

RESEARCH ARTICLE

New insights into convection-permitting model simulations from a Z_{DR} diagnostic for raindrops

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Abstract

A polarimetric radar forward operator to simulate differential reflectivity (Z_{DR}) from rain was developed to evaluate storms in the Met Office Unified Model (MetUM). Subkilometre simulations were carried out for two case days of the Wessex Convection Experiment (WesCon) field campaign in the summer of 2023. The joint distribution of reflectivity (Z_H) and Z_{DR} followed a one-to-one relationship for simulations using a single-moment microphysics scheme, in contrast with radar observations. Simulations using the Cloud AeroSol Interacting Microphysics (CASIM) double-moment microphysics scheme reproduced a spread in Z_{DR} values for a given reflectivity similar to observations. Vertical columns of Z_{DR} , indicative of strong updrafts, were overly intense and high in the single-moment simulations compared with the observations, whereas Z_{DR} column heights and intensities in the double-moment simulations were more comparable with observations. Vertical velocities did not vary much between the different model configurations, suggesting differences in mass distributions for different hydrometeor types. Z_{DR} from prognostic rain can thus reveal model biases and provides new avenues for future model evaluation and development.

KEYWORDS

convective storms, differential reflectivity, forward operator, model evaluation, polarimetric radar

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1 | INTRODUCTION

The representation of clouds and accurate prediction of precipitation in numerical weather prediction (NWP) and climate models remains a fundamental challenge (e.g., Boucher *et al.*, 2013; Clark *et al.*, 2016; Fosser *et al.*, 2024; Frogner *et al.*, 2019; Giorgi, 2019). Forecasting centres now run NWP models at convection-permitting kilometre to subkilometre resolutions (Reinert *et al.*, 2024; Seity *et al.*, 2011; Tang *et al.*, 2012). However, even at such resolutions, simulations may still fail to replicate cloud morphologies (Stein *et al.*, 2014) and updraft strengths (Nicol *et al.*, 2015). A better understanding of the differences between the observed and modelled properties of clouds helps to inform model improvement in the representation of convection. To improve the representation of convective storms within NWP, the parametrisation of cloud microphysics and its interaction with resolved model dynamics at such resolutions has to be understood well using both models and observations (Morrison *et al.*, 2020). Within NWP models, microphysical processes are usually parametrised using the bin or bulk approach (Khain *et al.*, 2015), with the latter being more common in operational models due to computational limitations. The Met Office Unified Model (MetUM) used a single-moment microphysics scheme based on a basic formulation described within Wilson and Ballard (1999) (hereafter WB). A newer double-moment microphysics, Cloud AeroSol Interacting Microphysics (CASIM: Field *et al.*, 2023), has become operational within MetUM since the writing of this study in January 2026. The goal of the current study is to explore the use of polarimetric radar data in evaluating the MetUM coupled to the two different microphysics schemes.

The horizontal equivalent radar reflectivity factor (Z_H) has often been used for model evaluation in past studies (e.g., Peter *et al.*, 2015; Stein *et al.*, 2014), as it is readily available from single-polarisation radars. The observable provides information on hydrometeor size if number concentration is unchanged, or on hydrometeor concentration assuming the same size of hydrometeors. However, the use of Z_H alone cannot constrain both hydrometeor number and size. Besides the use of Z_H for model evaluation, polarimetric radars that operate certain pulsing schemes provide observations of differential reflectivity (Z_{DR}). This quantity is the logarithmic ratio of received horizontally polarised to vertically polarised radar reflectivity factors, which is usually positive where oblate hydrometeors are present with a horizontal orientation in a radar sampling volume (e.g., Illingworth & Caylor, 1989; Kumjian, 2013a).

Intense updrafts in severe convection loft large oblate raindrops and wet ice particles into sub-freezing levels of

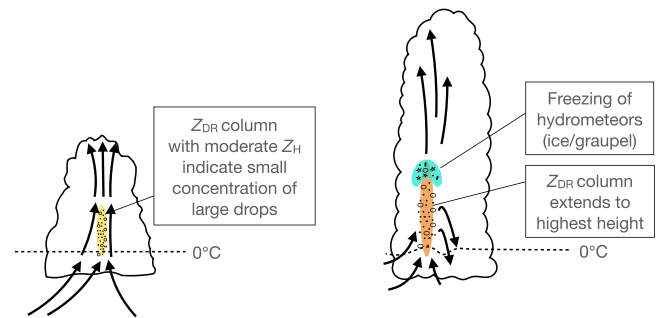


FIGURE 1 Conceptual diagrams showing (a) developing and (b) vigorous growth of a convective cell, focusing on Z_{DR} column evolution. Figure adapted from Lo *et al.* (2024).

a convective cell and are often collocated with enhanced values of Z_{DR} (taken to be ≥ 1.0 dB in Snyder *et al.*, 2015). These are known as Z_{DR} columns, which are regions of “enhanced Z_{DR} that extends above the environmental 0°C level” (Kumjian, 2013b), and are indicative of strong updrafts promoting the growth of raindrops by collision-coalescence, while supporting and lofting large oblate hydrometeors within convective storms, as seen in Figure 1. Z_{DR} columns are followed by increases in Z_H at the surface, as documented in a number of past observational and modelling studies (e.g., Kumjian *et al.*, 2014; Kumjian & Ryzhkov, 2008; Meischner *et al.*, 1991; Snyder *et al.*, 2015). Simulated Z_{DR} columns by Kumjian *et al.* (2014) were contained directly within strong updrafts of around $10 \text{ m} \cdot \text{s}^{-1}$ to more than $45 \text{ m} \cdot \text{s}^{-1}$. Some Z_{DR} columns extend up to several kilometres above the environmental freezing level, although their widths are usually of the order of one to a few kilometres. Polarimetric radar observations and phenomena such as Z_{DR} columns derived from radar observations offer in-depth information on the microphysics of clouds. Given that Z_{DR} is available operationally as an indication of strong updrafts in clouds, it serves as a useful proxy without the need for Doppler-derived updraft estimates. Considering the observed dimensions of Z_{DR} columns, convection-permitting simulations will need to be run at subkilometre grid lengths to allow a detailed evaluation of modelled microphysical and dynamics within such NWP models (e.g., Augros *et al.*, 2015; Putnam *et al.*, 2016; Shrestha *et al.*, 2022; Snyder *et al.*, 2017). A process-based evaluation of convective storms for cases of interest requires extensive observational coverage; the use of readily available operational radar data is beneficial for the on-demand evaluation of these cases of interest.

Operational polarimetric radar networks provide spatial coverage of the order of 1000 km, making them suitable for a robust evaluation of cloud representation and improving microphysical parametrisations in the spatial domain

of regional NWP models. The UK Met Office has upgraded its C-band radar network fully as of January 2018 to have polarimetric capabilities. Three-dimensional (3D) radar composite products that use data from the operational network (Scovell & al Sakka, 2016) and radar reflectivity from the composite have been shown to be effective in evaluating convective storms in the MetUM (Stein *et al.*, 2020). The 3D composite has since been extended to include Z_{DR} and its columns of enhanced values were used for exploring the Met Office nowcasting application (Lo *et al.*, 2024). Such previous works have shown the usefulness of 3D composite products derived from the UK's operational radar network. However, the application of Z_{DR} within the composite for the purposes of evaluating the MetUM coupled to CASIM has yet to be explored.

The large-scale precipitation scheme within the MetUM calculates Z_H as a diagnostic. Johnson *et al.* (2018) have previously evaluated the MetUM for two rainfall cases over South Korea against radar observations using a polarimetric radar forward operator. However, their study focuses on a single-moment microphysics scheme within the MetUM. While single-moment schemes tend to have a one-to-one relationship between mean drop diameter and number concentration, double-moment schemes are able to represent the broader range across which these two parameters can vary. A single-moment scheme would only simulate a near one-to-one relationship between the rain contributions of Z_H and Z_{DR} , since rain mass alone does not differentiate between a situation with a high number of small raindrops or a small number of large raindrops. The CASIM double-moment scheme with its prognostic hydrometeor number and mass could allow a more realistic joint distribution between Z_H and Z_{DR} , and thus a better constraint on the number concentration and mean drop diameter. The evaluation of CASIM requires a new forward operator that is consistent with double-moment microphysics.

This study implements a suitable forward operator within the MetUM to simulate Z_{DR} for rain. We then use this forward operator for comparing MetUM simulations of Z_H and Z_{DR} with those observed in the 3D radar composite, so as to evaluate both the single-moment microphysics scheme and the CASIM double-moment microphysics scheme.

In Section 2, the UK operational radar network and 3D composite are presented, as well as how Z_{DR} values from the radar composite are consistent with those from a research radar. The setup of the MetUM and its configurations are also introduced, alongside case studies that are used in this study. Section 3 details the design and implementation of the forward operator for rain, Z_{DR} , including its verification. The presence of Z_{DR} columns in the model simulations is evaluated against the 3D radar

TABLE 1 Met Office C-band radar long-pulse scan parameters.

Scan parameter	Value
Radar type	Dual-polarisation pulsed Doppler
Wavelength	5.6 cm
Polarisation mode	H and V transmit and receive
Pulse repetition frequency	300 Hz
Range	255 km
Range resolution	600 m
Beamwidth (FWHM; -3 dB, one-way)	1.1°
PPI elevations	0.5, 1.0, 2.0, 3.0, and 4.0°

composite in Section 4. Updraft magnitudes required to loft large hydrometeors are also explored. Recommendations for future model evaluation work are provided in the discussion and conclusions in Section 5.

2 | DATA AND METHODS

2.1 | UK operational radar network

The Met Office operational weather radar network consists of 15 C-band radars located across parts of the United Kingdom and has been upgraded to have dual-polarisation capability since January 2018 (Met Office, 2023). The radars carry out their long-pulse plan position indicator (PPI) scans with the scan strategy detailed in Table 1.

In order to exploit the benefits of data from the UK network of radars, Scovell and al Sakka (2016) formulated procedures to combine radar measurements from single radar sites into a three-dimensional Cartesian grid. The use of multiple radars in a dense network compensates for the missing coverage of a single radar. Such operational systems used by meteorological agencies have demonstrated the usefulness of three-dimensional gridded multi-radar reflectivity products (Bousquet & Tabary, 2013; Zhang *et al.*, 2011). The generation of these 3D composite products is used in this study for evaluating the representation of convective storms in the MetUM. The reliability of 3D radar composite products for model evaluation was demonstrated by Stein *et al.* (2020), who showed that equivalent storm diameter in the 3D radar composite data compares well with values derived from a research radar.

Following the vertical interpolation method in the construction of a 3D radar composite in Zhang *et al.* (2005), the radar data are interpolated onto a three-dimensional

Ordnance Survey National grid, with 1-km horizontal and 500-m vertical spacing. The reference height for altitude is above mean sea level. Using motion vectors derived from the radar composites at the two previous times separated by five minutes, advection corrections are applied to the composite valid for the current time. A range-dependent weighting scheme is used in regions of space where radar sampling volumes of two or more radars overlap. Finally, vertical linear interpolation is carried out to obtain values at the required point in dB units. This is done operationally for Z_H , with the product being available every five minutes.

Lo *et al.* (2024) have extended the composite to include Z_{DR} for the purposes of storm nowcasting. This study uses the 3D radar composite with Z_{DR} as described in that study, in which the Z_{DR} composite is constructed in the same manner as for Z_H , where interpolation occurs in units of dB. As the extension to include Z_{DR} in the radar composite is experimental, future work will be needed to quantify the uncertainty of composited Z_{DR} values accurately. The effect of interpolating in linear units rather than logarithmic units, as suggested by Warren and Protat (2019) for reflectivity, should also be explored in the future. Previous work compared radar composites against scans from a research radar with a narrower beam width of 0.28° (see details in the following subsection and in Appendix A). The thinner beam width allowed spatially fine radar features such as Z_{DR} columns to be observed at higher resolution and was thus used to validate the 3D radar composite product. The comparison showed that the median values Z_{DR} for each Z_H bin were approximately conserved by the compositing, which suggests the radar composite used here can represent enhanced Z_{DR} reliably for the detection of Z_{DR} columns. Details of this comparison are in Appendix A.

The Met Office also uses its radar network to generate precipitation estimates at 1-km resolution, referred to as Radarnet (Harrison *et al.*, 2009). The domain-averaged rainfall rate derived from Radarnet serves to verify the model-estimated rainfall in Section 2.4.

2.2 | Chilbolton Advanced Meteorological Radar

The Chilbolton Advanced Meteorological Radar (CAMRa) is a 3-GHz (S-band) polarimetric Doppler radar, calibrated with an uncertainty of 0.5 dBZ in Z_H and 0.1 dB in Z_{DR} (Goddard *et al.*, 1994; UKRI Science and Technology Facilities Council, 2011). The 25-m antenna on CAMRa allows range–height indicator (RHI) scans with 75 m of range resolution, 0.28° of beam width, and an antenna gain of 53.5 dBi, which permits observation of fine features with high sensitivity in convective cells. CAMRa's large

antenna, however, limits its scan rate to $2^\circ \cdot s^{-1}$, making it unsuitable for 360° PPI scans. Thus, it is insufficient to use on its own for our purposes of model evaluation. In this study, CAMRa is instead included as an independent radar dataset to provide confidence in the statistics from the 3D radar composite. Details of this comparison are provided in Appendix A.

2.3 | Model configuration

The MetUM is a seamless weather and climate modelling system, created by the UK Met Office and used by a number of National Meteorological Services globally as part of their operational weather forecasts. The MetUM operates with a nonhydrostatic, deep-atmosphere dynamical core and uses a semi-Lagrangian dynamical formulation (Wood *et al.*, 2014). The model uses a staggered regular latitude–longitude Arakawa C-grid in the horizontal, although this grid is rotated in regional runs such that the model domain is centred on the equator of the grid to maintain a consistent grid length. In the vertical, the model employs Charney–Phillips staggering (Charney & Phillips, 1953) implemented on a terrain-following height coordinate system.

For regional weather forecasts over the UK, the Met Office runs the MetUM with the third Regional Atmosphere and Land configuration for midlatitudes (RAL3: Bush *et al.*, 2025), which includes the radiation scheme from Edwards and Slingo (1996) and Manners *et al.* (2018), the double-moment microphysics scheme CASIM (Field *et al.*, 2023), the Joint UK Land Environment Simulator (JULES) surface-exchange scheme (Bush *et al.*, 2020), and a scale-aware non-local one-dimensional boundary-layer scheme (Boutle *et al.*, 2014; Lock *et al.*, 2000) that treats vertical mixing in turbulence. Radiative impact of cloud water and total ice and snow is handled by the radiation scheme.

For the regional simulations used in this study, the mass-flux convection scheme by Gregory and Rowntree (1990) is switched off to allow explicit convection. Although the regional simulations are kilometre and subkilometre scale, the MetUM employs one of several cloud-fraction schemes to represent subgrid humidity and to carry out condensation of liquid. Two diagnostic cloud schemes are available: the Smith (1990) cloud scheme, which uses a prescribed critical relative humidity for cloud formation, and a bimodal cloud scheme (Van Weverberg *et al.*, 2021) that links cloud formation to turbulence diagnostics from the boundary-layer scheme and hydrometeor properties from the cloud microphysics (Furtado *et al.*, 2016). The bimodal scheme is currently used in regional forecasts over the UK. The Smith scheme was used in the past, as it was deemed to produce realistic

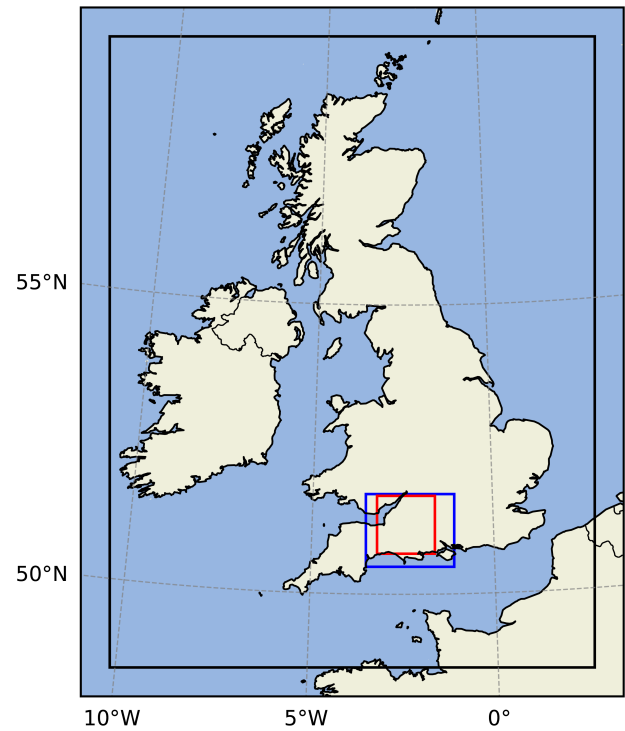
TABLE 2 Model resolution, number of grid points, and time steps of the model hierarchy shown in Figure 2.

Model resolution (m)	Total grid points	Inner grid points	Levels	Time step (s)
1500 (UKV)	950 × 1025	622 × 810	70	60
300 (WMV)	856 × 774	510 × 421	70	12
100 (WMV100)	2094 × 1819	1531 × 1261	120	4
55 (Wessex55)	2000 × 2000	–	120	2

cloud distribution and predicted cloud water content that verified well with microwave radiometer measurements at the time of implementation. The regional model also implements a Smagorinsky–Lilly type subgrid mixing scheme, described in Hanley *et al.* (2019), as a first-order closure scheme to represent subfilter scalar fluxes through gradient diffusion and momentum fluxes via an eddy viscosity.

A modelling suite was set up to perform regional MetUM simulations initialised at 0000 UTC for this study. The suite first uses archived MetUM global model data from the global forecasts to drive a 1.5-km horizontal resolution regional model (UKV) on a domain run covering most of the UK and Ireland. This is then used to initialise simulations of 300-m (WMV) and 100-m (WMV100) horizontal resolution on a smaller domain nested within the 1.5-km simulation. The inner nesting includes a stretching region that helps to transition smoothly between coarser and finer resolutions. The number of total grid points and those in the inner domain are shown in Table 2. A 55-m horizontal resolution model (Wessex55) is nested within the 100-m model. Lateral boundary conditions for the nested simulation are derived from the preceding resolution at 15-minute intervals. In other words, the driving model updates boundary conditions for the 1.5-km simulation, in turn updating the boundary conditions for the simulations of finer resolution. Our expectation is that, at higher resolutions, the model should be able to generate stronger updrafts, albeit on a small scale (Nicol *et al.*, 2015), which might allow a higher-resolution model to support Z_{DR} columns better.

Despite only utilising outputs from the 300-, 100-, and 55-m simulation outputs for the purposes of understanding Z_{DR} representation, the 1.5-km runs are needed to provide appropriate boundary conditions. At present, it would also be computationally infeasible to extend the 300-m domain significantly to cover the entirety of the UK. The 300- and 100-m simulations share the same domain. Figure 2 shows the locations of the nested domains and their coverage of England and Wales. The 300-m simulations are run with 70 vertical levels, whereas the 100- and 55-m simulations are run with 120 vertical levels. The spacing between levels increases quadratically with height throughout the 40-km depth of the model. The increased

**FIGURE 2** Model domain of the 1.5-km (largest rectangle), 300-m (medium rectangle), 100-m (medium rectangle), and 55-m (smallest rectangle) resolution MetUM simulations.

number of vertical levels should resolve vertical motion and gradients of temperature and humidity within clouds better, and also ensures the horizontal grid length is greater than the vertical grid length just above the boundary layer, as preferred by the subgrid mixing scheme. All simulations have a fixed model lid at 40 km above sea level, which encompasses tropospheric convection. Table 2 details the two model resolutions, domain sizes, and number of grid points.

The NWP model simulations described in this study implement the proto-operational Regional Atmosphere Land version 3.2 (RAL3.2) configuration (Bush *et al.*, 2025). RAL3.2 is a new physics configuration that implements CASIM double-moment microphysics and uses the bimodal diagnostic partial cloud-cover scheme. CASIM represents cloud by using five hydrometeor species, namely cloud liquid, rain, ice, snow, and graupel. These species are all specified by two prognostic moments,

namely the mass mixing ratio and species number concentration. This is in contrast with the MetUM's previously operational single-moment scheme based on WB, which prognoses cloud water and rain mass mixing ratio in the liquid phase, and ice water content in the solid phase. Despite WB being known as a single-moment scheme, the intercept parameter of the rain particle size distribution is parametrised, rather than fixed as a constant (Abel & Boutle, 2012).

Grid-box partitions are used in the precipitation schemes of the MetUM. A grid box within the coarser resolution simulations will contain a degree of heterogeneity in its cloud field. Grid-box fractions are used to represent the proportion of hydrometeors occupying a grid box, so microphysical transfer rates are consistent when applied to the whole grid box. In WB, the rain fraction C_{rain} is diagnosed by considering its overlap maximally with liquid-only cloud, mixed-phase cloud, and ice-phase cloud in that order. In CASIM, rain fraction is diagnosed as the maximum between liquid cloud fraction and rain fraction from the model level above. This ensures continuity between liquid cloud and rain fractions between levels and that rain precipitating from a higher level contributes to an equal or a larger rain fraction in the lower levels. The rain fraction C_{rain} is used in the forward operator described in Section 3.

To isolate differences in Z_{DR} columns due to the microphysics scheme, we carry out a separate set of simulations using the same model physics (RAL3.2), but coupled with the WB single-moment scheme in place of CASIM. This set of runs will be known as RAL3.2WB. Additional sensitivity tests carried out in this study are also based on RAL3.2, with any changes detailed in the relevant results sections.

2.4 | Case overviews

This study focuses on two case days, June 12 and August 3, 2023, which are intensive observation periods (IOPs) 01 and 18 of the Wessex Convection Experiment (WesCon) field campaign (Barr et al., 2026). WesCon was a UK summertime convection experiment conducted in 2023. The field campaign collected observational data for better understanding of the dynamical aspects of convection to improve the next generation of km and sub-km NWP models.

2.4.1 | IOP01

During IOP01, a weak low-pressure system was situated above the UK accompanied by a slack pressure pattern, as

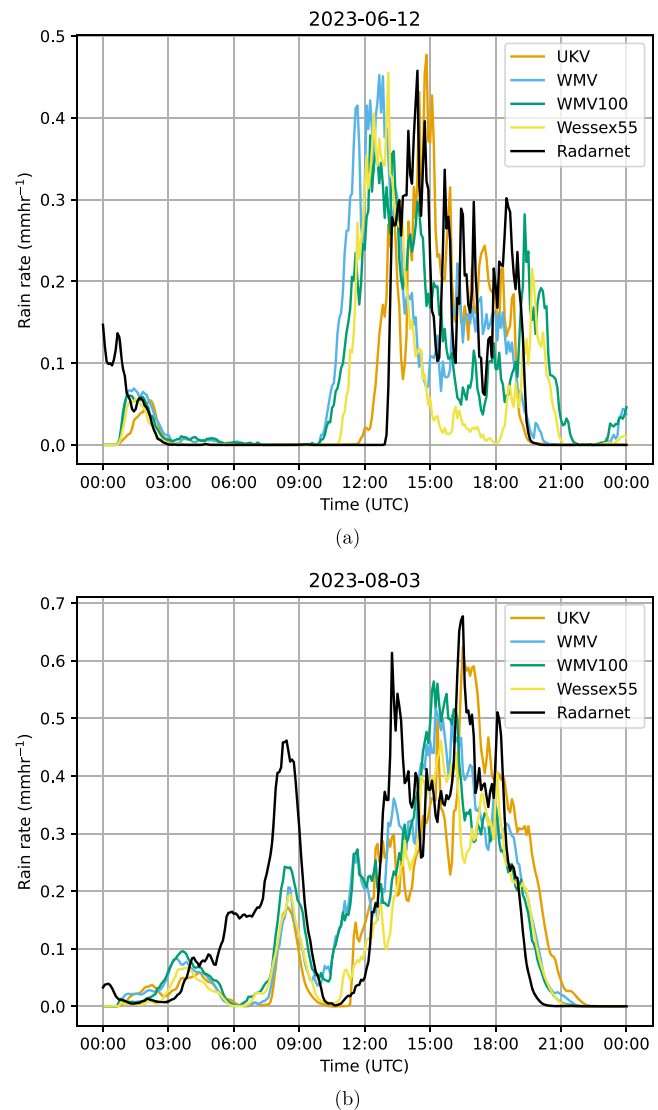


FIGURE 3 Domain-averaged rainfall rate of all model resolutions and radar-derived observations for (a) IOP01 and (b) IOP18. Model resolutions are defined in Table 2.

seen in Appendix B, Figure B1a. A contorted high wet-bulb potential temperature θ_w plume brought potential deep instability to the UK, with convective release in response to diurnal input. Showers initiated over southern Wales, the Midlands, and areas around Bristol shortly after 1230 UTC and into the afternoon, as evident in the increase in observed domain-averaged rainfall rate in the early afternoon shown in Figure 3a. Showers developed and merged into larger clusters in the latter part of the afternoon, forming intense and widespread mesoscale convective systems.

Similarly, model outputs show areas of simulated rainfall within the common domain, although spacing between convective features and intensity varies with model resolution. When compared with observations in

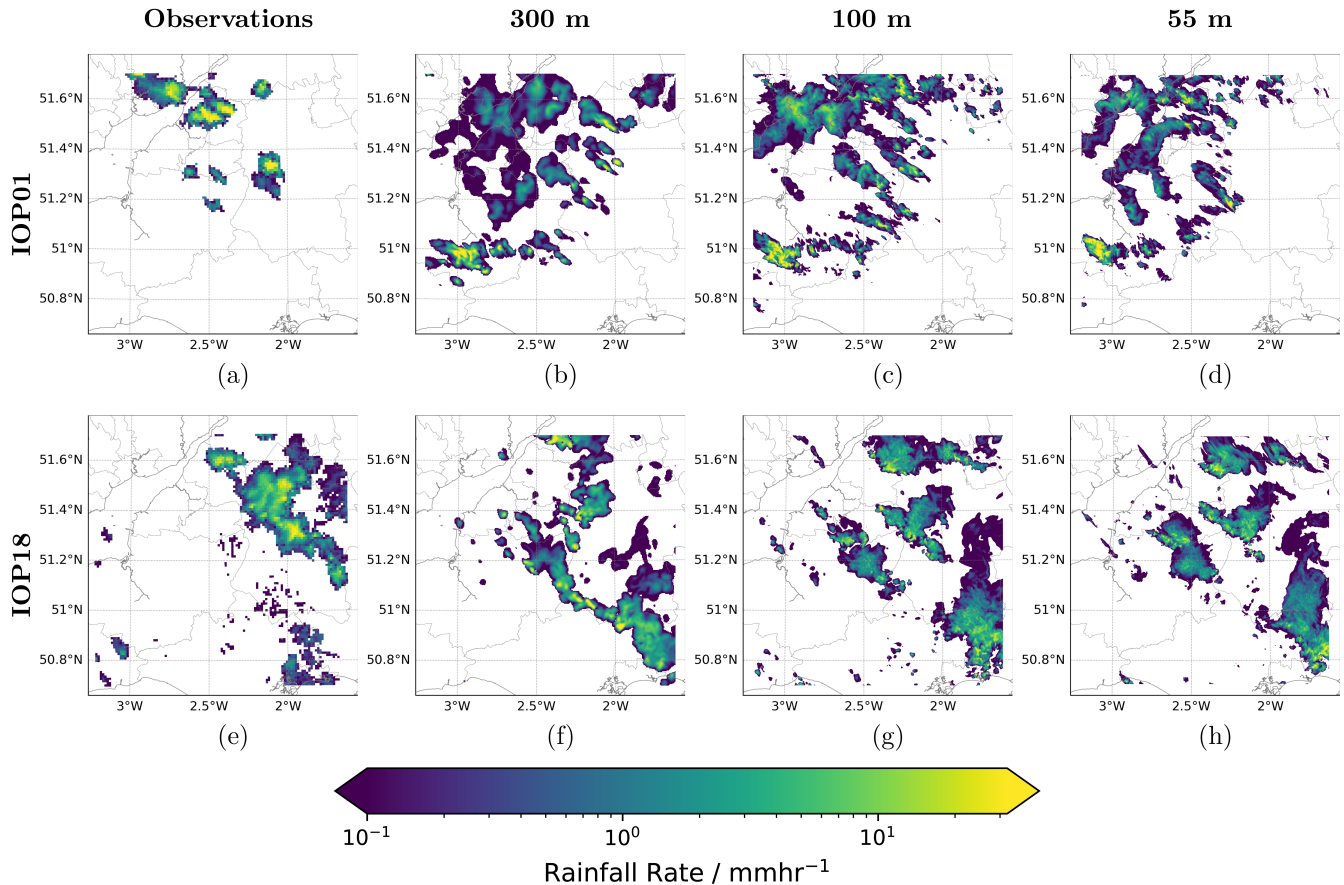


FIGURE 4 Fields of observed and modelled rainfall rates for (top row) IOP01 1400 UTC and (bottom row) IOP18 1600 UTC. The leftmost panels (a, e) show observations, with outputs from (b, f) 300-, (c, g) 100-, and (d, h) 55-m RAL3.2 control model simulations shown in the other panels.

Figure 4a, model outputs show more densely clustered cells, with less intense rainfall intensity and with more widespread stratiform regions (see Figure 4b–d). The discrepancy between observations and model for this case can also be seen in the timing of convection; models simulating the first signs of a positive rainfall rate were up to three hours earlier than the observations, as seen in Figure 3a. We also see that areas of rainfall in Figure 4b–d are more organised than the single cells in Figure 4a.

IOP01 is a suitable case for this study, considering that Z_{DR} columns were observed by operational and research radars with heavy rain over parts of the west Midlands and southwest England. A convective available potential energy (CAPE) value of $1150 \text{ J} \cdot \text{kg}^{-1}$ was also recorded by a radiosonde on that day, which was the highest measured out of all IOPs.

To capture statistics in both model and observations despite discrepancies in the timing of convection, subsequent analysis of this case will include hourly radar composite and model outputs between 0900 and 1700 UTC inclusive.

2.4.2 | IOP18

On IOP18, the UK was under the influence of a northerly Arctic maritime airmass, as seen in the surface synoptic chart (Appendix B, Figure B1b). Through the afternoon, a corridor of higher θ_w lying from northeast Scotland to southwest England slowly transferred southeast, but with limited forcing to provide mesoscale ascent. There were narrow potential vorticity filaments advecting across southwest England in the late afternoon, where temperatures aloft were already colder, which are conducive to convection.

After passage of an occlusion in the early hours and broken altostratus persisting up to midday, scattered showers broke out across the region of southwest England from around 1200 UTC, becoming increasingly large with some mesoscale organisation later in the afternoon, as observed in Figure B1b.

All model resolution outputs show more widespread clustering of cells compared with the observed organisation of rainfall (see Figure 4f–h). Considering

domain-averaged rainfall rate in Figure 3b, the onset and duration of afternoon rainfall predicted by the models is consistent with observations with higher rainfall rate extremes in the observations. The development of scattered cells into more intense organised mesoscale convective systems suggests there could be Z_{DR} columns, making this an interesting case to study. Although convective cells in this case were shallower, in contrast to IOP01, there were also a similar number of Z_{DR} column detections in observations. The Facility for Airborne Atmospheric Measurements (FAAM) aircraft flew into convective cells and recorded updraft values of at least $8 \text{ m} \cdot \text{s}^{-1}$, which is sufficient to loft millimetre-sized raindrops (Beard, 1976) and could therefore support the generation of Z_{DR} columns. Subsequent analysis of this case will include hourly radar composite and model outputs between 1000 and 2000 UTC inclusive.

3 | FORWARD OPERATOR FOR RAIN DIFFERENTIAL REFLECTIVITY

3.1 | T-matrix calculations

WB and CASIM represent raindrop particle size distributions using gamma distributions. In WB, the parameters of the distribution are determined by the hydrometeor mass mixing ratio q in $\text{g} \cdot \text{kg}^{-1}$, whereas those in CASIM are computed from the number concentration N in kg^{-1} and the mass mixing ratio of hydrometeors. See Appendix C for a mathematical derivation.

Forward operators used by past studies run in real time for evaluating the MetUM have assumed Rayleigh scattering, whereby the radar wavelength is significantly longer than the hydrometeor size (Stein *et al.*, 2014). Raindrops were also assumed to be spherical. This was done out of convenience and for computational efficiency, but involves disregarding the effects of Mie scattering. This is only appropriate when evaluating against S-band [3-GHz] radars, such as CAMRa used in Stein *et al.* (2014), but will result in errors for C-band [5-GHz] comparisons. In addition, the non-sphericity of multi-millimetre raindrops, while not parameterised in the MetUM, is essential for deriving Z_{DR} .

In this study, we focus on the unattenuated Z_H and Z_{DR} values. Consequently, we do not forward-simulate attenuation, unlike studies such as Reimann *et al.* (2023), which include attenuation-corrected reflectivity to support data assimilation. Along-beam attenuation would require specification of radar locations and viewing angles, as we would need to calculate the beam propagation path within the model. However, we are not concerned with the

specific location of storms with respect to any radar location in this study. Attenuation becomes significant in the C-band for widespread rainfall above $10 \text{ mm} \cdot \text{h}^{-1}$, which was rarely observed for the case studies considered in this study.

The forward operator implemented in this study uses the T-matrix method to simulate Z_H and Z_V , and hence Z_{DR} , for raindrops. In this study, we are mainly concerned with the rain contribution to the simulated radar observables. While it is certainly possible to forward-model Z_H and Z_V for other hydrometeors (e.g., Zeng *et al.*, 2016), our primary objective is to study the model's ability to represent Z_{DR} columns. These are composed predominantly of rain drops (Kumjian *et al.*, 2014), so calculations of Z_H and Z_V for rain should suffice for our study. However, it is worth noting that the upper parts of Z_{DR} columns likely constitute wet hail and freezing raindrops, so the full depth of the columns will likely not be simulated properly.

The PyTMatrix package (Leinonen, 2014) based on Mishchenko (2000)'s T-matrix code is invoked to calculate amplitude matrices for the backscatter cross-section of a single scatterer over a range of sizes, given the refractive index and aspect ratio function of raindrops. The refractive index of water is calculated using the model by Turner *et al.* (2016), assuming the radar wavelength in Table 1 and a constant hydrometeor temperature of -10°C . Below, we briefly introduce and justify our choices of aspect ratio and canting angle, and address the sensitivity of the forward operator to temperature.

To quantify deviations of the T-matrix calculations from Rayleigh scattering, predictions from the two schemes are compared in Figure 5, which shows how forward-modelled Z_H varies with q_{rain} for spherical raindrops and various scattering assumptions. Because the T-matrix calculation includes Mie scattering, it leads to a deviation from Rayleigh estimates for larger drop sizes. Two estimates of Rayleigh scattering are compared: the original Rayleigh estimate in the MetUM, which integrates gamma-distributed drop sizes from zero to infinite size, and Rayleigh scattering with a realistic maximum size of 1 cm. Note that the latter method gives better agreement with a discrete integration using the Rayleigh–Gans method (Seliga & Bringi, 1976).

The T-matrix calculation for Z_H and Z_V incorporates models for raindrop shape and orientation that are not simulated by the MetUM. We briefly consider the calculation's sensitivity to aspect ratio and canting angle.

3.1.1 | Aspect ratio

A key application of Z_{DR} is to capture the effects of raindrop size: as rain drops become larger than 1 mm in

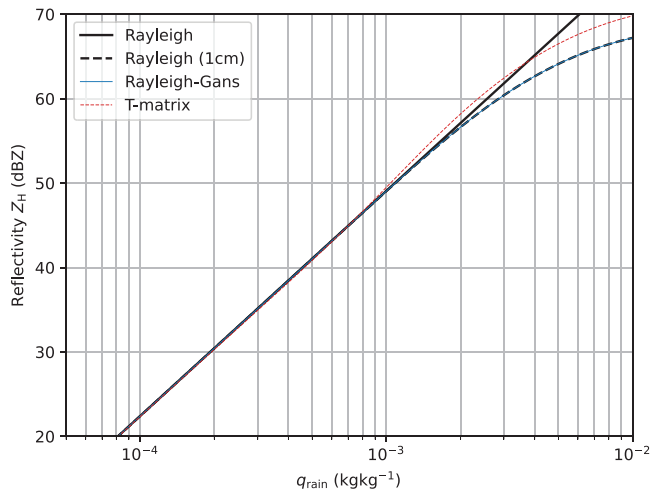


FIGURE 5 Forward-modelled reflectivity Z_H against rain mass fraction q_{rain} for spherical raindrops. The black solid line is the MetUM's forward operator assuming Rayleigh scattering. The dotted line truncates the particle size distribution at 1 cm. The thin solid and dashed lines are the results from using Rayleigh-Gans and T-matrix scattering formulations respectively.

diameter, they become less spherical, and their oblate shapes lead to differences between Z_H and Z_V . In order to capture this effect in PyTMatrix, we need to adopt a model for the raindrop aspect ratio. Figure 6a presents a number of aspect-ratio models, showing how aspect ratios vary with increasing equivalent volume diameter of a raindrop (the diameter of a sphere that has the same volume as the actual non-spherical raindrop). All drop aspect-ratio models show similar aspect ratios within 0.1 of each other as the drop equivalent diameter increases. However, it is worth noting that the Andsager *et al.* (1999) model is limited to drops smaller than 4.4 mm diameter.

Figure 6b shows forward-modelled Z_{DR} , as a function of rain mass fraction q_{rain} , for different aspect-ratio models and scattering computation methods. For spheres, Z_{DR} is zero, as expected for all values of q_{rain} . All aspect-ratio models produce comparable Z_{DR} values within 0.2 dB up to q_{rain} of $8 \text{ g} \cdot \text{kg}^{-1}$, yielding similar Z_{DR} for values between 1 and 4 dB, with the exception of the shape models of Andsager *et al.* (1999) (discrepancies that can be attributed to the limitations of this study mentioned above). It is clear that the forward operator is only sensitive to the choice of aspect-ratio models for very high q_{rain} values that give $Z_{\text{DR}} > 3 \text{ dB}$, which is far above our threshold of interest. Thus, the drop-shape model in Thurai *et al.* (2007), which considers drop sizes up to 10 mm and is relatively simple to implement, is used for the forward operator in this study. Using a two-dimensional video disdrometer, Thurai *et al.* (2007) constructed contour shapes of raindrops in an 80-m fall experiment. They were able

to find appropriate aspect-ratio models from previous studies to construct a piecewise aspect-ratio model assuming spheres if the equivalent diameter was smaller than 0.7 mm. The formulation of aspect ratio b/a from Thurai *et al.* (2007) is specified in Equation (1) as a function of equivalent diameter D_{eq} . We emphasise that, although the oblateness of raindrops is a physical phenomenon, this is not modelled in the MetUM.

$$\frac{b}{a} = \begin{cases} 1.0, & D_{\text{eq}} < 0.7 \text{ mm}, \\ 1.173 - 0.5165(D_{\text{eq}}) \\ + 0.4698(D_{\text{eq}}^2) \\ - 0.1317(D_{\text{eq}}^3) \\ - 8.5 \times 10^{-3}(D_{\text{eq}}^4), & 0.7 \leq D_{\text{eq}} \leq 1.5 \text{ mm}, \\ 1.065 - 6.25 \times 10^{-2}(D_{\text{eq}}) \\ - 3.99 \times 10^{-3}(D_{\text{eq}}^2) \\ + 7.66 \times 10^{-4}(D_{\text{eq}}^3) \\ - 4.095 \times 10^{-5}(D_{\text{eq}}^4), & D_{\text{eq}} > 1.5 \text{ mm}. \end{cases} \quad (1)$$

3.1.2 | Canting angle

Beard and Jameson (1983) theorised that a raindrop's orientation changes under the effect of turbulence and wind shear, which was observed by Bringi *et al.* (2008), but this effect is not normally something considered in NWP models such as the MetUM. When viewed at low elevation angles, a greater canting angle dampens the horizontal backscatter component and increases the vertical backscatter component, thus giving lower Z_{DR} . To understand the implication of drop canting, we assume that drop canting angles are normally distributed with a mean of zero and test the effect of increasing the canting-angle Gaussian distribution width. Figure 7 shows Z_{DR} as a function of q_{rain} for the T-matrix scattering formulation with a range of different Gaussian widths for the canting-angle distributions. Of the five different canting-angle distribution widths tested, the widest distribution gave the lowest Z_{DR} values, as expected. For the largest values of q_{rain} tested, canting distribution widths can cause differences of around 3 dB. On theoretical grounds, Beard and Jameson (1983) showed that the Gaussian canting-angle model is valid with a mean of 0° and standard deviation less than 5° . Also assuming a Gaussian model, Hendry *et al.* (1987), who also employed a Gaussian model, estimated a standard deviation of 6° from observations of variations in the cross-polar power as a function of the transmitted linear polarisation direction. Considering both studies and the insignificant effects on Z_{DR} of varying

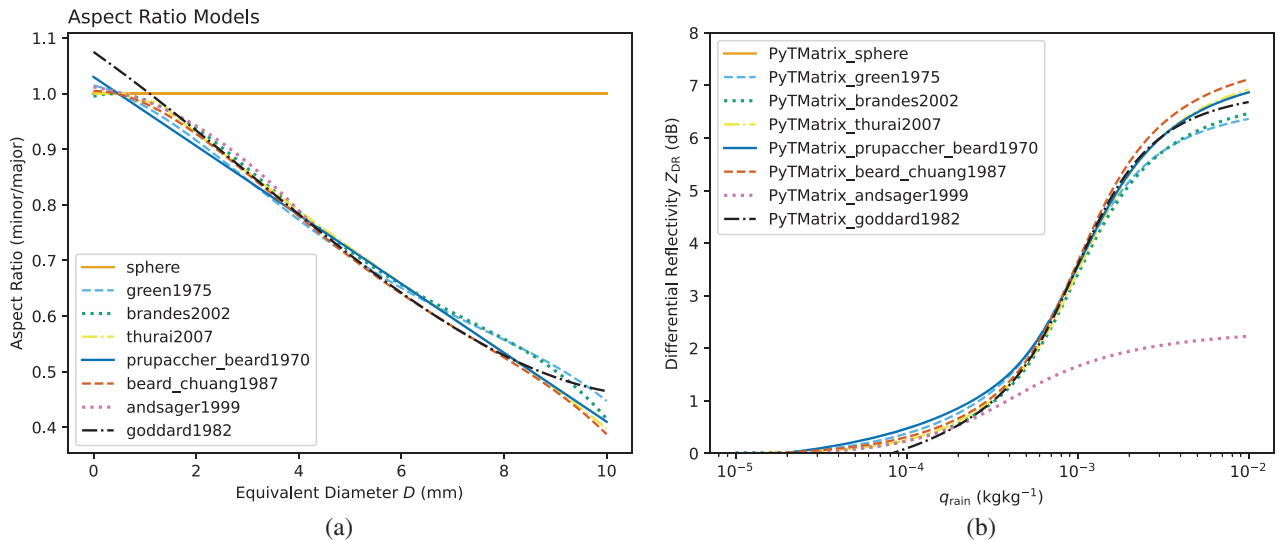


FIGURE 6 (a) Aspect ratio against equivalent raindrop diameter for various aspect-ratio models. Note that the Andsager *et al.* (1999) aspect-ratio model is truncated at 4.4 mm diameter. (b) Forward-modelled differential reflectivity Z_{DR} against rain mass fraction q_{rain} given in a single-moment microphysics scheme for different scattering theory and aspect-ratio model configurations.

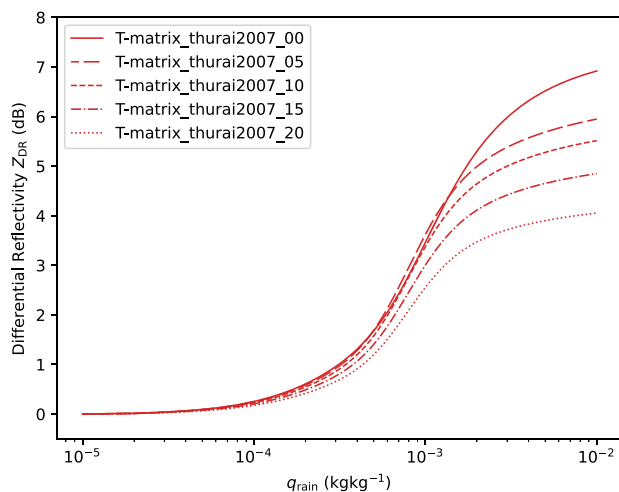


FIGURE 7 Forward-modelled differential reflectivity Z_{DR} against rain mass fraction q_{rain} for T-matrix method with canting-angle distribution widths ranging from 0° – 20° .

the canting distribution width between 0° and 5° , where we will primarily consider a threshold value of 1 dB, we conclude that a 0° canting distribution width, meaning no dispersion in canting angle, is thus a reasonable choice for the forward operator.

3.2 | Lookup table

The T-matrix method is computationally too expensive to run online as part of the NWP simulations in this study. Lookup tables of in-cloud mass concentration of rain in

a grid box W_{rain} and raindrop concentration per unit volume of air N_{rain} are used to give rain contributions of Z_H and Z_{DR} instead. The pre-calculated two-dimensional lookup table of Z_{DR} suitable for CASIM is provided in Appendix D. As the lookup table depends on rain particle size distribution in CASIM, the lookup table will have to be recalculated if the fixed parameter α_{rain} within the particle size distribution (see Appendix C) changes. As long as assumptions in the forward operator such as the drop aspect-ratio model are unchanged, this method is more convenient and efficient.

Considering that the rain mass fraction q_{rain} is an average over an entire model grid box, W_{rain} is computed in the model as

$$W_{rain} = \frac{q_{rain}\rho_{air}}{C_{rain}},$$

where ρ_{air} is the density of air and C_{rain} is the grid fraction occupied by rain.

Similarly, N_{rain} can be calculated from raindrop concentration per unit mass of air n_{rain} available from the model:

$$N_{rain} = \frac{n_{rain}\rho_{air}}{C_{rain}}.$$

The rain mass content W_{rain} , together with raindrop concentration per unit volume of air N_{rain} , allow us to compute parameters that describe the particle size distribution as detailed in Appendix C.

The lookup points for W_{rain} are spaced logarithmically between 1×10^{-8} and $1 \, kg \cdot m^{-3}$ with 500 bins, whereas those for N_{rain} are spaced logarithmically between 1×10^{-2}

and $1 \times 10^7 \text{ m}^{-3}$ with 500 bins. The bounds of lookup tables were informed by the likely minimum and maximum values possible from the model. The spacing of points in the lookup table ensures a precision of better than 0.1 dB of Z_{DR} when the scattering cross-sections are integrated over the rain particle size distribution comprised of 0.01-mm bins from 0–10 mm. Such a precision of 0.1 dB is comparable with those of observations from the radar composite.

3.2.1 | Temperature correction

The lookup tables generated assume a nominal scatterer temperature of -10°C , as we are interested primarily in supercooled raindrops. A variable temperature is also not used, as it increases the dimension of the lookup table and thus slows down the lookup significantly. However, Z_{DR} will be of interest to users at other temperatures as well. Once Z_{H} and Z_{DR} are calculated at a nominal temperature of -10°C , a first-order correction is applied to account for differences in the refractive index of liquid water. The resulting corrected $Z_{\text{DR } T}$ is calculated as

$$Z_{\text{DR } T} \approx Z_{\text{DR}} + \frac{\partial Z_{\text{DR}}}{\partial T} \Delta T,$$

where ΔT is the air temperature in the model grid box minus the nominal temperature of -10°C . The derivative $\partial Z_{\text{DR}}/\partial T$ is estimated from linear regression of Z_{DR} against T at a range of temperatures from -20°C to $+25^\circ\text{C}$ in 5°C steps for each grid point, based on lookup tables generated at the different temperatures. This correction scheme estimates Z_{DR} values for temperatures that are warmer or colder than the nominal temperature of -10°C used for generating the lookup tables. Without this temperature correction, there could be biases of up to 2 dB in both Z_{H} and Z_{DR} . This bias was estimated from the maximum difference between Z_{DR} at the nominal temperature and Z_{DR} calculated at the other temperatures.

4 | RESULTS

4.1 | Verification of the forward operator

Before utilising the Z_{DR} diagnostic in MetUM simulations, we wish to validate whether its relationship with Z_{H} and rainfall rate is broadly as expected. In Figure 8a,b, we show examples of the Z_{DR} diagnostic at 1-km altitude for a simulation using CASIM and a simulation using WB, together with the surface rainfall rates. We choose

this altitude, as it is well below the radiosonde-observed 0°C heights of 2.9 and 3.3 km at 1200 UTC for IOP01 and IOP18, respectively. Rain was likely the dominant hydrometeor species at 1-km height. By eye, it appears that rainfall rates correlate well with Z_{DR} for both configurations (Figure 8c,d). While Z_{DR} values appear large, with cores exceeding 5 dB, Gu *et al.* (2011) have observed such high values from disdrometer data, and Figure 7 shows that, for low canting-angle distribution widths, Z_{DR} can exceed 5 dB.

Figures 9d and 10d show the joint distributions of Z_{H} and Z_{DR} from the radar composite for IOP01 and IOP18 (see Section 2.4), respectively. The joint distributions are for the radar composite, so it includes both rain and frozen hydrometeors, as well as regions with low signal-to-noise ratio. In both cases, there is a mode of composite grid points with Z_{H} of 20 dBZ and Z_{DR} of 0 dB. For values of Z_{H} below 10 dBZ, the range of Z_{DR} values increases to around 3.0 dB, or even higher values of 8.0 dB in IOP18. Insects are the most likely explanation for this high Z_{DR} and low Z_{H} signature, which is more prevalent at 1-km height than at 3-km height. There is a “ridge” of frequently occurring Z_{DR} values along a 0 dB isoline, for values of Z_{H} in the range 0–25 dBZ, which is made up of rainfall (Figures 9e and 10e, showing grid points at 1-km height) and snow, which may also include graupel and hail when Z_{H} is 25 dBZ (Figures 9f and 10f, showing grid points at 3-km height). Another notable feature is the curved “branch” of positive Z_{DR} from about 20 dBZ onwards to 60 dBZ, which is indicative of large raindrops at a height of 1 km. This is not observed at 3 km, as size sorting within Z_{DR} columns results in sampled raindrops that do not follow the same curve. Such signatures are also observed from CAMRa with a co-polar correlation coefficient filter of $\rho_{\text{HV}} \geq 0.98$ applied, as shown in Figures 9a and 10a, thus indicating that these are not artefacts due to the construction of the 3D composite.

Figures 9g and 10g show joint distributions of simulated Z_{H} and Z_{DR} contributions from rain for all model grid points within the common domain for the RAL3.2 configurations for IOP01 and IOP18, respectively, whereas Figures 9j and 10j are from the RAL3.2WB configuration. In both IOPs, most model grid points have Z_{H} below 30 dBZ and Z_{DR} that does not exceed 1.0 dB. In the single-moment microphysics simulation RAL3.2WB, a large number of grid points have simulated Z_{H} and Z_{DR} following a curve with Z_{DR} that increases with Z_{H} . This curve resembles the expected relation between the two radar variables, considering the exact one-to-one mapping from the mixing ratio of rain q_{rain} to Z_{H} , and from q_{rain} to Z_{DR} for the single-moment WB scheme forward operator. A similar curve can also be discerned from the

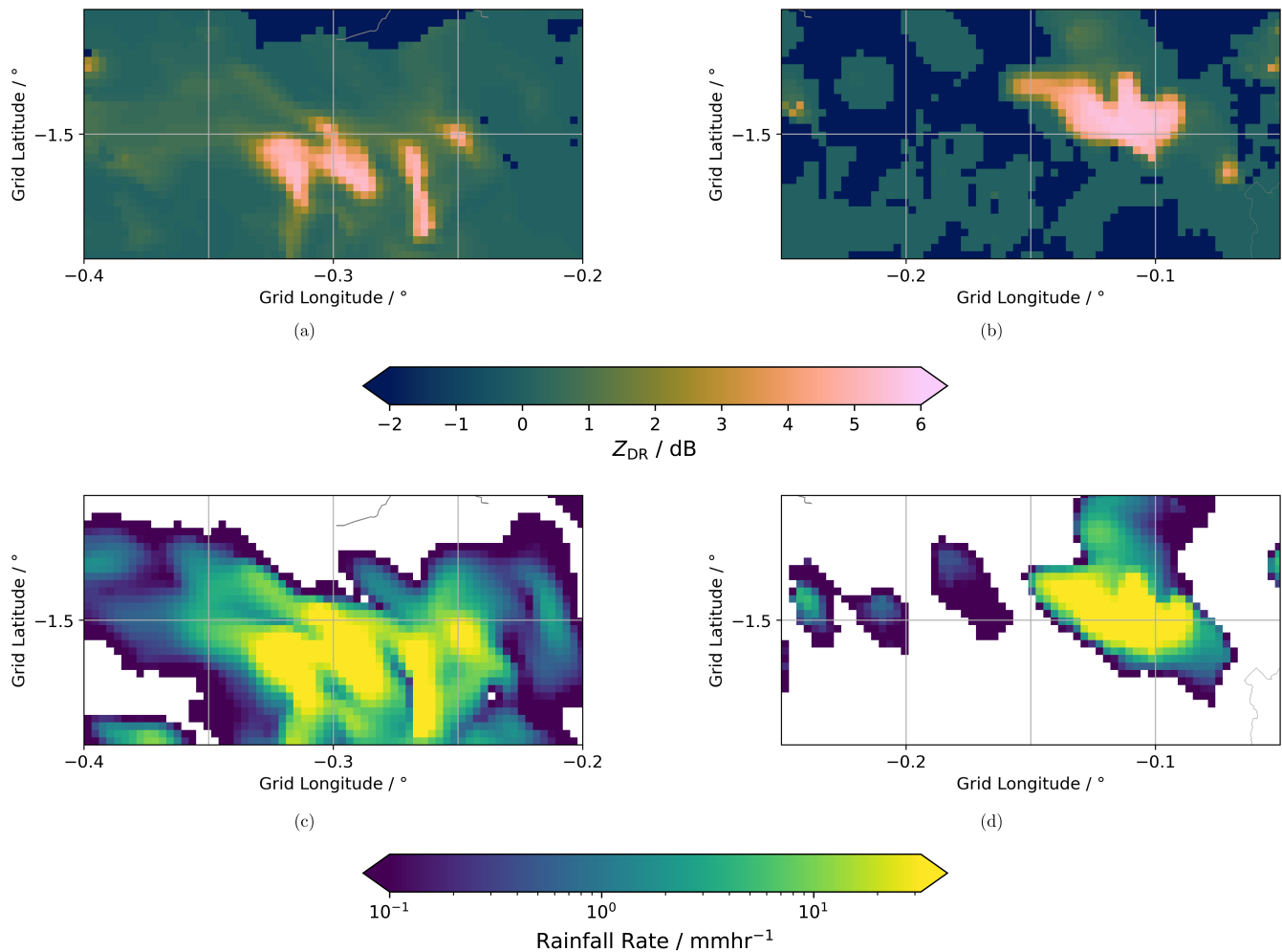


FIGURE 8 Simulation outputs of (a) RAL3.2 and (b) RAL3.2WB for June 12, 2023, 1400 UTC at 1 km in height, showing Z_{DR} fields for $20 \text{ km} \times 20 \text{ km}$ regions. The bottom row shows surface rainfall rate fields covering the same regions for (c) RAL3.2 and (d) RAL3.2.

CASIM run, but with notably different inflection points, as expected from different behaviours between microphysics schemes. The CASIM outputs exhibit a noticeably larger spread of points, with Z_{DR} values ranging from 0–5 dB at $Z_H = 40$ dBZ, compared with a narrower range of 2–5 dB in the WB outputs.

A spread of model grid points to the left of the curve in RAL3.2WB is explained by the use of the prognostic precipitation fraction C_{rain} in the calculation of rain mass fraction q_{rain} and as a multiplier for rain radar reflectivity. Prognostic precipitation fraction is a variable that represents the subgrid fraction of rain and should have a maximum of value of 1.0. Another reason for deviation from the theoretical curve, especially for high reflectivities exceeding 50 dBZ, is the first-order temperature correction for both Z_H and Z_{DR} and linear interpolation of both values from the lookup table. In the RAL3.2 simulation using CASIM, most model grid points also follow a positive relation between Z_H and Z_{DR} , albeit with a more diffuse distribution. Using both rain mass fraction q_{rain} and

number concentration of rain n_{rain} severs the one-to-one relation between Z_H and Z_{DR} .

The presence of a cluster of grid points in RAL3.2 with Z_{DR} values exceeding 6 dB is a known issue with CASIM microphysics, when it is used in the MetUM, whereby rain self-collection can lead to unrealistic decreases in number concentration, which physical-bounds checking in CASIM then eliminates. This results in the formation of “patches” with zero or very low values of rain number concentrations but unusually high values of Z_{DR} .

At 1 km in height, RAL3.2WB grid points in Figures 9k and 10k are still mostly constrained to the expected Z_H and Z_{DR} relationship. The joint distributions of RAL3.2 shown in Figures 9h and 10h compare better with the radar composite in Figures 9e and 10e, despite being underspread. Both RAL3.2 and RAL3.2WB have grid points with high simulated Z_{DR} exceeding 4–5 dB that are present for the C-band due to resonance effects. However, there is a much closer resemblance of RAL3.2 output to the distributions of Z_{DR} versus reflectivity in rain by Ryzhkov and Zrnice (2019),

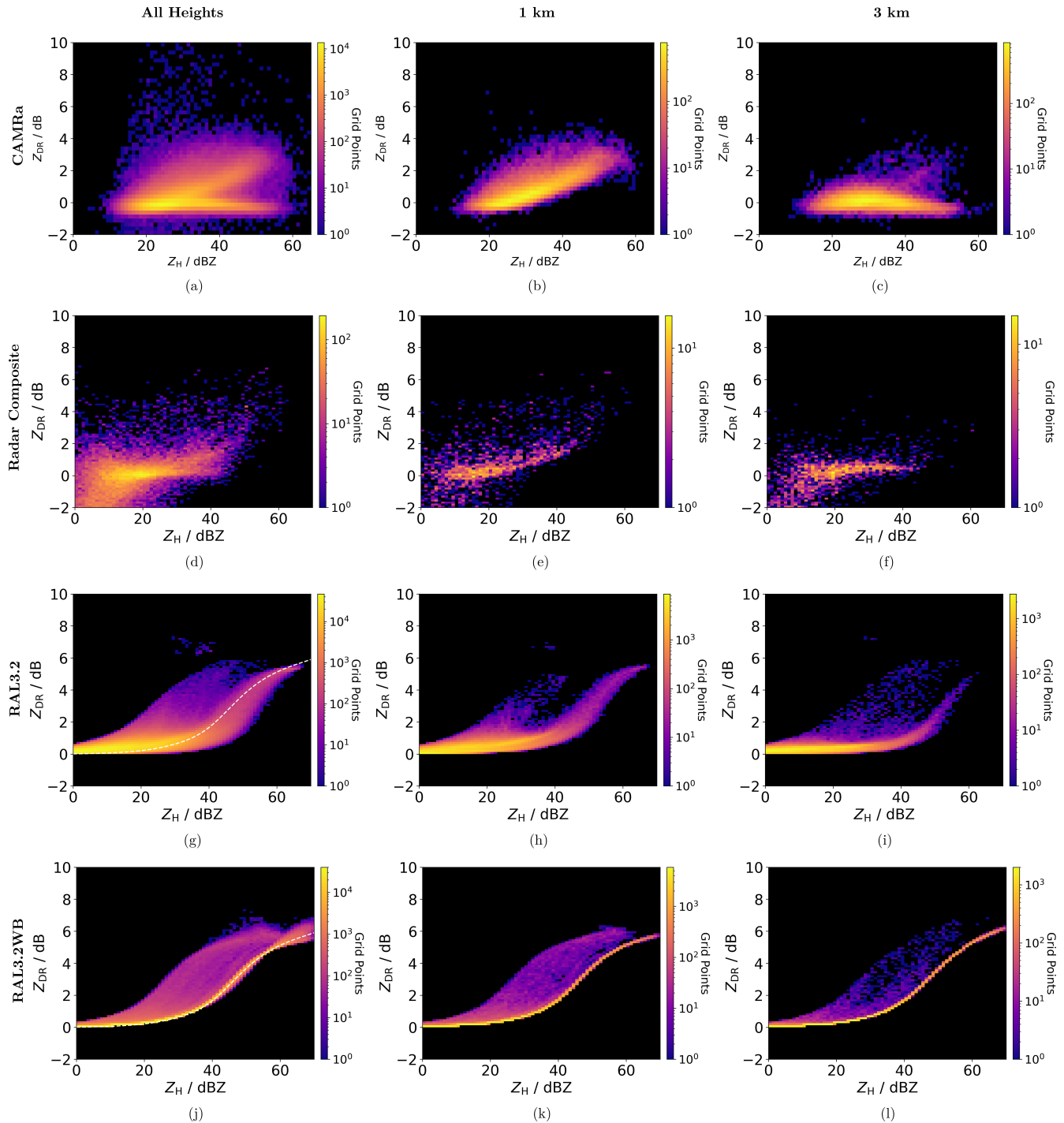


FIGURE 9 Joint distributions of reflectivity Z_H and differential reflectivity Z_{DR} values of grid points within (a, b, c) CAMRa, (d, e, f) the 3D radar composite, (g, h, i) RAL3.2 (CASIM) model output, and (j, k, l) RAL3.2 WB model output for IOP01. Simulated Z_H and Z_{DR} from model simulations are only from rain. The first column includes all grid points, whereas the middle column includes grid points at 1-km height and the right column includes grid points at 3-km height. The white dashed line is the one-to-one relation between Z_H and Z_{DR} assuming a temperature of 20 °C and an air pressure of 1000 hPa. Freezing height was at 2.9 km on this case day.

which were simulated from disdrometer data for a temperature of 20°C. This result suggests that RAL3.2 represents more realistically observed rain at temperatures above 0°C in this case study.

It is worth noting that the spread in the radar composite could be due to uncertainty in observed Z_H and Z_{DR} . Radar composite data for Z_H 40 dBZ are less populated than model output, likely due to the resolutions

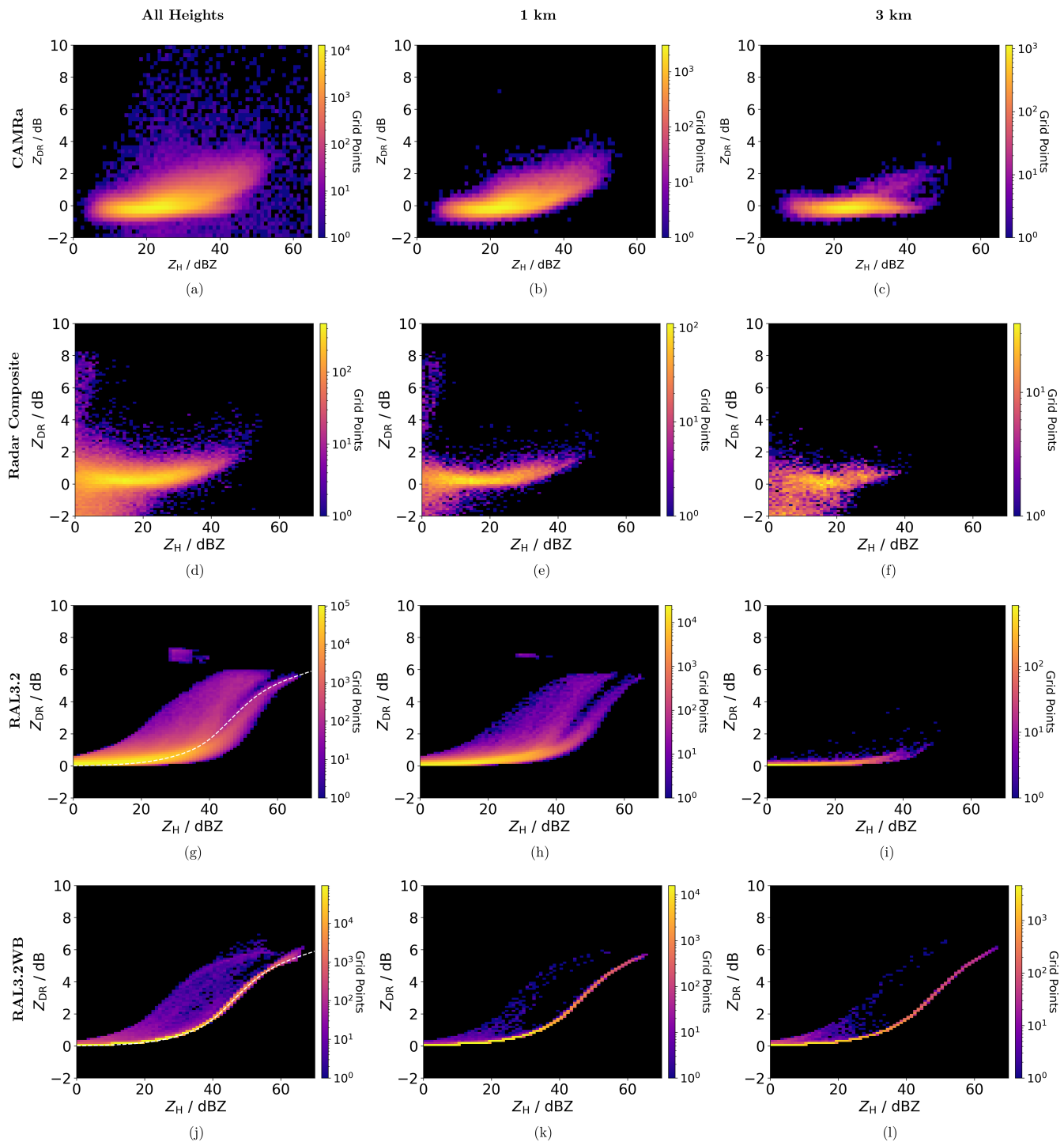


FIGURE 10 Similar to Figure 9 but for IOP18. Freezing height was at 3.3 km on this case day.

of both outputs. Although both outputs cover the same spatial domain, model output has a horizontal resolution of 300 m, compared with 1 km for the radar composite. It is also possible for the radar composite to underestimate peak reflectivity values for small convective cores of sizes that are subkilometre, due to a combination of the

radar-to-Cartesian grid interpolation to a 1-km grid and possible temporal mismatching of individual scans (Stein *et al.*, 2020).

There is also a population of grid points from CAMRa at 1-km height in Figure 9b with high reflectivities but lower positive Z_{DR} . This hints at mixed-phase precipitation

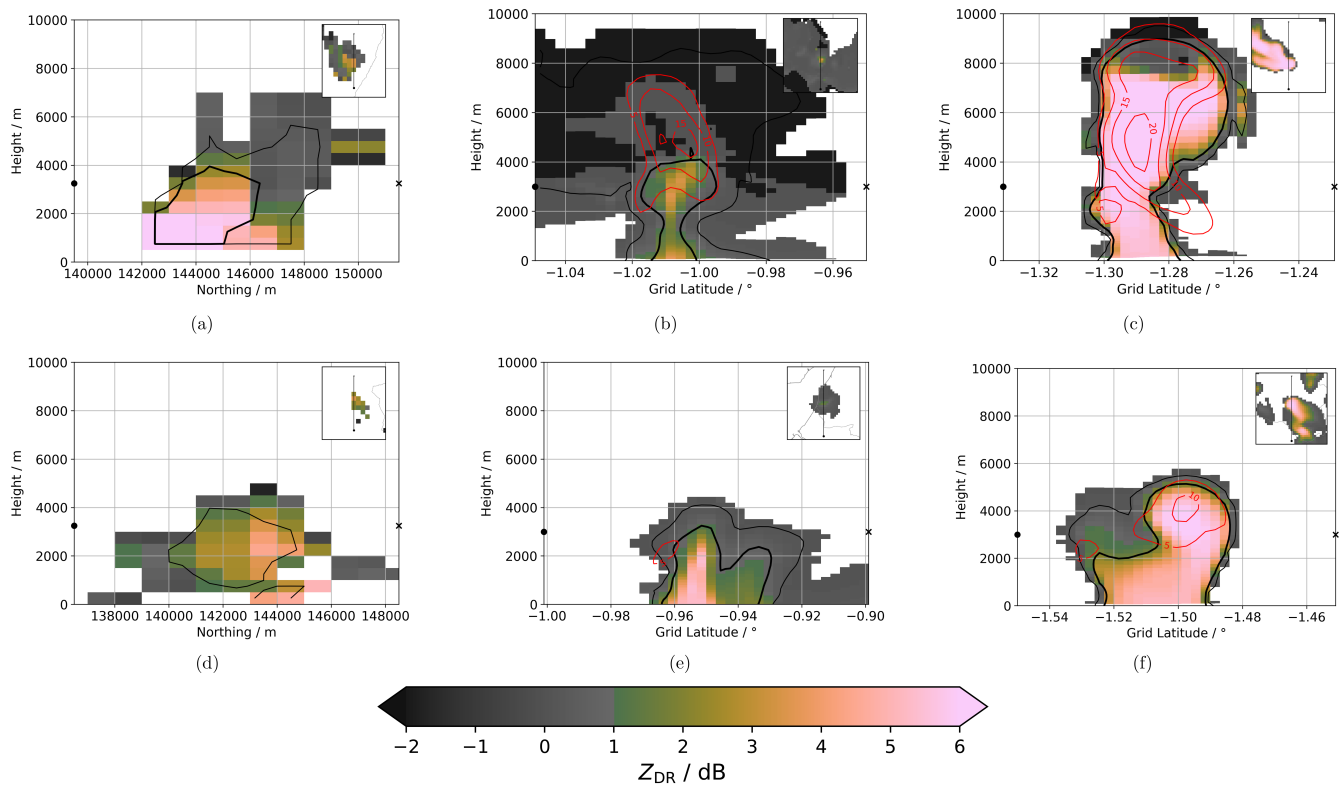


FIGURE 11 Chosen cross-sections showing Z_{DR} for convective cells within (a, d) radar composite, (b, e) RAL3.2, and (c, f) RAL3.2 (Wilson–Ballard) model simulations for (top row) IOP01 and (bottom row) IOP18. Thin and thick black contours denote Z_H of 20 dBZ and 40 dBZ, respectively. Red contours show updraft magnitudes every $5 \text{ m} \cdot \text{s}^{-1}$. The inset in each panel is Z_{DR} at around 3-km height, and shows the location of the transect marked by the dot and cross. Freezing height was at 2.9 and 3.3 km during IOP01 and IOP18, respectively.

such as melting hail, which could be more oblate than tumbling hail but more spherical than the equivalent fully melted raindrop.

In the radar composite at 3 km in height, where one could find supercooled raindrops within Z_{DR} columns, there is a mode of radar composite grid points at Z_H of 20 dBZ and Z_{DR} of 0 dB in both IOPs (Figures 9f and 10f), which suggests the presence of small, frozen hydrometeors with a mostly spherical geometry or small unaligned ice aggregates. It is also worth noting that, in addition to spherical geometry or “unaligned” ice crystals, very low-density ice particles with a corresponding low relative permittivity could also result in Z_{DR} near 0 dB, even if the particle is nonspherical or horizontally aligned. Although the RAL3.2WB plots (Figures 9l and 10l) still show grid points concentrated on the Z_H and Z_{DR} curve, the number of grid points in bins decreases by an order of magnitude compared with their distribution at 1 km. In the RAL3.2 runs (Figures 9i and 10i), there are not many grid points at 3 km with simulated Z_{DR} from rain exceeding 3.0 dB and reflectivities exceeding 50 dBZ. These results suggest a much lower rain mass just above the freezing level relative to warm levels in both observations and model output.

The presence of Z_{DR} exceeding 1.0 dB exists in all joint distributions, indicating potential Z_{DR} columns in both the radar composite and various model simulations.

4.2 | Presence of Z_{DR} columns

Results from the previous section demonstrate the presence of Z_{DR} exceeding 1 dB at sub-zero temperatures in both model simulations and observations, suggesting the presence of Z_{DR} columns. However, the results also indicate sensitivity of Z_{DR} statistics to model configuration. Here, we aim to identify whether the differences are likely due to first-order differences in the microphysics schemes that control rain mass and number concentrations directly, or second-order differences due to the impact of different microphysics on the model dynamics that influences the advection of rain mass.

Figure 11a,d shows the vertical cross-section of Z_{DR} from the radar composite for IOP01 and IOP18 respectively. These cross-sections were chosen by inspecting plan views above the freezing level and identifying areas of enhanced values of Z_{DR} visually. Using 1.0 dB as a nominal

threshold for defining a Z_{DR} column, the first example shows a Z_{DR} column extending to 3 km in height, which is about 2 km above the freezing level on that day, whereas a shallower column extends to 4 km in height in the second example, which is about 1 km above the freezing level on that day. In Figure 11b,e, which shows vertical cross-sections of cells simulated by RAL3.2, there are Z_{DR} columns that extend up to 1 km above the freezing level, lower than observations. In contrast, RAL3.2WB in Figure 11c,f exhibits intense, deep, and wide Z_{DR} columns extending 5 km above the freezing level, with a maximum Z_{DR} value exceeding 6.0 dB. In these examples within the MetUM, all simulated Z_{DR} columns are well collocated with or at the periphery of updraft cores. Although these are only single examples chosen from more intense convective cells, they indicate a drastically different microphysical structure in the two model simulations, neither of which resembles the observed height extents of Z_H and Z_{DR} closely. It is also worth noting once again that this comparison between simulated Z_{DR} from rain does not correspond directly to the observed Z_{DR} shown and should not be understood as an apples-to-apples comparison. To perform a statistical evaluation of the simulated radar quantities, we sample the model fields conditionally to avoid the edges of the rainfall features by selecting only those grid points where simulated total reflectivity exceed 20 dBZ.

Figure 12 shows contour frequency by altitude diagrams (CFADs: Yuter & Houze, 1995) of Z_{DR} versus height for grid points with $Z_H > 20$ dBZ, normalised by height. Taking 1.0 dB as a reference, the radar composite contains Z_{DR} features that extend to 5.5 and 4.5 km in IOP01 and IOP18, respectively. RAL3.2 contains Z_{DR} features that extend to 5.0 and 4.0 km in IOP01 and IOP18, respectively, which are comparable with observations, but with an order of magnitude smaller proportion of grid points exceeding 1.0 dB. The RAL3.2WB outputs have Z_{DR} features extending beyond 8.0 km in IOP01 and up to 5.5 km in IOP18, both being much higher than the radar observations. We also note that RAL3.2WB predicts a larger proportion of grid points with Z_{DR} exceeding 2 dB above the freezing level (located at 2.9 and 3.3 km in IOP01 and IOP18, respectively), in contrast to the radar observations and RAL3.2 (which both have no such grid points). From the cross-sections chosen and analysis of CFADs, it is clear that Z_{DR} column signatures from rain in simulations that use the single-moment WB microphysics are exaggerated in terms of height and intensity, whereas such features in the simulations coupled with the double-moment CASIM scheme are of similar intensity to the observations but extend to slightly lower heights compared with observations.

Moreover, a mode of grid points with Z_{DR} values increasing from 0 dB to 1 dB from a height of 4 km

towards the surface is apparent in the observations of IOP01. This feature is consistent with increasing oblateness of raindrops as they become larger with decreasing height during collision-coalescence and thus likely represents the self-collection of raindrops (Kumjian & Prat, 2014). This increase in Z_{DR} with decreasing height is also apparent in the RAL3.2 model output, but less so in RAL3.2WB.

Similarly to Field *et al.* (2023), we also study the variation of Z_H with height. The radar observations (Figure 13a,b) show a broad “wedge shape” and evenly distributed two-dimensional histogram with a maximum proportion of grid points between 10 and 20 dBZ for most heights. For the IOPs, the observations show large values of Z_H extending from 40 dBZ at 6 km to 55 dBZ at the surface. RAL3.2 is able to represent this feature of the observations better than RAL3.2WB. The RAL3.2WB simulations show modes and maximum heights similar to the observations for low Z_H below 20 dBZ. However, the presence of grid points above freezing heights for large values of Z_H at 60 dBZ is inconsistent with their absence in observations. This tells a similar story to the Z_{DR} CFADs, which also suggest the presence of too many large raindrops above freezing heights in RAL3.2WB simulations.

The two configurations RAL3.2 and RAL3.2WB differ only in terms of microphysics scheme, implying that the choice of microphysics scheme dominates the prevalence of Z_{DR} columns.

Between different resolutions, we do not see significant differences in the CFADs of Z_{DR} and Z_H in Figures 12 and 13, respectively. Values of Z_{DR} exceeding 1 dB remain below the freezing level in all RAL3.2 simulations regardless of model resolution. This is a surprising result, as the RAL3.2 configuration is expected to produce sufficiently strong updrafts to loft raindrops large enough to lead to a Z_{DR} exceeding 1 dB, especially at higher resolution. This prompts a closer look into whether there are stronger updrafts to loft rain mass to higher heights as model resolution increases. If strong enough updrafts are indeed present, the absence of Z_{DR} columns in RAL3.2 points to other model processes such as rain-droplet freezing during ascent.

4.3 | Updraft statistics with resolution and microphysics

Changes in the model resolution and microphysics scheme can affect dynamics through mechanisms such as latent heat release, cold pools, and hence updraft strengths, which are a main contributor to Z_{DR} columns. Therefore, investigating whether the change in microphysics scheme has led to a change in updraft characteristics is important,

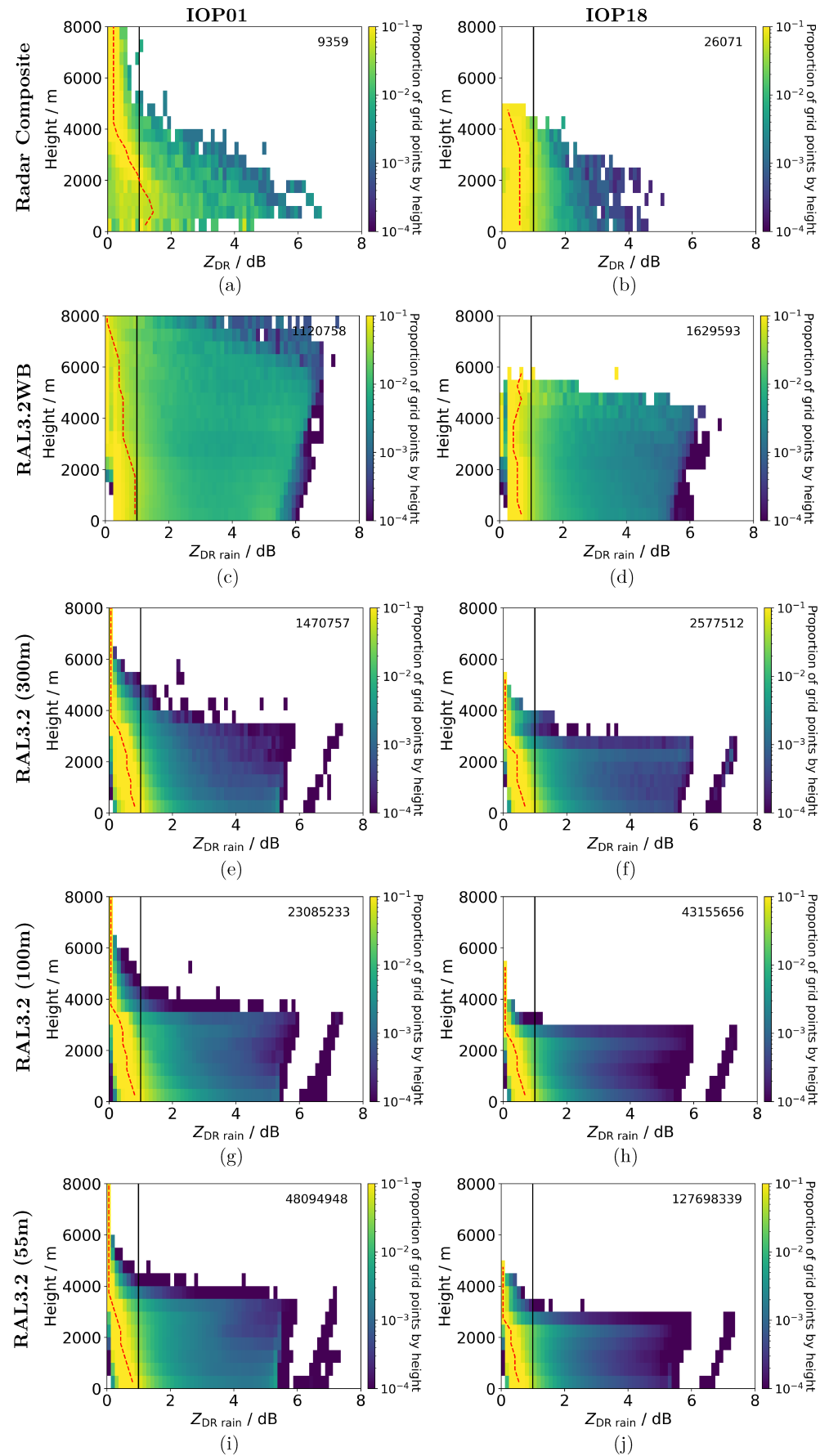


FIGURE 12 Contour frequency by altitude diagrams of differential reflectivity Z_{DR} coinciding with grid points of Z_H 20 dBZ normalised by height within the (a, b) radar composite, (c, d) RAL3.2 (Wilson-Ballard), (e, f) RAL3.2, (g, h) RAL3.2 (100-m), and (i, j) RAL3.2 (55-m) model simulations for (left column) IOP01 and (right column) IOP18. The number of grid points included in the analysis is displayed in the top right-hand corner of each panel. The dashed line shows the median of grid points at different heights. The vertical line shows Z_{DR} of 1.0 dB.

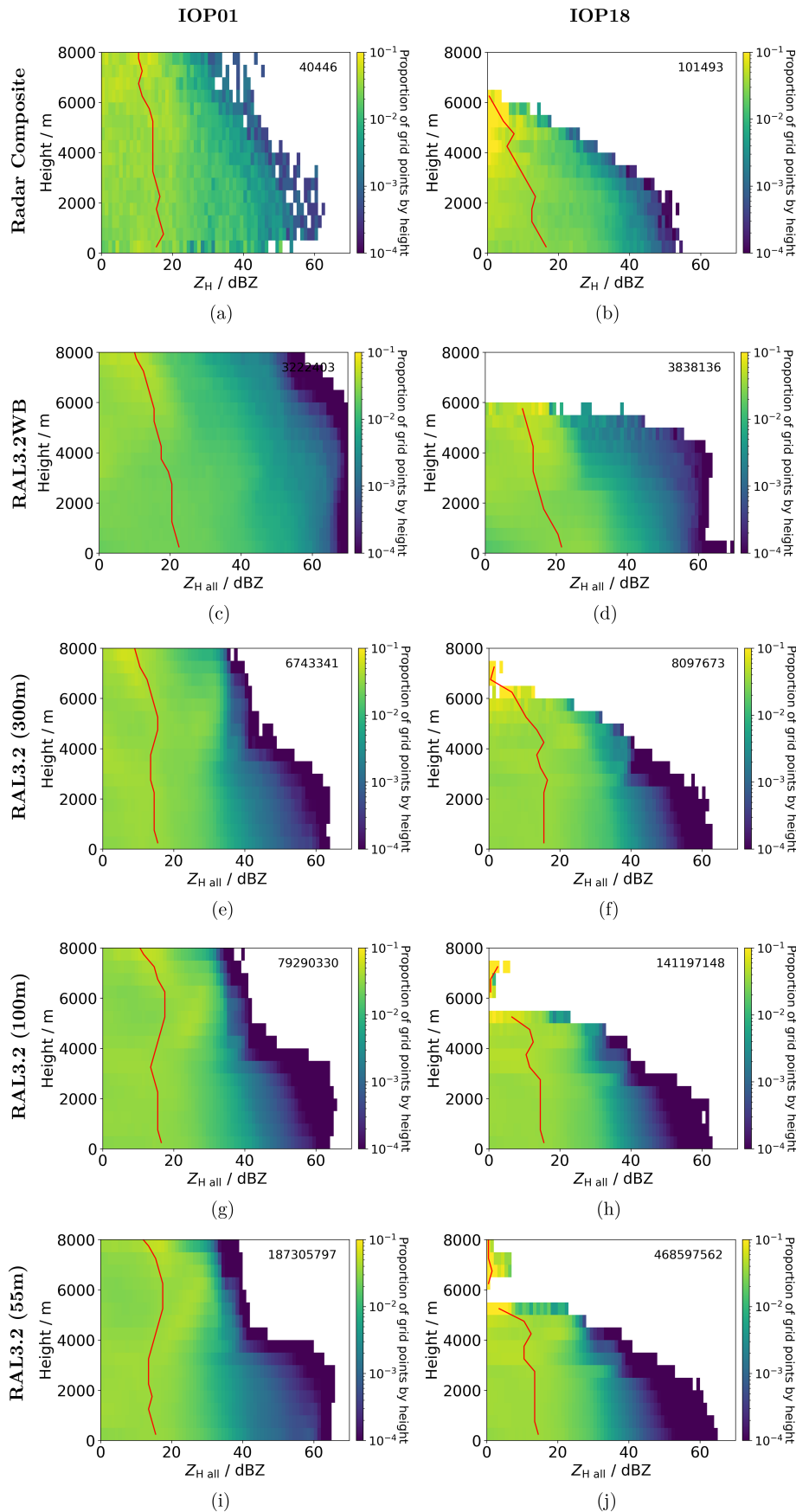


FIGURE 13 Contour frequency by altitude diagrams of reflectivity Z_H normalised by height for grid points within the (a, b) radar composite, (c, d) RAL3.2 (Wilson–Ballard), (e, f) RAL3.2, (g, h) RAL3.2 (100-m), and (i, j) RAL3.2 (55-m) model simulations for (left column) IOP01 and (right column) IOP18. The number of grid points included in the analysis is displayed in the top right-hand corner of each panel. The line shows the median of grid points at different heights.

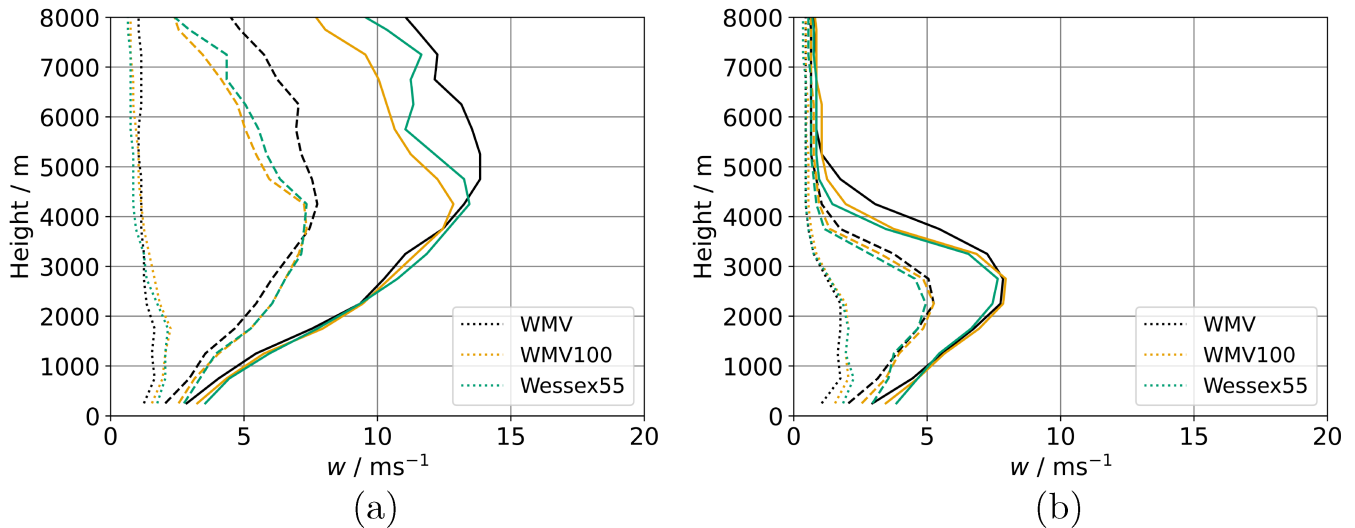


FIGURE 14 Upward air velocity values at 99th (dotted), 99.9th (dashed) and 99.99th (solid) percentiles for each model height, comparing between model simulations of different grid lengths for (a) IOP01 and (b) IOP18. Names for the different model resolutions are defined in Table 2.

as such changes could lead to differences in enhanced Z_{DR} values above the freezing height.

The updraft speeds required to loft raindrops that could give enhanced Z_{DR} signals can be calculated by considering the relationship between raindrop size, terminal fall velocity, and backscatter. Applying the T-Matrix method with the Thurai *et al.* (2007) aspect-ratio model and the raindrop diameter to terminal velocity relation of Beard (1976), an updraft exceeding $8 \text{ m} \cdot \text{s}^{-1}$ would be necessary to support a 2.0-mm raindrop that would give a Z_{DR} exceeding 1.0 dB.

To understand the differences in updraft magnitudes between model grid resolutions, Figure 14a compares updraft magnitudes and percentiles between three model runs of different resolution at model heights up to 8 km. For IOP01, all model runs regardless of resolution exhibit similar updraft values when considering the 99th-percentile value at each model level. On the other hand, updraft values of 7 and $12 \text{ m} \cdot \text{s}^{-1}$ at the 99.9th and 99.99th percentiles, respectively, diverge between simulations just above 4 km. This height is 1 km above the freezing level for this case, and is where one would expect Z_{DR} column signatures to appear. For IOP18 with shallower convection, as shown in Figure 14b, the most extreme updraft values of nearly $8 \text{ m} \cdot \text{s}^{-1}$ at the 99.99th percentile from the 300-m model diverge between simulations above 3 km. This set of results suggests that a difference in model resolution could account for differences in the extreme updraft values needed to support large drops, although there is not a clear negative correlation between model grid length and updraft magnitude.

To investigate how different microphysics configurations are associated with differences in updraft magnitudes, Figure 15a compares differences in updraft magnitudes and percentiles between RAL3.2, RAL3.2WB, and RAL3.2SMITH configurations of the model run at 300-m grid length. RAL3.2SMITH also has model physics identical to that of RAL3.2, except that the bimodal cloud scheme (Van Weverberg *et al.*, 2021) is replaced with the Smith cloud scheme (Smith, 1990). We run the RAL3.2SMITH simulation, as the Smith cloud scheme is known to condense liquid more easily in mixed-phase conditions, which could be dehydrating the lower parts of Z_{DR} columns, in contrast to the bimodal cloud scheme (Field, 2025, private communication). Because of this, it is possible for cloud water to be formed at higher heights using the Smith scheme and latent heating release to feed back into the updraft magnitudes.

For IOP01, all configurations show similar updraft magnitudes at the 99th percentile. However, the 99.9th and 99.99th percentile values begin to diverge at 4 and 3 km, respectively, with RAL3.2SMITH and RAL3.2WB runs containing more intense updrafts exceeding $14 \text{ m} \cdot \text{s}^{-1}$ than RAL3.2 at 4 km. Despite less significant differences in IOP18 (Figure 15b), we also see RAL3.2SMITH and RAL3.2WB with the more intense updrafts at the 99.99th percentile, with $6 \text{ m} \cdot \text{s}^{-1}$ at a height of 4 km. This similarity in updraft magnitudes of within $1 \text{ m} \cdot \text{s}^{-1}$ at the 99.99th percentile between RAL3.2SMITH and RAL3.2WB suggests that the moderate to strong updraft magnitudes needed to support large drops can mostly be attributed to differences in both cloud and microphysics schemes above the freezing level.

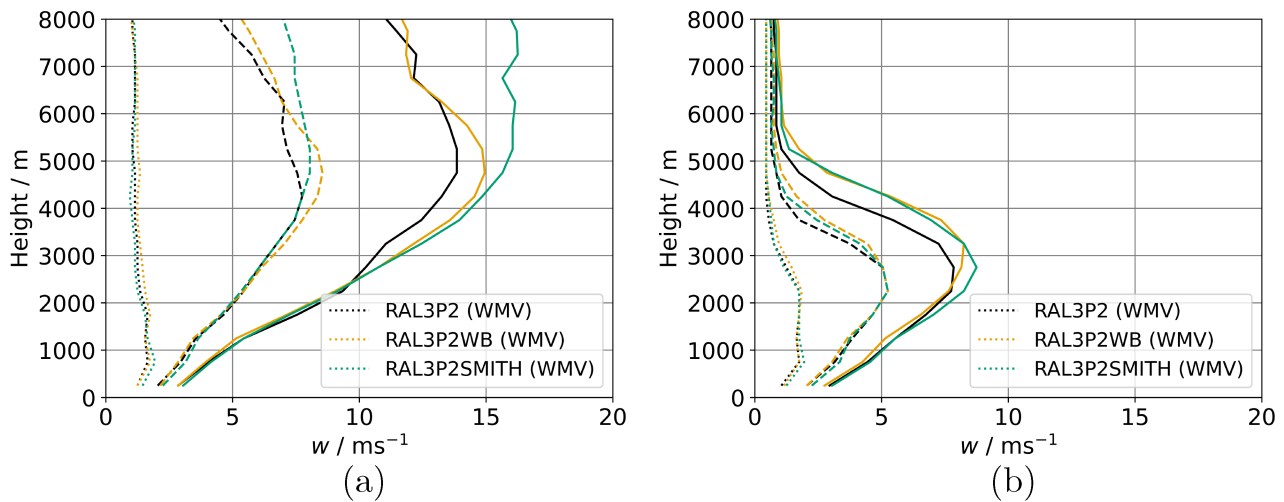


FIGURE 15 Upward air velocity values at the 99th (dotted), 99.9th (dashed), and 99.99th (solid) percentiles for each model height, comparing between model simulations of different microphysics configurations for (a) IOP01 and (b) IOP18. RAL3P2 is the default science configuration of RAL3.2, whereas RAL3P2WB uses the Wilson–Ballard microphysics scheme and RAL3P2SMITH uses the Smith cloud scheme. WMV refers to the 300-m resolution model simulation defined in Table 2.

As for CFADs of Z_{DR} , the RAL3.2SMITH simulation, however, shared a similar height distribution of Z_{DR} (not shown) to the RAL3.2 control run for both IOPs and thus did not lead to substantially different results. In other words, the cloud scheme has less of an effect on the presence of a simulated Z_{DR} column than the microphysics scheme.

5 | DISCUSSION AND CONCLUSIONS

Simulated Z_H and Z_{DR} contributions from rain were computed through the implementation of an online operator to calculate Z_H and Z_{DR} from model prognostic fields, based on lookup tables derived using the T-Matrix method (Mishchenko, 2000). The joint distribution of Z_H and Z_{DR} is indicative of the variety of rain processes and the existence above the freezing level of Z_{DR} due to rain is indicative of strong updrafts, making these new diagnostics a useful avenue for model evaluation. As expected, our MetUM simulations using a single-moment microphysics scheme are unable to reproduce the observed joint distribution of Z_H and Z_{DR} , instead generating a one-to-one relationship that can be predicted from the microphysics scheme formulation. In contrast, the configuration using a two-moment scheme (CASIM: Field *et al.*, 2023) does produce a spread in Z_H and Z_{DR} distributions that is comparable with our radar observations.

Chosen vertical cross-sections of convective cells show overly wide, deep, and intense Z_{DR} columns for simulations using the WB scheme, whereas CASIM

produces more realistic Z_{DR} column contributions from rain. Such results are not limited to the chosen cross-sections but are also supported by CFADs of Z_{DR} . We also found radar composite CFADs to be more similar to those of RAL3.2 than RAL3.2WB. Considering modelled physical processes, differences in rain contribution to Z_{DR} columns between model simulations could be due to both direct effects of microphysical freezing processes on the hydrometeor population and indirect, latent-heat induced modifications of updraft speeds that influence the presence of rain at heights above the freezing level.

Models that produce stronger updrafts could also generate more Z_{DR} columns. We therefore tested whether the different microphysical configurations lead to different updraft statistics, considering feedbacks between microphysics and dynamics. Separately, we considered whether 100- and 55-m grid-length simulations generate stronger updrafts and more Z_{DR} columns in CASIM. Stratifying updraft magnitudes by model height revealed similar updraft values exceeding $12 \text{ m} \cdot \text{s}^{-1}$ at the 99.99th percentile above the freezing level between model simulations with different resolutions and microphysics configurations for IOP01. CASIM produces sufficiently strong updrafts that support the simulation of Z_{DR} columns, which are shallower than those reported in the literature (3–4 km above the freezing-level height) associated with profoundly strong updrafts in supercells. Given also that freezing raindrops and wet hail were not considered, the depth of simulated columns could also be limited. Thus, the representation of Z_{DR} from rain in RAL3.2 is reasonably comparable with that of the radar composite.

However, model simulations with more intense updraft values were not associated with an abundance of enhanced Z_{DR} above freezing heights. This prompts a closer inspection of how microphysical schemes differ in rain source and sink processes and how these affect modelled Z_{DR} columns. This could include processes such as rain evaporation and graupel accretion, which may control the rain mass and thus Z_{DR} column presence near the freezing level. Also, given the likely microphysical feedback on the updraft strength to loft large raindrops beyond the freezing level, a further investigation into process rates such as latent heat release would be helpful (Tao & Li, 2016). It is worth noting that updrafts, although a necessary ingredient for Z_{DR} columns, do not uniquely control the amount of Z_{DR} columns.

The time-dependent process of freezing and inclusion of freezing drops is necessary to capture the full depth of Z_{DR} columns during their evolution, as seen in Kumjian *et al.* (2014). However, they also showed how subsequent growth of graupel into large hail could lead to the suppression of enhanced Z_{DR} column signals. Accretion of rain by frozen hydrometeors is a process present in both the WB and CASIM schemes, but is formulated differently in the two schemes. Experiments could be designed, with the implementation of a radar forward operator that accounts for the mixed phase, to test the effects of modifying these processes.

The effect of having different numbers of moments in each scheme has also yet to be tested. David *et al.* (2025) demonstrated that output from a two-moment microphysics outperformed a single-moment scheme when evaluating against observed radar variables. A fairer test to compare the effects of having different numbers of moments rather than different processes would require setting up a CASIM simulation with single-moment rain (i.e., omitting raindrop number concentration of hydrometeor species as a prognosed variable).

The currently implemented polarimetric radar operator only considers contributions from raindrops for the simulation of Z_H and Z_{DR} , because supercooled raindrops dominate the radar reflectivity. However, to simulate radar observations properly for the top of Z_{DR} columns and other parts of a convective storm dominated by frozen or mixed-phase hydrometeors, other hydrometeor classes modelled in the MetUM and their contributions to simulated polarimetric measurements should be included.

Future implementations of a forward operator within the MetUM could consider including the effects of the radar viewing angle and attenuation (Hogan, 2007). Alternatively, attenuation correction and other radar errors could be applied to radar observations using successive correction methods (Scovell & al Sakka, 2016) before

interpolating the corrected observations into a 3D radar composite for model evaluation.

Although the contrast in Z_{DR} representation between MetUM simulations coupled to different microphysical schemes remains an open question, this study has demonstrated the use of Z_{DR} in the evaluation of NWP models. The inclusion of a Z_{DR} diagnostic could be utilised in other cases of interest for the evaluation of frontal precipitation (e.g., Truong *et al.*, 2023) and warm rain (e.g., Wang *et al.*, 2023) simulated within the MetUM.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Radar data from the WesCon–WOEST field campaign may be found listed at CEDA's project page for WesCon–WOEST (<https://catalogue.ceda.ac.uk/uuid/d3685300168848f290dd3a9ec14cc8ac/>). Operational radar data are available through the CEDA Archive (<https://archive.ceda.ac.uk/>). MetUM model outputs used in this study are available from the corresponding author upon reasonable request.

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APPENDIX A. USING CAMRA TO BENCHMARK UNCERTAINTY FROM THE 3D RADAR COMPOSITE

Figure A1a,c presents joint distributions for 120 re-gridded CAMra RHI scans on June 7, 2016, partitioned into grid points higher and lower than the freezing height, respectively. This is done similarly for 120 corresponding composite-generated pseudo-RHIs in Figure A1b,d. Below

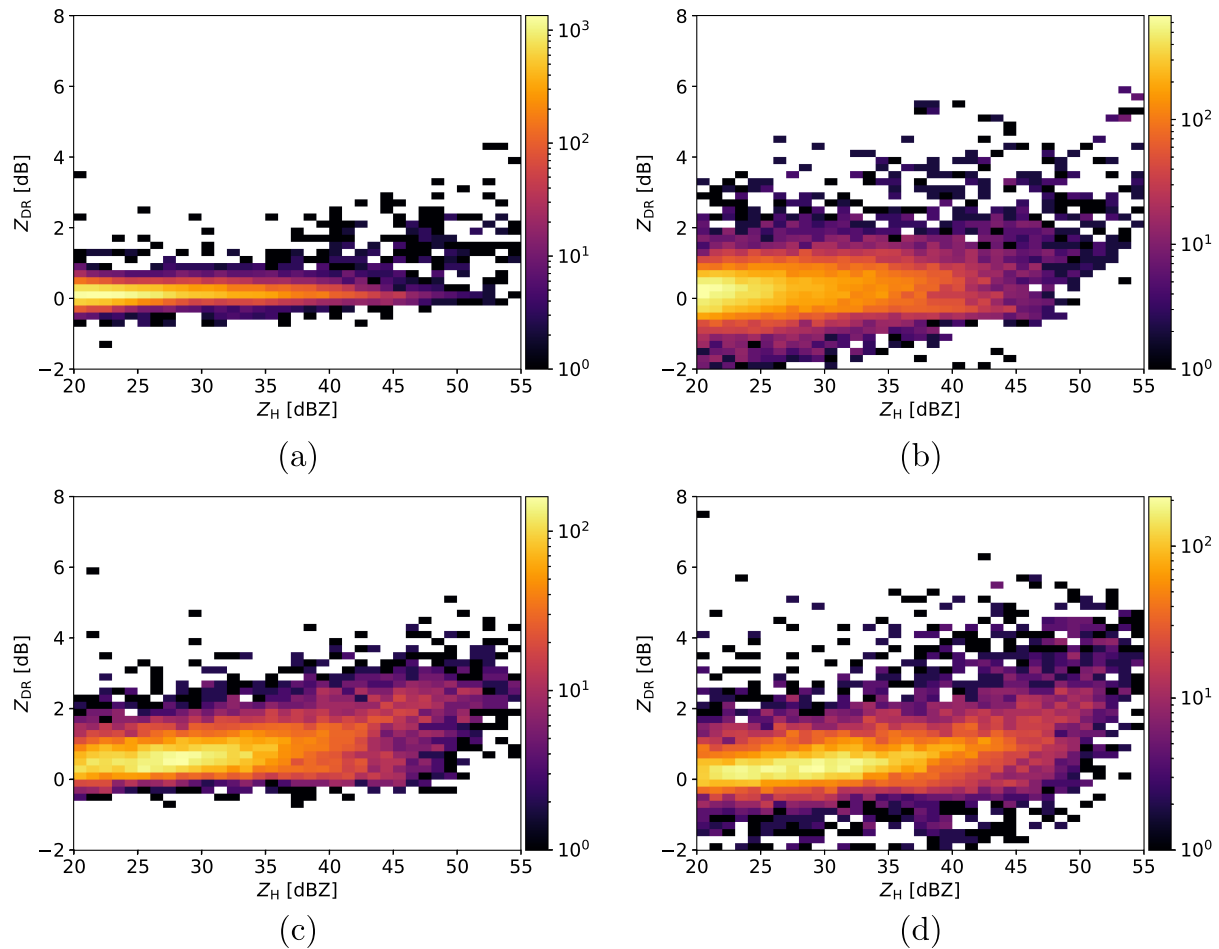


FIGURE A1 Joint distributions of Z_H and Z_{DR} for (a, c) re-gridded CAMra data and (b, d) composite-generated pseudo-RHIs, considering grid points above (top row) and below (bottom row) the freezing height. Note that the colour-bar ranges are different for different panels.

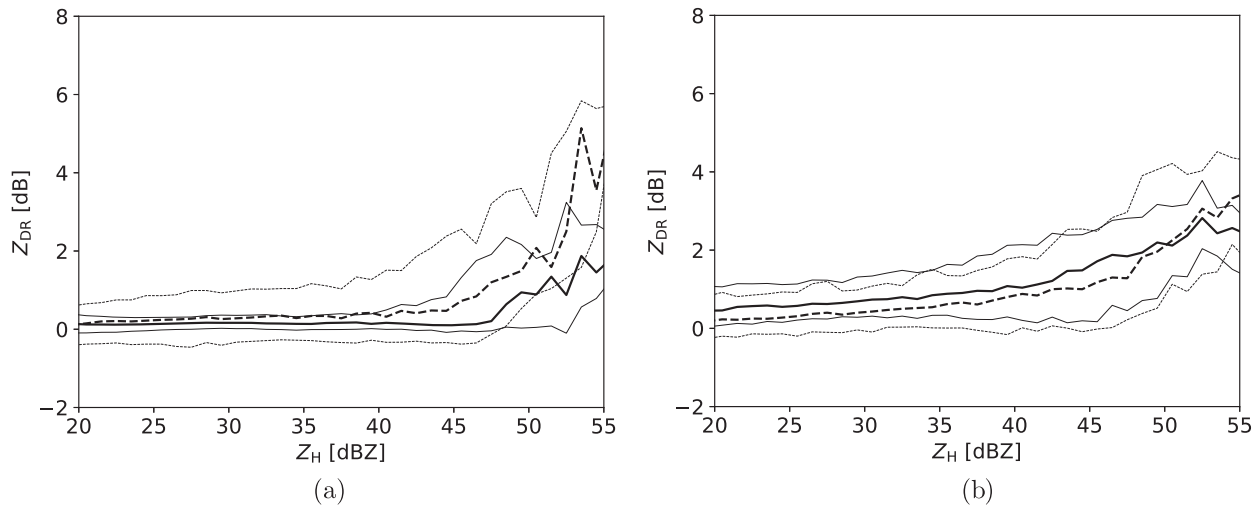


FIGURE A2 Median, 10th, and 90th percentile Z_{DR} values for each Z_H bin for grid points (a) above and (b) below the freezing height. Solid lines represent re-gridded CAMRa data, whereas the dotted lines represent composite data. Thicker lines show the median Z_{DR} values.

the freezing height, we observe similar Z_H and Z_{DR} distributions in both CAMRa and composite data, as expected. The mode of Z_{DR} is 0 dB below Z_H of 25 dBZ, but this increases to 2 dB of Z_{DR} for Z_H above 40 dBZ. Figure A2b shows the median, 10th, and 90th percentiles of Z_{DR} values in each Z_H bin for grid points below the freezing level. The positive curvature highlighted by the most populated bins resembles the microphysics of increasing oblateness of raindrops as they increase in size. Similarly to the joint distributions, the median highlights a positive correlation between the two radar observables below the freezing height. Using the 10th and 90th percentiles, we quantify the spread of the radar composite Z_{DR} values to be up to three times those from CAMRa, especially for higher values of Z_H .

Histograms describing Z_H and Z_{DR} distributions above the freezing height are also of interest, as this is where we expect the occurrence of Z_{DR} columns, especially for grid points fulfilling Z_H 10 dBZ and Z_{DR} 1.0 dB, as per the thresholds in Plummer *et al.* (2018). The branch of near-zero Z_{DR} for large Z_H above the freezing level (Figure A1a,b) is a signature of tumbling hail and is also reflected by the near-zero median Z_{DR} for Z_H less than 45 dBZ (Figure A2a). A larger spread of Z_{DR} values at higher reflectivity in the pseudo-RHIs is possibly due to nonlinear beam-filling effects (Ryzhkov, 2007). At heights of 3 km, which is above the freezing level, a radar beam is at least 700 m wide. The spread of Z_{DR} between CAMRa and the radar composite is similar above the freezing level.

APPENDIX B. SYNOPTIC SITUATION OF INTENSIVE OBSERVATION PERIODS

Figure B1 shows surface synoptic charts of IOP01 and IOP18 at 1200 UTC.

APPENDIX C. CASIM PARTICLE SIZE DISTRIBUTION

CASIM prognoses the number concentration of raindrops N_{rain} , otherwise known as the zeroth moment of mass:

$$N_{rain} = \int_0^{\infty} n_{rain}(D) dD. \quad (C1)$$

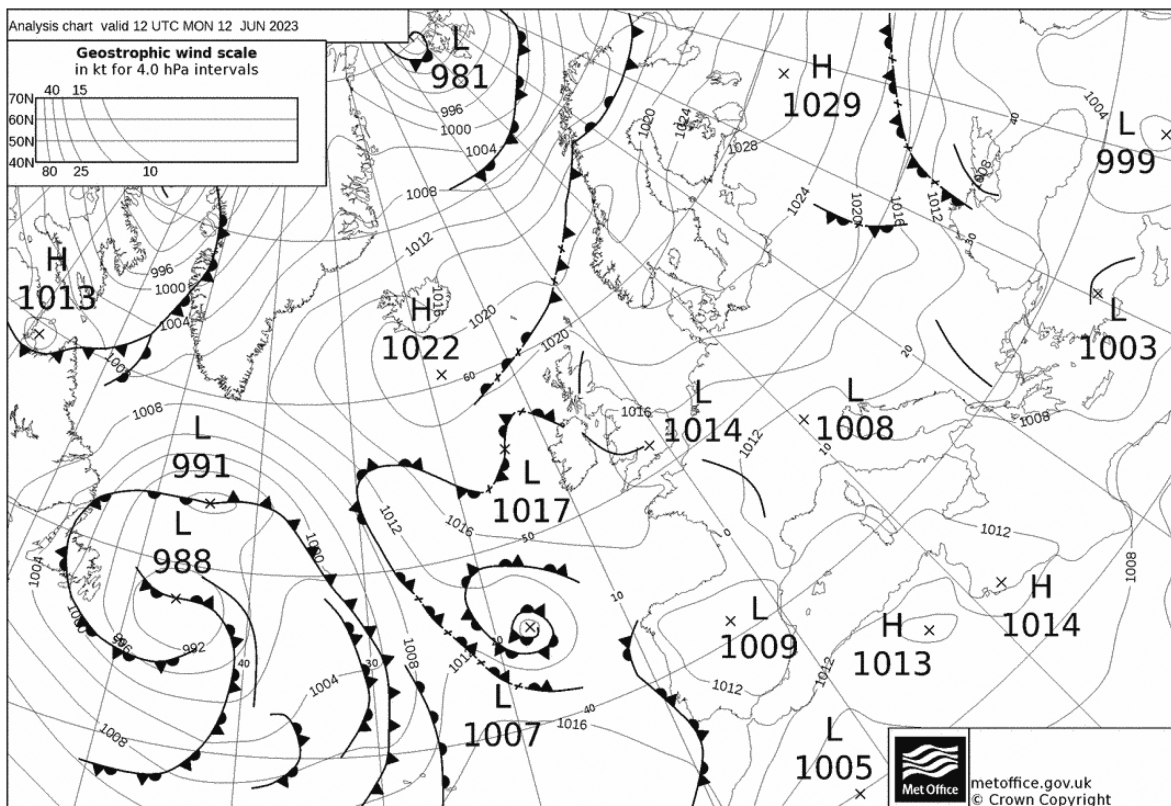
The raindrop size distribution is a general gamma distribution with an intercept parameter n_{0rain} and a shape parameter λ_{rain} that are both prognosed by the model. α_{rain} is a fixed parameter with the value 2.5.

$$n_{rain} = n_{0rain} D^{\alpha_{rain}} e^{-\lambda_{rain} D}. \quad (C2)$$

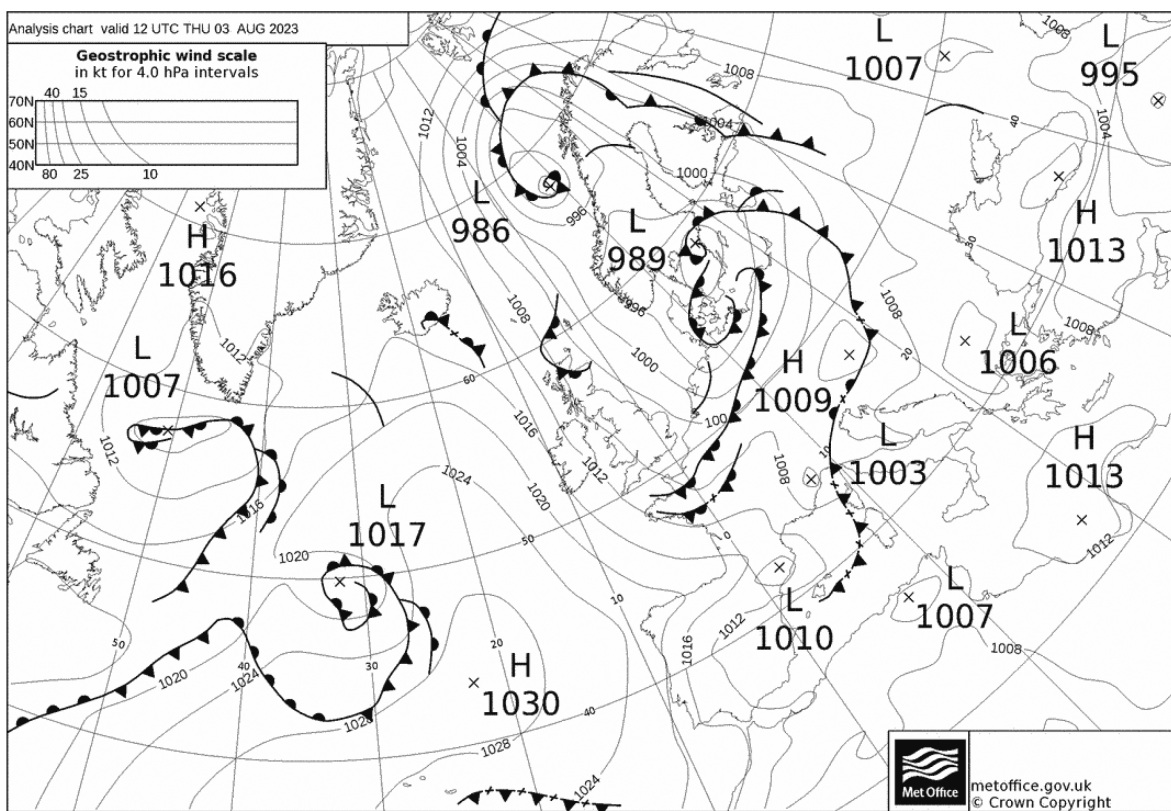
Integrating Equation (C1) gives us the number concentration of raindrops as

$$N_{rain} = n_{0rain} \Gamma(\alpha_{rain} + 1) \lambda_{rain}^{-(\alpha_{rain} + 1)}, \quad (C3)$$

where Γ is the gamma function. Rain water content is the integral of mass over the particle size spectrum, otherwise known as the first moment of mass. The quantity can be



(a)



(b)

FIGURE B1 Surface analysis chart issued by the UK Met Office valid on (a) June 12, 2023 at 1200 UTC and (b) August 3, 2023 at 1200 UTC.

calculated as

$$W_{\text{rain}} = \int_0^\infty M_{\text{rain}}(D) n_{\text{rain}}(D) dD. \quad (\text{C4})$$

Following the assumption of a spherical drop, the mass–diameter relationship implies that the mass of a raindrop will be the density of liquid water multiplied by the volume of a sphere of diameter D :

$$M_{\text{rain}} = a_{\text{rain}} D^{b_{\text{rain}}}. \quad (\text{C5})$$

Substituting into the integrand and integrating gives the rain water content:

$$W_{\text{rain}} = a_{\text{rain}} n_{0\text{rain}} \Gamma(b_{\text{rain}} + 1 + \alpha_{\text{rain}}) \lambda_{\text{rain}}^{-(b_{\text{rain}}+1+\alpha_{\text{rain}})}. \quad (\text{C6})$$

Dividing Equation (C4) by Equation (C3) and rearranging, we get an expression for λ_{rain} depending only on model parameters and prognosed variables:

$$\lambda_{\text{rain}} = \left[a_{\text{rain}} \frac{\Gamma(b_{\text{rain}} + \alpha_{\text{rain}} + 1)}{\Gamma(\alpha_{\text{rain}} + 1)} \frac{N_{\text{rain}}}{W_{\text{rain}}} \right]^{1/b_{\text{rain}}}. \quad (\text{C7})$$

To then solve for the intercept parameter, Equation (C3) is inverted.

$$n_{0\text{rain}} = \frac{N_{\text{rain}} \lambda_{\text{rain}}^{(\alpha_{\text{rain}}+1)}}{\Gamma(\alpha_{\text{rain}} + 1)}. \quad (\text{C8})$$

APPENDIX D. POLARIMETRIC RADAR FORWARD OPERATOR LOOKUP TABLE

Figure D1 shows the two-dimensional lookup table implemented within CASIM to compute simulated Z_{DR} values. The lookup table takes in rain water content W_{rain} and number concentration of rain per unit volume of air N_{rain} as inputs that can be derived from CASIM.

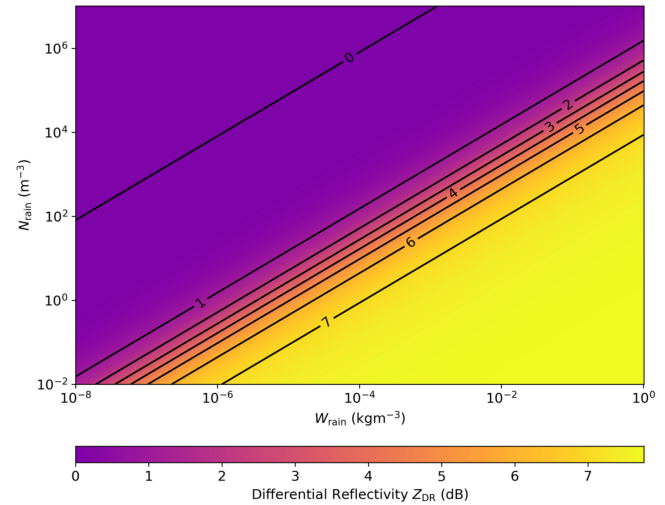


FIGURE D1 Lookup table showing simulated Z_{DR} computed from rain water content W_{rain} and number concentration of rain per unit volume of air N_{rain} . Both quantities can be derived from the CASIM microphysics scheme.