000 UTC 14 August 2012, for each of the three microphysics schemes as before. All three simulations provide realistic representations of the location and intensity of precipitation with respect to the rainfall radar (not shown). Domain-averaged precipitation rates for the IOP 14 control simulations are shown in Table 2. The three microphysics schemes produce very similar values throughout the evolution of the rainband, showing steadily higher precipitation rates from 1200 UTC onward as the system progresses northward. In each case, the average precipitation rates are between a factor of 2–3 larger than those quoted for IOP 13 in Table 1. A noteworthy feature of all the simulations is that they show evidence of being able to capture the two distinct precipitation bands over the southeast of England (see Fig. 16), a consequence of the gap between the system’s cold and warm fronts as shown in the analysis chart (Fig. 5a). Indeed, we did not detect any obvious major differences between the NTU-TC,
WSM3, and Ferrier control simulations for this case at either the synoptic or mesoscale, which is again suggestive of a lack of sensitivity to the details of the microphysics parameterization. To gain insight into the diabatic role of microphysical processes in this case, area-averaged vertical profiles of instantaneous heating and cooling rates from the NTU-TC scheme are shown in Fig. 17, valid at 1200 UTC 15 August. The heating rates are larger in IOP 14 than in IOP 13 (Fig. 8), by a factor of 2 or more for the processes of deposition, sublimation, and melting. Furthermore, the heating associated with condensation growth of liquid drops (solid red line in Fig. 17a) spans a greater altitude range than in IOP 13 (Fig. 8a), indicative of higher relative humidities and stronger vertical motions as suggested by the aircraft measurements.

We also ran additional test simulations with the NTU-TC scheme to isolate the effects of diabatic heating from deposition growth, and diabatic cooling from sublimation and melting. At the synoptic scale, switching off heating due to deposition growth of ice produced a similar effect as in IOP 13, influencing both the position and depth of the low pressure center, but the impact on the depth of the low is stronger here than in IOP 13 (Fig. 8). Figure 18 also shows that the effects of sublimation and melting, although still not enough to counteract the effects of deposition heating, also play a more appreciable role in this case compared to the weaker cyclone. These effects are not too surprising given the larger heating and cooling rates compared to IOP 13. This also confirms the idea that the cooling associated with sublimation and melting acts to limit the extent to which low pressure systems deepen in summer. In terms of mesoscale structure, comparison of Figs. 19a and 19b show that deposition heating also affects the distribution of the frontal precipitation, while also reducing the intensity by up to 34% on average by 1800 UTC (Table 2). However the cooling processes had less of an effect on the location and intensity of the rainband (Figs. 19c,d; Table 2). These results are qualitatively consistent with the findings from IOP 13.

1) A CLOSER LOOK AT DIABATIC PV STRUCTURE IN IOP 14

Figure 18 shows that the effect of deposition heating on cyclone evolution was greater in IOP 14 compared to IOP 13. This suggests that diabatic processes made a more important contribution to the intensification of the IOP 14 cyclone, through the generation of potential vorticity. A closer look at the PV structure in the IOP 14 simulations is thus useful to help explore this idea. Figure 20 shows vertical cross sections of the PV field through the center of the low pressure system, for both the NTU-TC control simulation and the test simulation with no deposition heating. In the control case, a diabatic PV tower (Rossa et al. 2000) is present at 0600 UTC in the troposphere around 50°N (corresponding to the location of the cyclone center), which is strongest between the surface and 4km in height. By 1200 UTC, the upper-level PV anomaly has become vertically

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2 A prominent PV tower feature is also evident in Met Office Unified Model simulations of this case (O. Martinez-Alvarado 2015, personal communication).
aligned with the low-level diabatically generated PV feature, signaling the end of baroclinic growth (indeed this is consistent with the plateauing of the low pressure minimum as shown by the black line in Fig. 18 after 1200 UTC, which is also evident in the Met Office analysis charts, albeit slightly earlier). The solid blue contours in Figs. 20a and 20b represent areas where the heating rate due to growth of ice via vapor deposition exceeds 1 K h\(^{-1}\). They show that deposition heating occurs over significant areas of the mid- to upper troposphere, either side of the diabatic PV tower. The region of deposition heating to the north of the diabatic PV tower (Fig. 20a) corresponds to the cloudy air mass of the warm conveyor belt; similarly the deposition heating to the south of the PV tower is likely to be associated with the cloudy air wrapped tightly around the cyclone’s center (see Fig. 5b). In the test simulation where deposition heating is disabled (Figs. 20c and 20d), values of potential temperature in the mid- to upper troposphere are clearly reduced relative to the control simulation, and there is also no real evidence of a coherent diabatic PV tower. Thus, we can conclude that the heat released during deposition growth of ice in IOP 14 contributed to the formation of the PV tower and the intensification of the cyclone up to 1200 UTC. This result is similar to the findings of Ahmadi-Givi et al. (2004), who showed that a diabatically generated low-level PV anomaly was largely responsible for the intensification of a rapidly developing cyclone during FASTEX.

2) SENSITIVITY TO PREDICTIVE HABIT

We now consider the role of the adaptive habit parameterization in terms of the effects on precipitation and the vertical structure of diabatic heating, in the same manner as was done for IOP 13. Vertical profiles of spatially and temporally averaged hydrometeor mass and number concentrations are shown in Fig. 21, from simulations of IOP 14 using NTU-TC microphysics both with and without the adaptive habit parameterization enabled. Figure 21 shows that the adaptive habit scheme produces a notable effect on the partitioning of ice mass between the pristine and aggregate categories. The impacts on the mass and number concentration of these categories due to inclusion of the adaptive habit scheme are more pronounced in IOP 14 compared to IOP 13. Number concentrations are increased by up to a factor of 3 typically, throughout the mid- to upper troposphere. The largest impact on the mass mixing ratio is between 4 and 6 km, with an increase in pristine ice mass of around
60%, and a reduction in snow mass by approximately 40%. However, as in IOP 13, there was much less of an effect on the rain and graupel categories, resulting in very little impact on surface precipitation rates. Despite the larger heating rates in IOP 14, use of the adaptive habit parameterization also failed to produce a significant change in the vertical distribution of heating (see Fig. 22). Taking the results from both case studies together, our simulations suggest that surface precipitation rates were mainly determined by the warm rain process and the melting of heavily rimed ice (graupel) in these cases, and that both these processes overshadow the changes in snow aggregate mass and number as a consequence of using the adaptive habit scheme.

5. Discussion

Collectively, our findings show that heat released during deposition growth of ice is important in terms of the synoptic-scale development of summer cyclones, where the effect is large enough to influence the depth of the low pressure systems by helping to drive stronger upper-level divergence. This is a potentially important result given the larger uncertainty range surrounding deposition growth rates of ice compared to condensation growth of liquid. With this in mind, it is appropriate to revisit the original aim of this paper—to shed light on whether existing operational treatments are sufficient to capture this effect. Our modeling results certainly suggest that a single-moment scheme for ice could be sufficient, at least in summer, since the WSM3 scheme produced a very similar response to the much more sophisticated NTU-TC scheme in both instances. Indeed, our sensitivity studies with the NTU-TC scheme show that the inclusion of a shape and volume moment for the pristine ice category has very little impact on the representation of mesoscale structures in these two cases. Results generated with the Ferrier scheme, which uses an even simpler diagnostic treatment of ice, were also very similar to the other two schemes, although there was slightly more of an impact on the depth of the low and the position of the rainband in the IOP 13 case.

Although the inclusion of the additional shape and volume moments in the NTU-TC scheme did not make any obvious impact on the evolution of mesoscale structures, they did result in some noteworthy changes to the simulation of microphysical processes. For instance, in both case studies, enabling the adaptive habit parameterization resulted in a reduction in snow aggregate mass. A possible explanation for this is that the
fall speeds of the pristine ice crystals decrease when the shape evolution is considered, which reduces the “sweep volume” between pristine ice crystals. This would then reduce the collision rate among pristine crystals, and hence reduce the production rate of snow aggregate mass. The adaptive habit scheme was also found to affect the number concentration of pristine ice crystals, most notably in the IOP14 case. This can be understood in terms of how the NTU-TC scheme parameterizes heterogeneous ice nucleation. The NTU-TC simulations performed in this study use the DeMott et al. (2010) parameterization to represent ice nucleation in the deposition/condensation mode. Thus, the initiation of primary ice crystals in the model is constrained by the supersaturation with respect to ice. Hence, when the adaptive habit scheme is enabled, more water vapor is

| TABLE 2. Domain-averaged precipitation rates (mm h⁻¹) for simulations of IOP 14, at 3-hourly intervals (in UTC) valid at 15 Aug 2012. |
|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | 0600            | 0900            | 1200            | 1500            | 1800            |
| NTU-TC control  | 0.244           | 0.228           | 0.271           | 0.336           | 0.352           |
| Ferrier control | 0.244           | 0.237           | 0.274           | 0.362           | 0.356           |
| WSM3 control    | 0.247           | 0.237           | 0.264           | 0.330           | 0.355           |
| NTU-TC (no heating from deposition) | 0.213 | 0.215 | 0.202 | 0.228 | 0.231 |
| NTU-TC (no cooling from sublimation) | 0.258 | 0.232 | 0.272 | 0.366 | 0.411 |
| NTU-TC (no cooling from melting) | 0.258 | 0.240 | 0.271 | 0.352 | 0.396 |
consumed by the enhanced deposition growth rate compared to the assumption of spherical crystals. This results in lower supersaturations with respect to ice, which can reduce rates of ice nucleation via deposition/condensation nucleation.

We acknowledge that, at 5 km, the horizontal grid spacing of our model simulations may not fully resolve the vertical velocities associated with any convective motions embedded within the large-scale flow. At higher resolutions, the model may be able to better represent such vertical motions, which could have an impact on mesoscale structures and precipitation rates. Also, the production rate of secondary ice splinters in the NTU-TC scheme, which is based on Hallett and Mossop (1974), is dependent on the amount of riming occurring between $-3^\circ$ and $-8^\circ$C, and this may also be sensitive to the choice of model resolution. To investigate these possibilities, for both case studies we ran a nested domain ($800 \times 800$ grid points) at 1 km horizontal grid spacing using the NTU-TC scheme, over areas encompassing the low pressure centers and a large proportion of the frontal rainbands. Average precipitation rates within these nested domains were found to agree within 10% of those calculated for the equivalent region within the 5-km parent domains. Furthermore, this result did not change when the parameterizations of adaptive habit and secondary ice production were disabled.

Because of our limited domain size and relatively short integration times, we cannot necessarily extrapolate our results to global models, which run at lower horizontal resolutions, and of course are not constrained by external boundary conditions. At these coarser resolutions, convection schemes play a much more important role, and given that they are not generally designed to represent the details of ice phase microphysical processes, the balance between resolved and parameterized convection in global models could be important in determining the vertical structure of diabatic heating. Thus, in coarser-scale models, the representation of ice microphysical processes within convection schemes is potentially relevant, and

![Figure 16](image_url)

**Fig. 16.** Maps of surface precipitation rate (shading; mm h$^{-1}$) and sea level pressure (contours; hPa) from control simulations of IOP 14 using (a) NTU-TC, (b) WSM3, and (c) Ferrier microphysics. Plots are valid at 1200 UTC 15 Aug.

![Figure 17](image_url)

**Fig. 17.** As in **Fig. 8**, but from the simulation of IOP 14, valid at 1200 UTC 15 Aug.
6. Summary and conclusions

This paper has focused on establishing the diabatic role of ice processes in the evolution of U.K. summer cyclones, with a view toward exploring the potential for higher levels of microphysical sophistication in numerical models to impact forecast skill associated with mesoscale structures at short-range lead times. Two cyclones were considered that, although they exhibited differences in terms of their intensity and general synoptic structure, shared some common microphysical characteristics. For example in each case the freezing level was around 3 km, with similar variations in crystal habit as a function of temperature, and high ice number concentrations at relatively warm temperatures (around \(-5^\circ C\)), attributable to an active secondary ice multiplication mechanism. Numerical simulations of both case studies were performed using the WRF mesoscale model at a horizontal grid spacing of 5 km. Simulations were repeated using different microphysics formulations, and the impact on both the synoptic and frontal scales was assessed. Our conclusions are as follows. We stress that in reaching these conclusions, we have only considered the role of ice phase processes over relatively short time scales, out to a maximum of 42 h:

- In both cyclones, the transition of water from the vapor to solid phase was shown to have an important effect on the overall synoptic evolution. Sufficient energy was released in the form of latent heat during vapor growth of ice (deposition) to influence the depth of the surface lows during cyclogenesis. Additionally in the August case, the heating due to deposition at midtropospheric levels helped to establish a diabatic PV tower, which contributed to the intensification of the cyclone.
- Cooling associated with sublimation and melting also influenced the depth of the low pressure systems, and this effect was more pronounced in the more intense cyclone. However, in both cases, the effect of these cooling processes was overshadowed by the more dominant effects of heating due to deposition.
- In terms of mesoscale dynamics, cooling rates associated with sublimation and melting in the vicinity of fronts were in general relatively weak and did not occur in regions where they were able to influence the dynamics of the fronts to any great extent.
- Changes to the microphysical parameterization affecting the rate of deposition growth, including a predictive habit scheme for pristine ice crystals, had no significant influence on storm evolution.
- For these case studies, and at the grid-spacing used to simulate them, we saw no evidence for an obvious need to parameterize secondary ice crystal production via rime splintering.
- Our findings suggest that for summer cyclones, a single-moment treatment of the ice phase in operational convection-permitting models is probably sufficient to capture the key diabatic effects of ice phase processes.

Finally, although we have focused on summer cyclones, our results allow us to make inferences about potential impacts on winter cyclones as well. For instance, the effect of using the adaptive crystal habit method as opposed to the assumption of ice spheres led to an increase in the bulk mass of pristine ice, while at the same time reducing snow mass and number. Although this change did not significantly impact...
mesoscale dynamics or surface precipitation rates in the cases presented here, such effects may well be more important when temperatures are low enough to permit snow to reach the ground before melting. Such conditions are often encountered in winter in the eastern United States, for example, resulting in a range of observed crystal habits at the surface (Stark et al. 2013). Therefore, the results of this study would suggest that an adaptive treatment of ice crystal habit could be beneficial for the prediction of snowfall amounts, in line with previous studies (e.g., Woods et al. 2007).

**Acknowledgments.** This work was funded by the U.K. Natural Environment Research Council (NERC) as part of the Storm Risk Mitigation Programme (Grant NE/I005234/1) in collaboration with the Met Office. We acknowledge the Facility for Airborne Atmospheric Measurements (FAAM), who manage the BAe Systems 146 Atmospheric Research Aircraft on behalf of NERC and the Met Office, and DirectFlight Ltd who operate the aircraft. The authors would also like to thank Dr. Gary Lloyd (University of Manchester) for processing the aircraft microphysics data for IOP 13 that is used in Fig. 3a.

**APPENDIX**

**Details of the NTU-TC Microphysics Scheme**

Here we describe the key features of the NTU-TC scheme that are most relevant to this study. Note that for complete details, including full mathematical derivations of all equations used, the reader is referred to Tsai (2014).
a. Liquid processes

The version of the NTU-TC scheme used here is configured with a saturation adjustment treatment for condensation growth of liquid droplets, with droplet activation parameterized using the power-law relationship of Twomey (1959), with $c$ and $k$ parameters set to values of 100 and 0.4, respectively. No condensation onto rain drops is considered, only cloud droplets. Evaporation of rain is treated according to Morrison et al. (2005). The warm rain processes of auto-conversion, accretion, self-collection, and break up of rain drops are all parameterized following Chen and Liu (2004).

b. The bulk adaptive habit parameterization for pristine ice

CL94a developed a theory-based method to describe ice crystal shape evolution for use in spectral bin models. A bulk parameterization of this method has recently been developed by Chen and Tsai (2016), and this approach has been implemented within the NTU-TC scheme to track the evolution of ice crystal shape and density. The key features of this modal adaptive habit scheme are summarized below.

By representing pristine ice crystals as spheroids, their shape can be represented to first order as the ratio of the $c$ and $a$ axis lengths (CL94a, their Fig. 1). These two lengths have been found by many observations (e.g., Heymsfield and Knollenberg 1972; Jayaweera and Ohtake 1974) to be related through an exponential relationship as follows:

$$c = \eta a^\beta , \quad (A1)$$

where $\eta$ and $\beta$ are positive constants that have specific values for a given crystal type. These fixed-form equations were almost exclusively used for describing ice crystal shapes in some earlier modeling studies until the theory-based parameterization of CL94a, who derived the equation:

$$\frac{dc}{da} = \Gamma(T)\phi , \quad (A2)$$

where $\Gamma(T)$ is the inherent growth ratio and $\phi(=c/a)$ is the aspect ratio. The parameter $\Gamma(T)$ is calculated from the ratio of the condensation coefficients for the basal and prism faces driven by surface kinetic processes and is primarily a function of temperature. CL94a then
linked the conventional mass growth equation with Eq. (A2) to account for the effects of evolving crystal shape during deposition growth. Equation (A2) expressed in an integrated form \[ c_a G(T) \] is identical to Eq. (A1), with \( G(T) \) corresponding to the exponent \( b \).

In the bulk method of Chen and Tsai (2016), crystal shape is assumed to follow the power law of Eq. (A1), the key difference being that the exponent \( b \) is not determined by temperature as in CL94a. Instead \( b \) is redefined as an adaptive growth ratio, which retains the growth history of ice crystals in the new parameterization, and, therefore, changes gradually from its earlier value by adapting to the new ambient temperature, and is thus different from \( G(T) \). The advantage of this method is that \( f \) can be determined by knowledge of \( b \) alone, as opposed to tracking the two axis lengths individually [as is the case in Harrington et al. (2013a,b), who use this approach to diagnose both the aspect ratio and particle density]. The expression for \( f \) is derived as

\[
 f = \frac{D}{D_0} \frac{3(\beta - 1)\beta + 2}{\beta^2}, \quad (A3)
\]

where \( D \) is the equivalent diameter and \( D_0 \) is the threshold size for isometric growth. However, \( b \) is not an extensive property and, thus, cannot be conserved during spatial advection. Instead a prognostic variable for the volume-weighted (or third-moment weighted) bulk ice shape moment is used in the parameterization:

\[
 M_\phi = \int \phi D^3 N(D) dD = \int \left( \frac{D}{D_0} \right)^{3\zeta} D^3 N(D) dD = D_0^{-3\zeta} M_{3\zeta+3}, \quad (A4)
\]

where \( M_k = \int D^3 N(D) dD \) is the \( k \)th moment of the size distribution, and \( \zeta = (\beta - 1)/(\beta + 2) \). Ice density is also not an extensive property, but can be diagnosed from the mass mixing ratio and the volume of ice particles. Hence, another prognostic variable representing the bulk ice volume moment is introduced:

\[
 M_V = \frac{\pi}{6} \int D^3 N(D) dD = \frac{\pi}{6} M_3. \quad (A5)
\]

These two new bulk moments, representing shape and volume, are advected along with the mass mixing ratio and number concentration moments for the pristine ice category. Note that this is different to the approach of Harrington et al. (2013a,b), who predict the \( a \)-axis and

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**FIG. 21.** Vertical profiles from simulations of IOP 14 with NTU-TC microphysics, showing area-averaged (48°–55°N, 20°W–6°E) and time-averaged (0600–1800 UTC 15 Aug) (a)–(c) hydrometeor mass mixing ratio and (d)–(f) number concentration for the pristine ice, snow aggregates, and graupel categories for the NTU-TC control (solid line) and the test simulation with adaptive habit disabled (dashed line).
c-axis lengths individually to diagnose the aspect ratio and particle density. Further, the scheme of Harrington et al. applied a double-moment approach to describe the size spectrum of pristine ice crystals, whereas prediction of the volume moment in the present scheme enables a triple-moment approach, which Chen and Tsai (2016) demonstrate that it is important for the evolution of ice mass with respect to spectral bin calculations.

The particle size distribution is assumed to follow a gamma distribution, of the following form:

\[ N(D) = N_0 D^a \exp(-\lambda D), \]  

(A6)

where \( N_0, \lambda, \) and \( \alpha \) are the intercept, slope, and shape parameters, respectively. The prediction of the volume moment for pristine ice enables the shape parameter \( \alpha \) to evolve, along with \( \lambda \) and \( N_0 \). Note that when the adaptive habit parameterization is disabled, the density of pristine ice is held constant at 910 kg m\(^{-3}\) and the crystals are assumed to be spherical (\( \phi = 1 \)).

Power-law relationships are used to represent the variation of mass, fall speed, and cross-sectional area as a function of particle size. The additional shape and density information allows the coefficients used in these power-law relationships to vary with the change in habit of ice crystals, instead of being held constant as in other schemes. Terminal velocities are determined based on the parameterization of Mitchell and Heymsfield (2005), while ventilation effects are calculated based on Hall and Pruppacher (1976).

c. Other ice processes

In addition to pristine ice, this version of the NTU-TC scheme uses a two-moment approach to represent snow aggregates, graupel, and hail. The particle size distribution for these categories is assumed to follow a gamma distribution as in Eq. (A6), but with \( \alpha = 0 \), thereby reducing to a negative exponential distribution (Marshall and Palmer 1948). For these additional frozen categories, growth and evaporation by vapor diffusion is based on the approach of Morrison et al. (2005).

Transitions from the pristine ice category to the snow category can occur only as a result of the aggregation of pristine ice crystals. Hence, snow is strictly regarded as an aggregate category. Conversion rates are based on the method described in Cotton et al. (1986), with modifications to account for the effect of crystal shape in terms of the cross-sectional area and fall speed. The collection efficiency, which is independent of crystal shape, is determined from the maximum value between that used by Cotton et al. (1986) and Chen and Lamb (1994b).

Self-collection of snow aggregates is based on Passarelli (1978), where the aggregation efficiency is adopted from the maximum value from Chen and Lamb (1994b) and Ferrier et al. (1995). The density of snow aggregates is diagnosed from the mean bulk size, following Passarelli and Srivastava (1979). The density of the graupel and hail categories is fixed at 400 and 900 kg m\(^{-3}\), respectively.

The shape and volume variables for pristine ice are influenced by riming growth, following Chen and Lamb (1994b). Graupel can be formed by riming of both cloud droplets and rain onto snow and pristine ice. The shape of pristine ice crystals is accounted for during riming in a similar way to that of aggregation [i.e., in terms of the cross-sectional area (which is diagnosed from the crystal shape moment) and fall speed]. Diagnosis of the cross-sectional area benefits the calculation of collection kernels and radiative transfer. Collection efficiencies between pristine ice crystals (columnar and planar) and cloud droplets are referred to in Wang and Ji (2000).

Ice multiplication, initiated from the splintering of graupel and snow aggregates during riming at temperatures between \(-3^\circ\) and \(-8^\circ\)C, is based on Hallett and Mossop (1974). The ice splinters are assumed to be isometric upon creation, with an initial density of 910 kg m\(^{-3}\) and an initial diameter of 6 \( \mu \)m. Details of all other solid and mixed-phase processes are given in Tsai (2014).

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