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Particle Inertia Effects on Radar Doppler Spectra Simulation

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Abstract. Radar Doppler spectra observations provide a wealth of information about cloud and precipitation microphysics and dynamics. The interpretation of these measurements depends on our ability to simulate these observations accurately forward. The effect of small-scale turbulence on the radar Doppler spectra shape has been traditionally treated by implementing the convolution process on the hydrometer reflectivity spectrum and environment turbulence. This approach assumes that all the particles in the radar sampling volume respond the same to turbulent scale velocity fluctuations and neglects the particle inertial effect. Here, we investigate the impact of particle inertia on the forward modelled radar Doppler spectra. A physics-based simulation is developed to demonstrate that big droplets, with large inertia, are unable to follow the rapid change of velocity field in a turbulent environment. These findings are incorporated to a new radar Doppler spectra simulator. Comparison between the traditional and the newly formulated radar Doppler spectra simulators indicates that the conventional simulator leads to an unrealistic broadening of the spectrum, especially in strong turbulence environment. Doppler spectra observed from the W-band Cloud Radar at South Great Plain (SGP) observatory are used to validate the fidelity of the two Doppler spectrum simulation methods. The result indicates that the Doppler spectrum generated from the proposed approach is more consistent to the observed Doppler spectrum while the conventional simulator misrepresents the Doppler spectrum morphology. This study provides clear evidence to illustrate the droplets inertial effect on radar Doppler spectrum and develops a physics-based simulator framework to accurately emulate the Doppler spectrum for a given Droplet Size Distribution in turbulence field. The proposed simulator has various potential applications to the cloud/precipitation studies and provides a valuable tool to decode the cloud microphysics and dynamics properties from Doppler radar observation.

1 Introduction

The radar Doppler spectrum represents the frequency (velocity) distribution of the backscattered radar signal at a particular range. In a vertically pointing radar, the Doppler spectra provides the distribution of the backscattered signal over a range of Doppler velocities, whose value depends on the dynamical (i.e., vertical air motion) and cloud microphysical (i.e., hydrometeors concentration and sizes) properties within the radar sampling volume. A variety of research applications that utilize the full radar Doppler spectrum have been developed. For instance, Doppler spectrum can be used to resolve rain Droplet Size Distribution (DSD) (Atlas et al., 1973), remove clutters and identify hydrometers signals (Williams et al., 2018;Luke et al., 2008;Moisseev and Chandrasekar, 2009), identify drizzle development stage (Zhu et al., 2022;Acquistapace et al., 2019), retrieve vertical air motion (Kollias et al., 2002;Williams, 2012;Zhu et al., 2021), characterize the melting-layer properties (Li and Moisseev, 2020;Mróz et al., 2021), and to validate and improve the microphysical modeling process (Kollias et al., 2011b). Combined with the depolarization capability, Doppler spectrum can also be used for cloud-phase classifications and to investigate ice-cloud microphysical process (Luke et al., 2010;Luke et al., 2021;Kalesse et al., 2016;Oue et al., 2018). The list of widely application of the Doppler spectrum in the cloud-precipitation research mentioned above is by no means exhaustive.

Even though the significance of radar Doppler spectrum is highly recognized, spectrum itself is challenging to be unambiguously interpreted to characterize the cloud/precipitation properties. One important reason is a lack of fully understanding of the entanglement between the hydrometer microphysics and environment dynamics as well as their manifestation on the Doppler spectrum morphology (Kollias et al., 2002). More specifically, Doppler spectrum is contributed by hydrometer DSD, vertical air motion and environment turbulence: the width of Doppler spectrum is contributed by both DSD and small-scale turbulence, while the Doppler frequency shift is a combined measure of the air motion and the particles falling velocity (Doviak, 2006). A successful separation of the microphysical and dynamical contributions to Doppler spectrum is essential to reduce the retrieval uncertainties and to better characterize the cloud-precipitation properties (Zhu et al., 2021).

Radar Doppler spectra simulators have been invaluable for the interpretation of the radar Doppler spectra shape (Capsoni et al., 2001;Oue et al., 2020;Kollias et al., 2011a;Maahn et al., 2015). Traditionally, the impact of turbulence on the shape of the radar Doppler spectrum is represented by the convolution of the quiet air (no air motion) power spectrum with a Gaussian distribution (Gossard and Strauch, 1989). The width of the Gaussian distribution is parameterized as a function of the radar parameters and the turbulence intensity often represented in terms of eddy dissipation rate (Borque et al., 2016). This approach is only valid under the assumption that the droplet inertia effect is negligible and droplets with different sizes can follow exactly the environment wind field. In reality, however, big droplets with large inertia cannot follow the rapid change of wind velocity field as the small droplets perform (Yanovsky, 1996;Lhermitte, 2002). Not accounting for the particle inertia effect can lead to a misinterpretation of the Doppler spectrum and cause large uncertainties for the retrieval product (Nijhuis et al., 2016).

Several physics-based frameworks have been proposed to simulate the droplet motions in turbulence (Khvorostyanov and Curry, 2005;Lhermitte, 2002). Here, the approach proposed by Lhermitte (2002) is used to illustrate the droplets inertial effect and to investigate this effect on the radar Doppler spectrum. In detail, we aim to answer the following questions: 1) How inertia affect the response of a droplet in a fluctuating turbulent wind field? 2) Is this effect significant on simulated and observed radar Doppler spectra? and 3) How can we account for the droplet inertia in radar Doppler spectra simulators? Building on these investigations, a new approach to generate radar Doppler spectra is described.

The structure of this paper is organized as follows: section 2 introduces the observational dataset used in this study; section 3 describes the physical modeling framework used to simulate the droplet movement and to illustrate the droplets inertia effect in a turbulent environment; section 4 proposes the physics-based Doppler spectrum simulator and compares the emulated spectra to the ones generated from the traditional method; section 5 uses real observed Doppler spectra to validate the fidelity of the proposed spectrum simulator; section 6 concludes the major results of this study and followed by a discussion.

2 Data

The dataset used in this study are collected at the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) Southern Great Plain (SGP) observatory at Lamont, OK. The primary instrument being used is the W-band ARM Cloud Radar (WACR). WACR is a vertical pointing radar operating at 95.04 GHz with a range resolution of 42.8 m and a temporal resolution of 4.28 s. Since 2005, WACR has been continuously collecting Doppler spectra with 256 Doppler velocity bins and with a Nyquist velocity of ± 7.8 ms^{-1}. (Kollias et al., 2016). Doppler spectra post-processing algorithm (Hildebrand and Sekhon, 1974) is implemented to remove noise and identify the hydrometer signals. In addition, impact disdrometer which records the DSD of raindrops is used to evaluate the radar Doppler spectrum near surface. Disdrometer measures rain drop size over the range from 0.3mm to 5.4 mm categorized by 20 diameter bins with a time resolution of 1 minute (Wang et al., 2021). The specified accuracy of drop size measurement is estimated as ±5%.

3 Simulation of raindrops movement in turbulence environment

In this section, a physics-based simulation framework to illustrate the droplets inertia effect in given turbulence environment is presented. First, we will introduce the equations being used to describe droplets movement according to Lhermitte (2002). Then a generated turbulent wind field is applied to resolve the droplets velocity and to discuss the implication of inertia effect on the simulated Doppler spectrum.

3.1 Motion of droplets in a turbulent environment

Assuming a liquid droplet with a diameter of D , the motion of the droplet can be described as:

$$F = m\frac{dV_D}{dt} \tag{1}$$

where m is the droplet mass, V_D is the droplet velocity, F is the drag force exerted by wind expressed as:

$$F = \frac{C_d S \left(V_w - V_D \right)^2 \rho_a}{2} \tag{2}$$

where C_d is the wind drag coefficient, V_w is wind velocity, ρ_a is air density, S is the droplet cross section normal to wind direction. For spherical droplets, S can be calculated as:

$$S = \frac{\pi D^2}{4} \tag{3}$$

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and droplet mass (m) is calculated as:

$$m=\frac{1}{6}\pi\rho_l D^3 \tag{4}$$

where ρ_l is liquid water density. Finally, wind drag coefficient C_d is obtained from an experimental fitted function adapted from (Lhermitte, 2002)

$$\log C_d = 1.445 - 0.8796\times\log Re + 0.0642\times(\log Re)^2 + 0.0104\times(\log Re)^3 \tag{5}$$

where R_e is the Reynolds number estimated as:

$$Re = \frac{\left(V_w - V_D\right) D \rho_a}{\mu} \tag{6}$$

where μ is the air dynamic viscosity. Here, ρ_a, ρ_l, and μ are used as $1.22\ kg\ m^{-3}$, $1000\ kg\ m^{-3}$, $1.81\times10^{-5}\ kg\ m^{-1}\ s^{-1}$ as a representation of environment with $15^{\circ}C$ and 1000 hPa.

Combining (1)-(6), the droplet velocity (V_D) as a function of time can be calculated numerically if the wind field (V_w) is given.

3.2 Illustration of droplet inertial effect

We first illustrate the inertial effect by calculating droplets motion under a constant wind velocity field. Seven droplets with diameters of 10 μm, 50 μm, 100 μm, 500 μm, 1 mm, 2 mm, 5 mm are selected to cover the size range of cloud, drizzle and raindrops. Initial velocity of all the droplets is 0 ms^{-1}, a constant wind velocity with 10 ms^{-1} is exerted upon the droplets when t > 0 s. Due to the drag force, droplets start to move but with different accelerations depending on droplet inertia: droplets with small inertia are accelerated more quickly than larger ones. This effect is clearly illustrated in Figure 1: droplet with diameter of 10 μm quickly reach to the wind velocity within only 0.002s, while droplets with 1 mm and 5 mm need 5 and 50s respectively to adjust their motion to the exerted wind velocity. The different response time of droplets with different

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sizes to the exerted wind velocity suggests that small droplets are more capable to follow the velocity variation than their large counterparts.

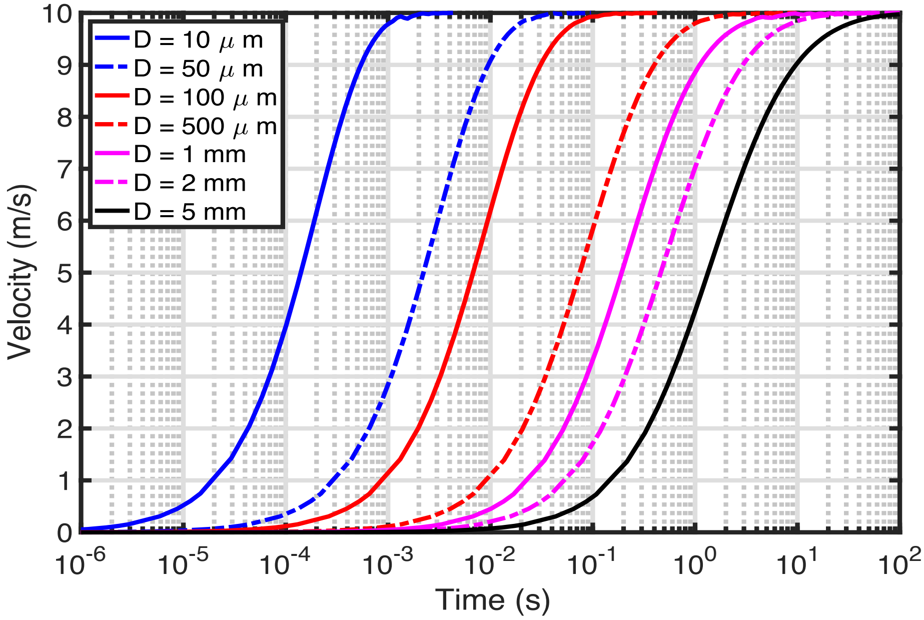

Figure 1. Velocity of droplets with diameter of 10 μm (blue solid line), 50 μm (blue dash-dot line), 100 μm (red line), 500 μm (red dash-dot line), 1 mm (magenta solid line), 2 mm (magenta dash-dot line) and 5 mm (black solid line) as function of time after exerted by a constant wind with 10 ms^{-1}velocity.

In real atmosphere, air velocity is not constant but fluctuates with time as a representative of turbulent nature. In order to emulate the turbulence environment, a 1-D turbulence field is generated with 2 Hz sampling frequency, 1000s duration and with a standard deviation of 0.3 ms^{-1} using the method proposed by Deodatis (1996). The selection of 0.3 ms^{-1} standard deviation is based on a quantitatively estimation of cloud radar observation under a typical stratiform environment (Zhu et al., 2022). Specifically, for cloudy condition with an eddy dissipation rate (EDR) of 1×10^{-3} m^2 s^{-3}, Doppler spectrum width observed from radar with 30m range resolution and 0.3° beamwidth at 1km height is estimated to be 0.27 ms^{-1} (Borque et al., 2016). The spectrum and time series of the generated air velocity are shown in Figure 2: the turbulence spectrum (Figure 2a) characterizes typical inertial subrange of the turbulence scale with a standard deviation of 0.3 ms^{-1}(Figure 2b).

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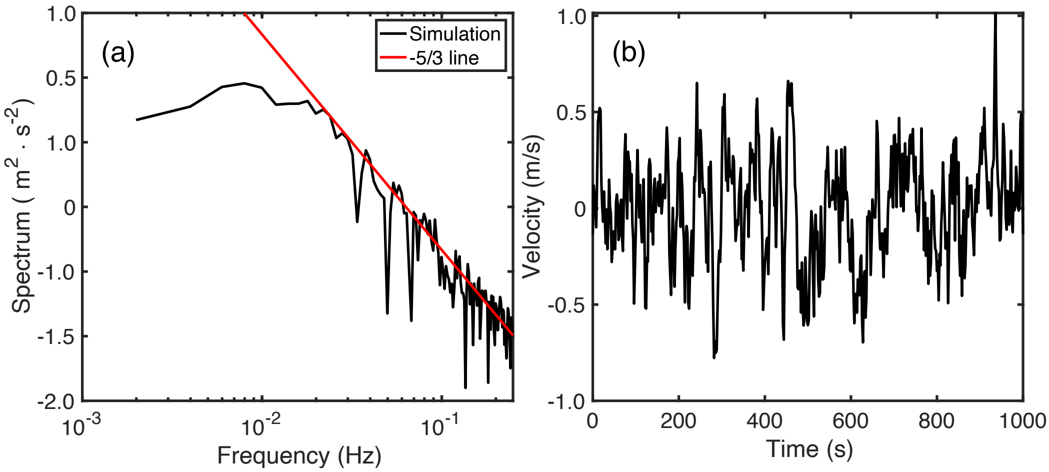

Figure 2. (a) Spectrum of the simulated turbulence (black line), red line represents the -5/3 slope. (b): Time series of vertical velocity for the simulated turbulence.

The generated air velocity is assigned to V_w(Eq. (2)) to simulate the motion of droplets. Figure 3a shows the time-depended velocity of droplets with selected diameter of 0.5 mm, 1 mm, 2 mm, 3 mm. Droplets with different sizes response differently with the change of wind velocity, and there are two notable characteristics due to the inertial effect (highlighted in the black oval in Fig. 3a). First, large droplets need longer time to adjust to the wind velocity, and thus there is a distinct time-lag when the peak velocity is reached for different particles. Second, in addition to the time-lag, the peak velocity reached by the large droplets is smaller than the small droplets. Here, we use correlation coefficient between the actual wind velocity and the droplet velocity to quantify the inertial effect. A correlation coefficient of 1 represents droplets can follow exactly the wind velocity and a correlation coefficient less than 1 indicates a time-lag effect between the wind and droplet velocity due to droplet inertia. Figure 3b shows that the correlation coefficient is close to 1 when the droplets are smaller than 50 μm but it decreases dramatically as droplet size increases. The correlation coefficient reaches to 0 when diameter reaches to 2000 μm. In addition, for droplets with diameters smaller than 300 μm the standard deviation of the actual droplet velocity is 0.29 ms^{-1} (blue curve, Figure 3b), which is closely to standard deviation of the background wind field. As droplet size increases, the velocity variation decreases due to droplet inertial effect.

The simulation results shown in Figure 3 suggest that small droplets are equivalently inertia-free and can instantaneously adjust their velocity to that of the imposing wind field, and thus, small cloud droplets can be treated as perfect air tracers (Kollias et al., 2001). On the other hand, large droplets (D > 0.5 mm) exhibit a time lag in their response to the air motion and an amplitude reduction (inertial-based filtering). As the observed Doppler velocity is a combined measure of the droplet velocity and the ambient air motion, this droplet inertial effect is expected to have a considerable effect on the generated radar Doppler spectrum. In the following section, we will illustrate how the radar Doppler spectrum is affected by droplet inertia and how to account for this effect in radar Doppler spectrum simulations.

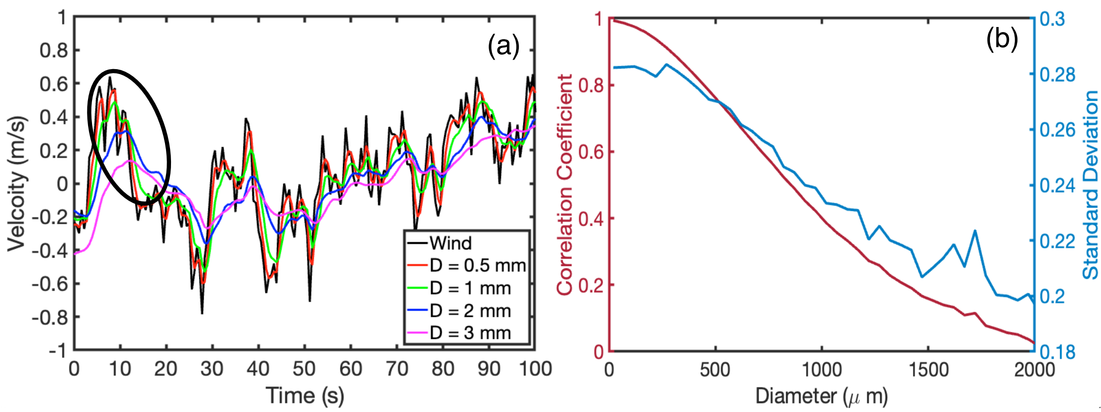

Figure 3. (a) Generated wind velocity filed (black line) and the resolved velocity for particles with diameter of 0.5mm (red line), 1mm (green line), 2mm (blue line) and 3mm (magenta line). The black oval indicates the period showing clear droplet inertia effect. (b) Left axis: correlation coefficient between wind filed and droplet velocity for different droplets size; right axis: standard deviation of the droplets velocity with different droplets size. Only droplets with size from 0 μm to 2000 μm are shown for the sake of clarity.

4 Radar Doppler spectrum Simulator

Two methodologies for simulating the radar Doppler spectrum for a given DSD and turbulence conditions are used here. The first approach is the traditional one. All droplets, independent of their sizes, are assumed to have no inertial effects and thus act like perfect tracers. In this case, the effect of turbulence is represented through the convolution of a Gaussian distribution determined by EDR and the radar specifications with the quiet air radar Doppler spectrum depending on cloud droplet size distribution(Gossard, 1981; Kollias et al., 2011, Zhu et al., 2021). A brief overview of the traditional method is described in section 4.1.

The second approach is based on the physics-based simulation described in Section 3.1 which will resolve the exact droplets velocity at each specific time. The time step of the simulation is set as 0.05s to accommodate the typical ARM cloud radar setting with appromiately 40 spectra being averaged in 2s. The corresponding Doppler spectrum at each timestep is estimated and the final Doppler spectrum is obtained by averaging the spectra over the simulation duration. The second method is designed to capture the inertia effect of the droplets and it can be used as a benchmark to validate the Doppler spectrum generated from the traditional way. It is noted that the Doppler spectrum simulator discussed in this study is only applied to the vertical pointing radars.

4.1 Traditional Doppler spectrum simulator

For a given DSD described by a number concentration *N(D)* per unit of volume in m^{-4}, the radar reflectivity $d\eta(D)$ (m^2/m^3) from particles with diameter between D to $D + dD$ can be expressed as:

$$d\eta(D) = N(D)\sigma_b(D)dD \tag{7}$$

where $\sigma_b(D)$ is the backscatter cross section (m^2) of a particle with diameter D in m. Mie scattering theory is used to estimate $\sigma_b(D)$. In this formulation, the radar power spectrum distribution is provided in terms of particle size. Profiling radar do not observe the radar backscatter-energy power spectrum $d\eta(D)$ but the radar Doppler spectra density $S_q(V_t)$ where V_t in the droplet fall velocity in ms^{-1}. The conversion from droplet size to droplet fall velocity requires a $V_t(D)$ relationship. Here, the expression proposed by (Lhermitte, 2002) is used to relate the droplets fall velocity (V_t) as a function of diameter (D):

$$V_t(D) = 920 \times (1 - exp(-6.8 \times D^2 - 4.88 \times D)) \tag{8}$$

where the unit of D and V_t is in cm and cms^{-1} respectively. Subsequently, the radar Doppler spectral density $S_q(V_t)$ in units of $m^2m^{-3}/(ms^{-1})$ is given by:

$$S_q(V_t) = \frac{d\eta}{dV_t} = \frac{d\eta}{dD}\frac{dD}{dV_t} = N(D)\sigma_b(D)\frac{dD}{dV_t} \tag{9}$$

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where $\frac{dD}{dV_t}$ is estimated from Eq. 8.

The $S_q(V_t)$ is the "quite-air" radar Doppler spectrum where the only velocity contribution is the droplet fall velocity. In the real atmosphere, the observed velocities from the radar include the turbulent motions with scales larger or smaller than that of the radar sampling volume (Kollias et al., 2001;Borque et al., 2016). One parameter that is typically used to describe turbulence intensity is the eddy dissipation rate (EDR in m^2s^{-3}). The EDR value can be converted to a radar Doppler spectrum broadening term σ_t in ms^{-1} (Borque et al., 2016). It is important to note that the σ_t value strongly depend on the radar sampling characteristics (Kollias et al., 2005). For the same EDR value, σ_t is lower for radar systems with short time dwell, narrow beamwidth and short pulse length (Borque et al., 2016). The σ_t is typically used to introduce the effect of turbulence on the radar Doppler spectrum. Under the assumption of isotropic turbulence, the distribution of the turbulent motions within the radar sampling volume can be approximated using a Gaussian function (Gossard and Strauch, 1989):

$$G(v) = \frac{1}{\sigma_t\sqrt{2\pi}} \times \exp\left(-\frac{1}{2}\left(\frac{v}{\sigma_t}\right)^2\right) \tag{10}$$

And its impact on the radar Doppler spectra is formulated using the convolution of $S_q(V_t)$ and *G(v)* as:

$$S(v) = \left(S_q * G\right)(v) = \int_{-\infty}^{\infty} S_q(u)G(v-u)du \tag{11}$$

4.2 Physics-simulation based Doppler spectrum simulator

In this approach, instead of using a Gaussian distribution to parameterize turbulence field and applying the convolution process to represent the interaction between DSD and environmental turbulence, the radar Doppler spectrum generation is based on a large number of real droplet velocity simulations for a given turbulence intensity. Droplet velocity of each diameter at each given time ($V(D,t)$) is resolved in the entire simulated time domain based on the equations described in Section 3.1. At each time step, the DSD Doppler spectrum is simulated similar as Eq 9:

$$S_t(V_t) = N(D)\sigma_b(D)\frac{dD}{dV_t} \tag{12}$$

Here $\frac{dD}{dv_t}$ is obtained from the resolved $V(D,t)$.

The final Doppler spectrum is obtained by averaging all the DSD Doppler spectra (S_t) at each timestep:

$$S(v) = \frac{1}{N_t}\sum_{n=1}^{n=N_t} S_t \qquad (13)$$

where N_t is the total simulation timesteps:

$$N_t = T \times f$$

Where T and f is the time duration and the sampling frequency for the generated turbulence wind field.

4.3 Doppler spectra comparison from two simulators

Both simulators described above are applied to emulate the Doppler spectrum observed by a 94-GHz (W-band) profiling cloud radar for a given DSD and for a set of different turbulence environments. The W-band radar parameter settings are similar with of the W-band ARM Cloud Radar (WACR) operated at the ARM observatory at the SGP site. The Nyquist velocity is set at ± 6 ms^{-1} and a 256-point Fast Fourier Transform (FFT) is used to represent the WACR Doppler spectrum. The Marshall-Palmer exponential DSD (Marshall and Palmer, 1948) with $N(D) = N_0 e^{-\Lambda D}$ is used to represent the DSD in the WACR sampling volume. N_0 is intercept parameter of 0.08 cm^{-4} and Λ is slope factor of 15 cm^{-1}, droplets diameter ranges from 10 to 4000 μm with bin size as 1 μm. Turbulence field is generated with 20 Hz frequency (f),100s duration (T) and standard deviation (σ) with 0.05 ms^{-1}, 0.25 ms^{-1}, 0.35 ms^{-1}and 0.45 ms^{-1}, respectively. The reason of applying different turbulence settings is to better illustrate the droplet inertia effect under different turbulence environment. It is expected that with increasing turbulence intensity the droplet inertia effect will be manifested in larger differences for the generated radar Doppler spectrum from two methods. The selection of W-band radar and the use of a rain DSD is because it is well known that due to non-Rayleigh scattering, the W-band radar Doppler spectra in rain contains oscillations that can be used to pinpoint the differences between the two methodologies for simulating the radar Doppler spectrum (Kollias et al., 2002;Kollias et al., 2007). For the proposed simulation approach, an adjusted time is required for droplets reaching to steady state, after which the droplets of different size fluctuate near terminal velocity with variations induced by the forced wind. The adjusted time for the aforementioned setting is around 20s but may vary according to the wind field and droplets size being applied. To generate a smooth Doppler spectra and to avoid the updraft/downdraft trend in a relatively short period, sufficient number of simulated spectra needed to be averaged. Here the simulated spectra are averaged over 50s, this time is longer than the ARM cloud radar dwell time, but is a valid consideration under the assumption that turbulence is homogenous over time.

The results shown in Figure 4 echoes the expectation. In a turbulence environment with σ_t as 0.05 ms^{-1} (Figure 4a), the two simulated spectra (red and blue line in Figure 4a) and the simulated Doppler spectrum without turbulence broadening (black line) are almost overlapping with each other, indicating that the radar Doppler spectrum shape is dominated by the DSD shape and the droplets fall velocity in weak turbulence conditions. For σ_t equal to 0.25 ms^{-1}, the broadening of the right edge of the radar Doppler spectrum in the physics-simulation approach (red line in Figure 4b) is less than that produced with the convolution approach (blue line in Figure 4b). As σ_t increases to 0.35 ms^{-1}, the large difference right edges of the spectrum from two simulators are clearly identified. Moreover, the two non-Rayleigh scattering resonant notches in the radar Doppler spectrum (Kollias et al., 2002) also exhibit considerable differences. In addition, the convoluted Doppler spectrum (obtained from the traditional method, blue line in Figure 4c) that ignore droplet inertial effect fills more the scattering valley, while the simulated spectrum (obtained from the physics-simulation approach) results to less velocity spread and thus, less filling of the scattering minima (red line in Figure 4c). In particular, the second notch around 8 ms^{-1} from the convoluted spectrum begins to fill up, while it is still clearly identified for the simulated spectrum; when σ_t reaches to 0.45 ms^{-1}, the right edge velocity difference between two spectra is larger than 1 ms^{-1}, and the second notch on the convoluted spectrum (blue line in Figure 4d) completely disappears, while is still recognizable on the simulated spectrum(red line in Figure 4d). The first notch of the simulated spectrum is also deeper than that from the traditional method. Another notable finding is the left part of Doppler spectra (velocity smaller than 4 ms^{-1}) from two simulators almost overlap with each other in different turbulence scenarios, as this part of the spectrum is mostly contributed by small droplets with negligible inertial effect, and the

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corresponding Doppler spectrum can be correctly represented by the traditional convolution process.

Compared with the three generated Doppler spectra in Figure 4, we can clearly identify the effect of droplet inertia on Doppler spectrum morphology under different turbulence environments. In general, both two simulators indicate a wider Doppler spectrum under a large turbulence condition, but with different broadening magnitudes. The traditional approach generates a wider spectra and a larger notch power in a more turbulent environment. This overestimation of the turbulence broadening effect indicates that the convolution process used in the conventional simulator is unable to accurately represent the interaction between DSD and turbulence field. On the other hand, for the small droplets, the inertial effect is negligible and the generated Doppler spectra are consistent from two approaches. It is therefore concluded that the convolution process can simulate the Doppler spectrum for the light drizzle precipitation which mostly occurs in marine boundary layer clouds but it is inadequate to emulate Doppler spectrum for the heavy precipitation in deep convection, especially in the presence of strong turbulence environment.

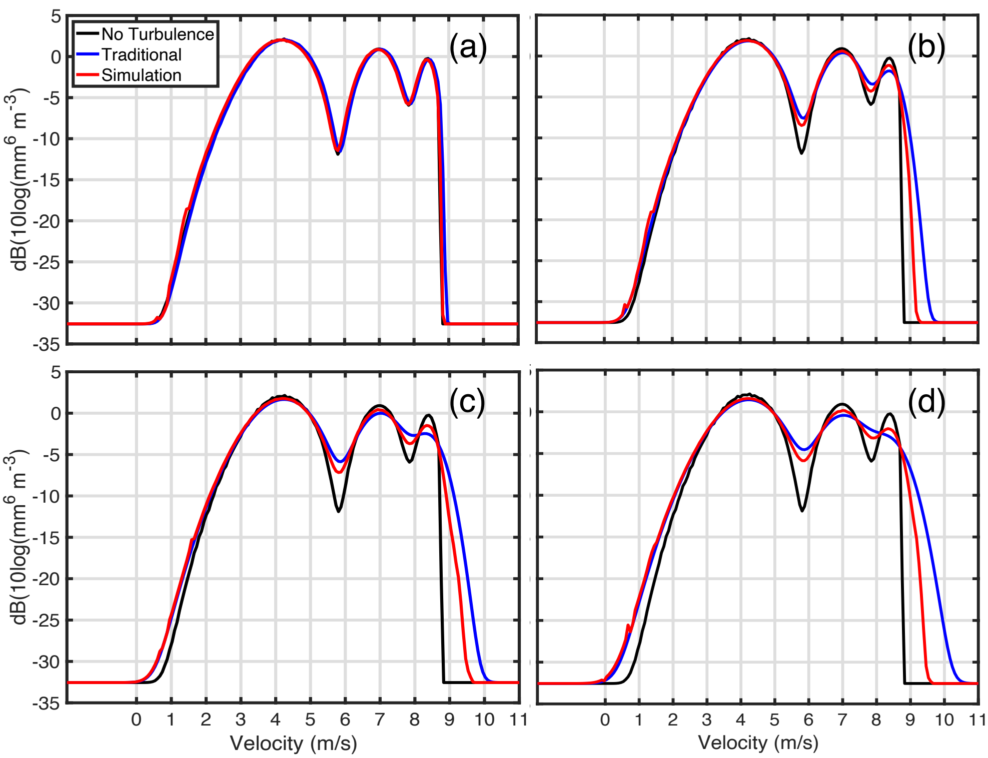

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Figure 4. Doppler spectra generated by traditional (blue line) and simulated (red line) approach for turbulence with (a) 0.05 ms^{-1}, (b) 0.25 ms^{-1}, (c) 0.35 ms^{-1}, (d) 0.45 ms^{-1}. Black line represents generated Doppler spectrum without turbulence ($\sigma_t = 0$).

5 Doppler spectra comparison with observation

Here, we use the WACR-observed Doppler spectrum during a heavy precipitation event to evaluate the two methodologies for simulating the W-band radar Doppler spectra in rain. The WACR observations were collected at the ARM SGP site on May 9, 2007. The rain DSD observed at the surface from a disdrometer is shown in Figure 5a. An exponential fit is applied to the recorded DSD to extract the Marshal-Palmer parameters that best capture the observed rain DSD (black line in Figure 5a). The WACR Doppler spectra at the lowest radar range gate (460m) are collected during the same period from 05:44 to 05:45 UTC coinciding with disdrometer observation. The turbulence parameter (σ_t) is calculated using the approach proposed by Borque et al. (2016) with average σ_t as 0.33 ms^{-1}. Based on the fitted DSD and retrieved σ_t, the simulated radar Doppler spectra from the traditional method (blue line) and from the physics-simulation method (red line) are estimated (Figure 5b).

The left part of the radar Doppler spectrum from the two simulators are similar and consistent to the observations. This is expected since the left part of the radar Doppler spectrum is occupied by small droplets and the droplet inertia is expected to be negligible. At the right part of the radar Doppler spectrum, three noticeable differences are identified (highlighted in the yellow oval). First, the right edge of the spectrum from the simulation-approach is consistent with the observed spectrum while the traditional approach generates a much wider spectrum. Second, the first notch (around 6ms^{-1}) of the simulated spectrum overlaps with the observed spectrum very well while the first notch from the traditional approach has larger spectral power related to the observation. Finally, the second notch (around 8ms^{-1}) in the simulated spectrum is distinguishable, while it completely disappears from the spectrum generated by traditional approach. It is noted, however, that both the simulated Doppler spectra near the second notch is not consistent with the real observation, these inconsistencies may be attributed to the fact that the fitted Marshal-Palmer relationship is not an adequate representation of the DSD observed from WACR.

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The spectra comparison shown in Figure 5 provides supporting evidence that the proposed physics-simulation approach can generate a more realistic Doppler spectrum as observed from real radar observation. Compared with the conventional approach, the proposed simulator has significant improvement to correctly emulate the turbulence broadening on Doppler spectrum due to the inertia effect of large droplets. This improved simulator provides a valuable tool to interpret the radar observation and to decode the precipitation DSD and environmental dynamics information contained in the Doppler spectrum.

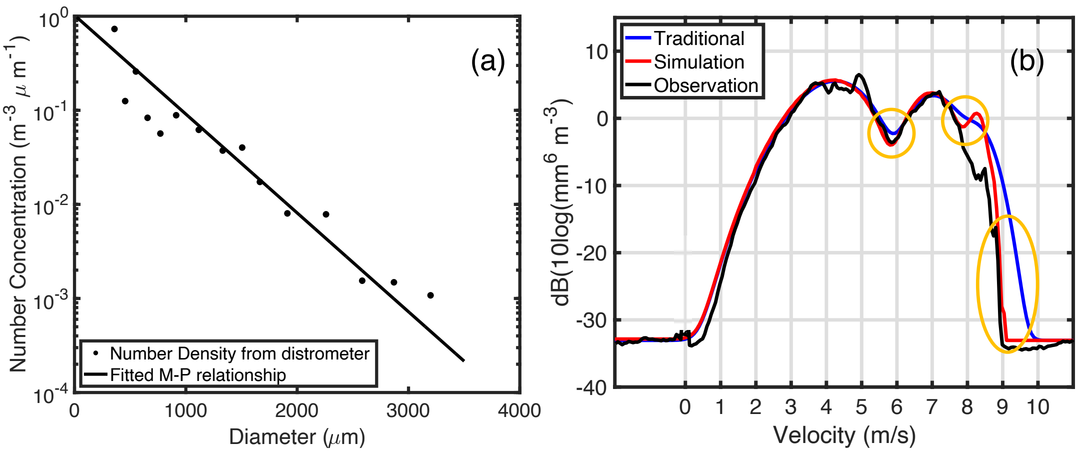

Figure 5. (a) Dots represent the observed raindrop number concentration from disdrometer at 05:44 (UTC) on May 9, 2007 on SGP site, black line represents the fitted Marshall-Palmer relationship with slope (Λ) of 24 and intercept (N_0) of 0.01 cm^{-4}. (b) Doppler spectra generated from simulation (red) and traditional (blue) method. Black line is the observed spectrum from WACR.

6 Conclusions

The radar Doppler spectra offer unprecedent capabilities for studying cloud and precipitation microphysics. Recent advancements in radar technology and signal processing have enable the continuous recording of high-quality radar Doppler spectra observations from a wide range of profiling radar systems (Kollias et al., 2005;Kollias et al., 2016). Until now, the simulation of the radar Doppler spectra was based on well-established techniques (Gossard, 1988;Kollias et al., 2011a). However, inertial effect of large droplets is constantly being neglected in the design of current simulators. Here, the impact of the droplet's inertia in the representation of atmospheric turbulence on the shape of the radar Doppler spectrum was investigated. A physics-based simulation framework is developed to resolve the droplets velocity in a given turbulence environment. It demonstrates that big droplets with large inertia will take longer time to adapt to the change of velocity filed, indicating large droplets are incapable to follow the turbulence wind as small droplets behave.

Building on the simulation framework, a new approach is proposed to emulate Doppler spectrum by resolving the velocity of each droplet during the entire time domain. The simulated W-band radar Doppler spectrum is compared with the one generated from the traditional method for a typical DSD with four different turbulence environments. The comparison indicates that the traditional Doppler simulator without considering the inertial effect generates an artificially broader spectrum and a misrepresentation of the spectrum notch power. This inertia effect becomes more noticeable as turbulence intensity increases. This finding suggests that special caution should be taken for the applicability of using convolution process to represent DSD-turbulence interaction in heavy precipitation. In the case of light precipitation mostly happening in marine boundary layer cloud, the droplet inertia effect on Doppler spectrum is negligible and the traditional simulator generates consistent results with the proposed simulator.

The WACR Doppler spectra collected from the SGP observatory are compared with the simulated spectra to testify the fidelity of the two simulators. The results show that the proposed physics-simulation approach has a better representation of the observed Doppler spectra morphology compared with the traditional simulator. The convolution process used in the conventional simulator fails to consider the large droplet inertia effect thus results in an overestimation of the turbulence broadening effect and a broader Doppler spectrum.

An accurate simulation of the Doppler spectrum is essential to improve the fundamental understanding of radar observation. The proposed Doppler spectrum simulator, with the ability to resolve the individual droplet movement, can emulate a more realistic Doppler spectrum and provide various of potential applications to the research community. For instance, neglecting droplet inertia effect on radar Doppler spectrum increases the retrieval uncertainty of the eddy dissipation rate (Nijhuis et al., 2016). This simulator can quantitively estimate the inertia effect and improve the retrieval accuracy. The forward Doppler spectra simulator can also be utilized to connect radar observation and modeling output to evaluate the model performance (Oue et al., 2020;Mech et al., 2020;Silber et al., 2022). We expect this proposed Doppler spectrum simulation

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framework can stimulate more studies to better interpret the Doppler radar observation and to advance the understanding of the microphysics and dynamics information concealed in radar Doppler spectrum.

Competing interests.

P. K. is the associate editor of AMT and the peer-review process was handled by an independent editor. The authors have no other competing interests to declare.

Code/Data availability

Ground-based data were obtained from the Atmospheric radiation measurement (ARM) user facility, a U.S. Department of Energy (DOE) Office of Science user facility managed by the Office of Biological and Environment Research.

W-Band (95 GHz) ARM Cloud Radar (WACRSPECCMASKCOPOL). 2007-05-09 to 2007-05-10, Southern Great Plains (SGP) Central Facility, Lamont, OK (C1). Compiled by K. Johnson, D. Nelson and A. Matthews. ARM Data Center. Data set accessed 2022-07-05 at http://dx.doi.org/10.5439/1025318.

Impact Disdrometer (DISDROMETER). 2007-05-09 to 2007-05-10, Southern Great Plains (SGP) Central Facility, Lamont, OK (C1). Compiled by D. Wang. ARM Data Center. Data set accessed 2022-07-05 at http://dx.doi.org/10.5439/1025181.

The codes being used in this study (section 3.2) to generate the turbulence field can be accessed from (https://github.com/ECheynet/windSim_textBased).

Author contributions

Zeen Zhu implemented the method, performed the analysis, produced the figures, and wrote the inertial draft of the manuscript. Pavlos Kollias supervised and provided advice and guidance on all aspects of the analysis and contributed to the writing of the manuscript. Fan Yang advised on results interpretation and manuscript editing. All authors read the manuscript draft and contributed comments.

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Reference

Acquistapace, C., Löhnert, U., Maahn, M., and Kollias, P.: A New Criterion to Improve Operational Drizzle Detection with Ground-Based Remote Sensing, Journal of Atmospheric and Oceanic Technology, 36, 781-801, 2019.

Atlas, D., Srivastava, R., and Sekhon, R. S.: Doppler radar characteristics of precipitation at vertical incidence, Reviews of Geophysics, 11, 1-35, 1973.

Borque, P., Luke, E., and Kollias, P.: On the unified estimation of turbulence eddy dissipation rate using Doppler cloud radars and lidars, Journal of Geophysical Research: Atmospheres, 121, 5972-5989, 2016.

Capsoni, C., D'Amico, M., and Nebuloni, R.: A multiparameter polarimetric radar simulator, Journal of Atmospheric and Oceanic Technology, 18, 1799-1809, 2001.

Deodatis, G.: Simulation of ergodic multivariate stochastic processes, Journal of engineering mechanics, 122, 778-787, 1996.

Doviak: Doppler radar and weather observations, Courier Corporation, 2006.

Gossard, E. E.: Measuring drop-size distributions in clouds with a clear-air-sensing Doppler radar, Journal of Atmospheric and Oceanic Technology, 5, 640-649, 1988.

Gossard, E. E., and Strauch, R. G.: Further guide for the retrieval of dropsize distributions in water clouds with a ground-based clear-air-sensing Doppler radar, NASA STI/Recon Technical Report N, 90, 11911, 1989.

Hildebrand, P. H., and Sekhon, R.: Objective determination of the noise level in Doppler spectra, Journal of Applied Meteorology, 13, 808-811, 1974.

Kalesse, H., Szyrmer, W., Kneifel, S., Kollias, P., and Luke, E.: Fingerprints of a riming event on cloud radar Doppler spectra: observations and modeling, Atmospheric Chemistry and Physics (Online), 16, 2016.

Khvorostyanov, V. I., and Curry, J. A.: Fall velocities of hydrometeors in the atmosphere: Refinements to a continuous analytical power law, Journal of the atmospheric sciences, 62, 4343-4357, 2005.

Kollias, Albrecht, B. A., Lhermitte, R., and Savtchenko, A.: Radar observations of updrafts, downdrafts, and turbulence in fair-weather cumuli, Journal of the atmospheric sciences, 58, 1750-1766, 2001.

Kollias, Clothiaux, E. E., Albrecht, B. A., Miller, M. A., Moran, K. P., and Johnson, K. L.: The atmospheric radiation measurement program cloud profiling radars: An evaluation of signal processing and sampling strategies, Journal of Atmospheric and Oceanic Technology, 22, 930-948, 10.1175/jtech1749.1, 2005.

Kollias, Clothiaux, E., Miller, M., Albrecht, B., Stephens, G., and Ackerman, T.: Millimeter-wavelength radars: New frontier in atmospheric cloud and precipitation research, Bulletin of the American Meteorological Society, 88, 1608-1624, 2007.

Kollias, Remillard, J., Luke, E., and Szyrmer, W.: Cloud radar Doppler spectra in drizzling stratiform clouds: 1. Forward modeling and remote sensing applications, Journal of Geophysical Research-Atmospheres, 116, 10.1029/2010jd015237, 2011a.

Kollias, Szyrmer, W., Remillard, J., and Luke, E.: Cloud radar Doppler spectra in drizzling stratiform clouds: 2. Observations and microphysical modeling of drizzle evolution, Journal of Geophysical Research-Atmospheres, 116, 10.1029/2010jd015238, 2011b.

Kollias, P., Albrecht, B. A., and Marks, F.: Why Mie? Accurate observations of vertical air velocities and raindrops using a cloud radar, Bulletin of the American Meteorological Society, 83, 1471-1483, 10.1175/bams-83-10-1471, 2002.

Kollias, P., Clothiaux, E. E., Ackerman, T. P., Albrecht, B. A., Widener, K. B., Moran, K. P., Luke, E. P., Johnson, K. L., Bharadwaj, N., and Mead, J. B.: Development and applications of ARM millimeter-wavelength cloud radars, Meteorological Monographs, 57, 17.11-17.19, 2016.

Lhermitte, R. M.: Centimeter & millimeter wavelength radars in meteorology, Lhermitte Publications, 2002.

Li, H., and Moisseev, D.: Two layers of melting ice particles within a single radar bright band: Interpretation and implications, Geophysical Research Letters, 47, e2020GL087499, 2020.

Luke, E. P., Kollias, P., Johnson, K. L., and Clothiaux, E. E.: A technique for the automatic detection of insect clutter in cloud radar returns, Journal of Atmospheric and Oceanic Technology, 25, 1498-1513, 10.1175/2007jtecha953.1, 2008.

Luke, E. P., Kollias, P., and Shupe, M. D.: Detection of supercooled liquid in mixed-phase clouds using radar Doppler spectra, Journal of Geophysical Research-Atmospheres, 115, 10.1029/2009jd012884, 2010.

Luke, E. P., Yang, F., Kollias, P., Vogelmann, A. M., and Maahn, M.: New insights into ice multiplication using remote-sensing observations of slightly supercooled mixed-phase clouds in the Arctic, Proceedings of the National Academy of Sciences, 118, e2021387118, 2021.

Maahn, M., Loehnert, U., Kollias, P., Jackson, R. C., and McFarquhar, G. M.: Developing and Evaluating Ice Cloud Parameterizations for Forward Modeling of Radar Moments Using in situ Aircraft Observations, Journal of Atmospheric and Oceanic Technology, 32, 880-903, 10.1175/jtech-d-14-00112.1, 2015.

Marshall, J. S., and Palmer, W. M. K.: The distribution of raindrops with size, Journal of meteorology, 5, 165-166, 1948.

Mech, M., Maahn, M., Kneifel, S., Ori, D., Orlandi, E., Kollias, P., Schemann, V., and Crewell, S.: PAMTRA 1.0: the Passive and Active Microwave radiative TRAnsfer tool for simulating radiometer and radar measurements of the cloudy atmosphere, Geoscientific Model Development, 13, 4229-4251, 2020.

Moisseev, D. N., and Chandrasekar, V.: Polarimetric spectral filter for adaptive clutter and noise suppression, Journal of Atmospheric and Oceanic Technology, 26, 215-228, 2009.

Mróz, K., Battaglia, A., Kneifel, S., von Terzi, L., Karrer, M., and Ori, D.: Linking rain into ice microphysics across the melting layer in stratiform rain: a closure study, Atmospheric Measurement Techniques, 14, 511-529, 2021.

Nijhuis, A. C. O., Yanovsky, F. J., Krasnov, O., Unal, C. M., Russchenberg, H. W., and Yarovoy, A.: Assessment of the rain drop inertia effect for radar-based turbulence intensity retrievals, International Journal of Microwave and Wireless Technologies, 8, 835, 2016.

Oue, M., Kollias, P., Ryzhkov, A., and Luke, E. P.: Toward exploring the synergy between cloud radar polarimetry and Doppler spectral analysis in deep cold precipitating systems in the Arctic, Journal of Geophysical Research: Atmospheres, 123, 2797-2815, 2018.

Oue, M., Tatarevic, A., Kollias, P., Wang, D., Yu, K., and Vogelmann, A.: The Cloud-resolving model Radar SIMulator (CR-SIM) Version 3.3: description and applications of a virtual observatory, Geoscientific Model Development (Print), 13, 2020.
Silber, I., Jackson, R. C., Fridlind, A. M., Ackerman, A. S., Collis, S., Verlinde, J., and Ding, J.: The Earth Model Column Collaboratory (EMC 2) v1. 1: an open-source ground-based lidar and radar instrument simulator and subcolumn generator for large-scale models, Geoscientific Model Development, 15, 901-927, 2022.
Wang, D., Bartholomew, M. J., Giangrande, S. E., and Hardin, J. C.: Analysis of Three Types of Collocated Disdrometer Measurements at the ARM Southern Great Plains Observatory, Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States). Atmospheric …, 2021.
Williams: Vertical air motion retrieved from dual-frequency profiler observations, Journal of Atmospheric and Oceanic Technology, 29, 1471-1480, 2012.
Williams, C. R., Maahn, M., Hardin, J. C., and de Boer, G.: Clutter mitigation, multiple peaks, and high-order spectral moments in 35 GHz vertically pointing radar velocity spectra, Atmospheric Measurement Techniques, 11, 4963-4980, 10.5194/amt-11-4963-2018, 2018.
Yanovsky, F.: Simulation study of 10 GHz radar backscattering from clouds, and solution of the inverse problem of atmospheric turbulence measurements, IEE Conference Publication, 1996, 188-193,
Zhu, Z., Kollias, P., Yang, F., and Luke, E.: On the estimation of in-cloud vertical air motion using radar Doppler spectra, Geophysical Research Letters, 48, e2020GL090682, 2021.
Zhu, Z., Kollias, P., Luke, E., and Yang, F.: New insights on the prevalence of drizzle in marine stratocumulus clouds based on a machine learning algorithm applied to radar Doppler spectra, Atmospheric Chemistry and Physics, 22, 7405-7416, 2022.