On the estimation of in-cloud vertical air motion using radar Doppler spectra

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Key Points

- A new, unbiased retrieval technique for the estimation of the vertical air motion in clouds based on radar Doppler spectra is presented.
- Comparison with independent measurements and simulations indicate that the retrieval technique is unbiased.
- The air motion retrieval can be used to characterize the updraft and downdraft motions in clouds as a function of environmental parameters.

Abstract

Measurements of in-cloud vertical air motion are key to quantitatively describe cloud dynamics and their role in cloud microphysics. Here, a retrieval technique for estimating the in-cloud vertical air motion using the upward edge of the radar Doppler spectrum is presented. An additional broadening correction factor that depends on the signal-to-noise ratio (SNR) is introduced. A variety of independent measurements are used to assess the performance of the new retrieval. The vertical air motion is unbiased with an uncertainty of 0.2 ms^{-1} for SNR less than 30. The properties of in-cloud vertical air motion are investigated from one-year of ground-based observations of warm marine boundary layer clouds. Clouds with higher LWP are characterized by stronger vertical air motions compared to those having lower LWP values.

Plain Language Summary

Knowledge of the strength of updrafts and downdrafts in clouds is important for understanding the role of cloud dynamics on cloud lifetime. Short-wavelength radars are capable of detecting and penetrating clouds; however, the use of the Doppler velocity to estimate the vertical air motion is not straightforward, due to the contribution of the particle sedimentation velocity. Here, a previously proposed technique is revisited, and a crucial correction is introduced. The improved retrieval technique provides unbiased vertical air motion estimates with an uncertainty of 0.2 ms^{-1}. The technique is applicable to both stratiform and cumulus clouds with and without precipitation.

1. Introduction

In-cloud vertical air motion [V_{air}] is a key parameter for determining the strength of convection, the vertical transport of heat and moisture and entrainment rate [*Donner et al.*, 2016]. These processes affect cloud fraction and lifetime [*Park et al.*, 2016]. Measurements of V_{air} are necessary for characterizing the dynamical structure of clouds [*Blyth et al.*, 2005; *Kollias et al.*, 2001] and its impact on cloud microphysics [*Kollias et al.*, 2003; *Korolev and Isaac*, 2003; *Takahashi et al.*, 2017]. The vertical air motion statistics are also important in model parameterization schemes as it relates to the cloud base buoyancy and entrainment rate [*Bretherton et al.*, 2004; *de Roode et al.*, 2012].

Despite their importance, in-cloud V_{air} measurements are sparse, especially in shallow convection. Aircraft-based in-situ V_{air} measurements are of high quality but limited to the flight level during field campaigns [*Telford and Warner*, 1962; *Wang et al.*, 2012]. Surface-based Doppler lidars have proven to be very useful in providing V_{air} measurements in the subcloud layer [*Ansmann et al.*, 2010; *Lamer and Kollias*, 2015; *Lareau et al.*, 2018]. Profiling Doppler radars, especially mm-wavelength radars have the ability to both detect and penetrate clouds and thus, provide detailed information on cloud dynamics [*Kollias et al.*, 2007a]. When pointing vertically, the observed radar Doppler velocity V_d is the sum of the V_{air} and the reflectivity-weighted particle size distribution (PSD) sedimentation velocity V_{sed}. To separate these two velocity contributions, assumptions are needed. One, widely used decomposition technique is to assume that over a long temporal averaging period (20 – 60 min) the mean V_{air} is zero. Using this assumption, empirical relationships between the radar reflectivity factor (Z) and V_{sed} can be constructed and the residual vertical air motion can be retrieved as $V_{air} = V_d - V_{sed}(Z)$ [*Delanoe et al.*, 2007; *Kalesse and Kollias*, 2013; *Protat and Williams*, 2011]. However, this approach is only valid in non-convective regimes (e.g., cirrus clouds and large-scale stratiform precipitation). Another approach is to assume that $V_{air} = V_d$ [*Gossard*, 1994; *Kollias et al.*, 2001]. This assumption is valid in non-precipitating clouds ($V_{sed} \approx 0$).

If the entire radar Doppler spectrum is available, several additional techniques have been proposed. In particular, *Wakasugi et al.* [1986] and *Williams* [2012] utilized radar Doppler spectra from radar wind profilers (RWP's) to estimate V_{air}, and more recently, *Radenz et al.* [2018] combined spectra from a RWP and a cloud radar to estimate in-cloud vertical motion. However, the RWP-based techniques require a coherent (Bragg) scattering return and their temporal-spatial resolution is poor. Finally, *Kollias et al.* [2002] took advantage of the non-Rayleigh scattering signatures on 94-GHz radar Doppler spectra in rain to retrieve the vertical air motion. The aforementioned techniques certainly advanced our ability to retrieve V_{air} in deep convective clouds with heavy precipitation; however, these methods do not apply to the warm shallow cloud systems with light precipitation (e.g., drizzling stratocumulus and shallow convection).

Here, the lower-bound method [*Battan*, 1964], the first proposed radar Doppler spectra technique for the estimation of V_{air} is revisited. According to this method, an assumption is made about the minimum drop size present in the radar scanning volume. This minimum size corresponds to a minimum fall speed, usually taken to be around 1 ms^{-1}. The difference between the assumed slower falling Doppler spectrum edge and that observed with the radar is the vertical air motion. Several factors limit the lower-bound method, particularly the sensitivity of the radar, the noise level in the Doppler spectrum and the turbulence broadening of the spectrum. In this study, the technique is applied in warm phase clouds using a sensitive mm-wavelength radar; thus, the smallest particles are cloud droplets that have negligible fall velocity [*Luke and Kollias*, 2013]. This eliminates the uncertainty introduced by the radar's sensitivity. In addition, we rely on improved estimates of the turbulence broadening [*Borque et al.*, 2016] and on well-established techniques for the removal of the spectral broadening due to turbulence, wind shear and the radar beamwidth [*Shupe et al.*, 2008]. The aforementioned advantages were implemented in the Shupe et al., 2008 study; however, the estimates of V_{air} showed a persistent bias when compared to aircraft measurements indicating the need for an additional correction. Here, the bias of the estimated V_{air} is corrected by considering the influence of signal-to-noise ratio (SNR) on spectral broadening. We will demonstrate this influence using numerical simulations and provide the correction factor as a function of SNR and turbulence. The uncertainty of the proposed V_{air} retrieval technique is demonstrated using case studies and statistical comparisons. Finally, some preliminary results are presented to show the potential application of the retrieval product.

2. Instrument and Data

The data used in this study were collected at the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) Eastern North Atlantic (ENA) observatory at Graciosa Island on the Azores archipelago. The primary instrument used in this study is the Ka-Band ARM Zenith Radar (KAZR, [*Kollias et al.*, 2016]). The KAZR is a vertically pointing 35-GHz cloud radar with a 30 m range and 2 s temporal resolution. It records the radar Doppler spectrum in 256 FFT bins with a Nyquist velocity of ± 6 ms^{-1}. Post-processing algorithms are used to estimate noise [Hildebrand and Sekhon, 1974], SNR and several Doppler moments. In addition to original spectra data, the Microscale Active Remote Sensing of Clouds (MicroARSCL) product [Kollias et al., 2007b] will be used in this study to identify the spectral upward edge location. For this study, positive velocity always represents upward motion. In addition, observations from a profiling Doppler Lidar (DL) are used. The DL operates at a wavelength of 1.5 μm and is able to measure high precision wind velocity with an uncertainty below 0.2 ms^{-1} [Frehlich, 2001]. Finally, we use Liquid Water Path (LWP) estimates from the Microwave Radiometer (MWR) with an uncertainty of 20 – 30 gm^{-2} [Turner et al., 2007].

Besides the observational products, independent retrievals are also used in the algorithm. The turbulence induced radar Doppler spectra broadening σ_t is estimated using the methodology described in [*Borque et al.*, 2016]. In the subcloud layer, drizzle microphysical retrievals are estimated using the radar-lidar technique developed by [*O'Connor et al.*, 2005]. A detailed description of the drizzle retrievals used in this study can be found in [*Lamer and Kollias*, 2019]. Finally, the V_{air} in the subcloud layer is estimated from the difference between the observed Doppler velocity and the reflectivity weighted drizzle sedimentation velocity.

3. Methodology

Cloud droplets have negligible sedimentation velocities (e.g., 0.03 ms^{-1} for a 10 μm diameter droplet), and in non-turbulent conditions, their radar Doppler spectra will resemble a very narrow delta function-like spectral peak (solid line in Fig. 1a). The location of this spectral peak in the recorded radar Doppler spectrum is the vertical air motion. However, due to the presence of turbulence and wind shear, the contribution of the observed cloud droplets to the radar Doppler spectrum is broader (dashed line in Fig. 1a). In this study we first proposed that besides turbulence and wind shear, SNR also significantly modulates upward edge broadening and should be corrected in the retrieval algorithm. Thus, the vertical air motion can be obtained from the spectrum upward edge as:

$$V_{air} = V_{edge} - \sigma_t - \sigma_s - \delta_{SNR} \quad (1)$$

Where σ_t and σ_s are the turbulence, wind shear broadening factors estimated using the [*Borque et al.*, 2016] methodology. δ_{SNR} is the SNR broadening factor and will be demonstrated and estimated in the following section. It is noted that spectrum broadening due to radar beamwidth, estimated as 0.03m/s, is smaller than other terms by an order of magnitude and is thus neglected in the algorithm.

a. Influence of SNR on spectrum upward edge

A radar Doppler spectrum simulator was developed by [*Kollias et al.*, 2011] to generate Doppler spectra once the shape of Particle Size Distribution (PSD), Liquid Water Content (LWC), median volume diameter (D_o), effective radius of cloud/drizzle and turbulence broadening (σ_t) are provided. This simulator is used to demonstrate the SNR effect on the velocity difference between the Doppler spectra edge (V_{edge}) and V_{air}. Fig. 1b shows two radar Doppler spectra generated using the same turbulence broadening σ_t of 0.2ms^{-1} but with different SNR values (0 and 15 dB, dashed and solid lines respectively). The two radar Doppler spectra are generated using the same cloud Particle Size Distribution (PSD) shape (lognormal) and effective radius (10 μm) and the different SNR values are generated by increasing the total cloud Liquid Water Content (LWC). The high SNR Doppler spectrum has a 0.2ms^{-1} more upward V_{edge} compared to the low SNR Doppler spectrum. Considering that the cloud PSD broadening effect is negligible for both simulated radar Doppler spectra and that we used the same turbulence broadening, the disagreement of upward edge was then due to the SNR broadening effect.

The SNR broadening effect on V_{edge} is explored using extensive forward radar Doppler spectra simulations with a range of SNR from -10 to +50 dB for given σ_t values of 0.1, 0.2, 0.3 and 0.4 ms^{-1}. For each σ_t scenario, a total of 10,000 Doppler spectra are generated with various SNR values. We assume the SNR broadening can be ignored for the smallest SNR (i.e. SNR = -10 dB). The SNR broadening term (δ_{SNR}) for larger SNR is calculated as the velocity displacement of the upward edge of the simulated Doppler spectra from that of the minimum SNR value (i.e. SNR = -10 dB) for a given σ_t value. The relationship between SNR and δ_{SNR} for different σ_t are shown in Fig. 1c (solid circles). A third order polynomial function was used to fit scatters for each turbulence scenario; 2^{rd} and 4^{rd} order polynomials were also tried but turned out to result in either underfitting or overfitting (supplement Fig. S1). The aforementioned forward simulations are conducted using only cloud PSD's where the SNR changes with corresponding changes in LWC. Two distinct characteristics are evident in Fig. 1c: (1) for the same turbulence, δ_{SNR} increases with SNR, corresponding to the SNR broadening effect; (2) for the same SNR value, δ_{SNR} also differs according to turbulence, indicating SNR broadening is also related to turbulence. Both of these dependences will be considered in the retrieval algorithm.

For a typical mm-wavelength radar, cloud detections rarely exceed +15 dB; thus, the assumed high-SNR cloud scenario in Fig. 1c merely aimed to show the effect of SNR broadening on cloud droplets without drizzle influence. Next, the analysis is extended to include a combination of cloud and drizzle PSDs. In the simulation, the cloud LWC varies between 0 and 1.0 gm^{-3} with a step of 0.005 gm^{-3}, the cloud effective radius is fixed to be 10 μm and the drizzle LWC is set to be 10% of the cloud LWC. The final drizzle input parameter in the simulator is the drizzle median volume diameter (D_0). The input D_0 is estimated using the following iterative process. A first estimate of D_0 is obtained using a D_0 – LWC drizzle relationship using the radar/lidar-based drizzle retrievals in the subcloud layer (black line in supplement Fig. S2). The initial D_0 estimate is used to predict the reflectivity weighted drizzle sedimentation velocity V_{dr}. Finally, V_{dr} is used to update D_0 using the V_{dr} – D_0 relationship derived from the subcloud layer drizzle retrievals (black line in supplement Fig. S3). The updated D_0 along with other drizzle and cloud input parameters are used to generate the radar Doppler spectrum of the cloud and drizzle mixture. Following the same procedure used in the case of cloud-only simulations, the δ_{SNR} is calculated and fitted with a third order polynomial function with SNR for each turbulence scenario (black lines in Fig. 1d). It can be seen that δ_{SNR} increases quickly when SNR is small, as the cloud peak signal continues to grow and pushes the edge away. Once SNR exceeds 10, the drizzle signal begins to expand but not enough to affect the upward edge; thus the black line becomes flat. After SNR exceeds 30, the drizzle signal starts to influence the spectrum edge and δ_{SNR} grows quickly again. Similar to the cloud scenario, δ_{SNR} increases with turbulence for a given SNR, which indicates δ_{SNR} should again be determined jointly by SNR and turbulence. δ_{SNR} can be described as function of SNR for each turbulence category as follows:

$$\delta_{SNR} = \begin{cases} 0.061 + 0.005 * SNR - 1.96 * 10^{-4} * SNR^2 + 3.88 * 10^{-6} * SNR^3, & \sigma_t \leq 0.1\, m/s \\ 0.154 + 0.011 * SNR - 4.84 * 10^{-4} * SNR^2 + 8.44 * 10^{-6} * SNR^3, & 0.1 < \sigma_t \leq 0.2\, m/s \\ 0.192 + 0.018 * SNR - 7.16 * 10^{-4} * SNR^2 + 1.26 * 10^{-5} * SNR^3, & 0.2 < \sigma_t \leq 0.3\, m/s \\ 0.39 + 0.032 * SNR - 1.2 * 10^{-3} * SNR^2 + 1.668 * 10^{-5} * SNR^3, & 0.3 < \sigma_t \end{cases}$$

b. Uncertainty estimation

The uncertainty in the V_{air} estimation depends on how accurately we can estimate the radar Doppler spectra broadening terms. The uncertainty of the SNR broadening term (δ_{SNR}) is mainly derived from the LWC partitioning between cloud and drizzle in the spectral simulations. To estimate this effect, sensitivity tests were applied by setting drizzle LWC to be 5, 10, 15 and 20%, of the cloud LWC. δ_{SNR} was fitted with SNR for each LWC setting and the resulting distribution, shown as the shaded area in Fig. 1d, attributed to uncertainty. It shows the uncertainty also grows with SNR, and is bounded by 0.1ms^{-1} for SNR smaller than 30, after which the uncertainty increases rapidly as strong drizzle signal starts to control V_{edge}. Considering that the uncertainty of σ_t was around 0.1 ms^{-1}, the accuracy of retrieved air velocity was safely estimated to be 0.2ms^{-1} for SNR smaller than 30.

4. Evaluation of the V_{air} retrievals

The proposed V_{air} retrieval technique has been applied to one-year of observations (2016) at the ARM ENA site. The quality of the retrievals has been evaluated using case studies of several hours duration and statistically using independent retrievals or observations. In case-based evaluations of the technique, the vertical air motion below the cloud base from the radar-lidar technique [*O'Connor et al.*, 2005] is compared to the vertical air motion retrievals above the cloud base using the proposed technique.

Fig. 2 shows an example of precipitating boundary layer clouds observed at ENA on June 18, 2017. The reflectivity and doppler velocity in the first two rows are characteristic of a typical cumulus case. Fig. 2c shows the combined air velocity above cloud base from the spectrum technique of this study and the independent velocity retrieval in the sub-cloud layer. As the drizzle retrieval is applied starting from three range gates below cloud base to eliminate range gates with a mixture of cloud and drizzle, there is a blank space below cloud base. These two products show good consistency around cloud base, with the strong upward motions at around 19:05, 19:15 and 19:35 UTC seen in both retrievals having similar magnitude. A strong upward/downward air motion core is seen in the retrieval at 19:45 UTC, which is consistent with the characteristics of shallow cumuli described by [*Kollias et al.*, 2001]. There are also inconsistencies between the two: at 19:50, the retrieved air velocity from the spectrum technique seems to underestimate the V_{air} compared with sub cloud air velocity, which may be attributed to the uncertainty of the drizzle retrieval. Overall, the continuity of vertical air motion near cloud base indicates a fairly reliable ability of the technique to retrieve air motion in cumulus clouds.

The statistical evaluation is based on two different independent datasets. First, in drizzle-free clouds (dBZ < -20), the retrieved V_{air} is compared to the mean KAZR Doppler velocity, which is a very good estimator of the vertical air motion in cases limited to drizzle free conditions. Second, as the DL is often used as a benchmark to validate vertical air velocity at cloud base [*Endo et al.*, 2019] , retrieved V_{air} is also compared to the observed vertical air motion from the DL at cloud base, as shown as Fig. 3.

In both comparisons, the retrieval agrees with observations fairly well and shows no systematic bias. 64% of the difference between the V_{air} retrieval and Doppler velocity from the KAZR are bounded by the 0.2 m/s uncertainty shown as the dashed lines (Fig. 3a); 42% difference of the V_{air} and DL velocity at cloud base are within the retrieval uncertainty (dashed lines in Fig. 3b). This comparison indicates that the proposed technique is able to properly account for the Doppler spectrum broadening. Moreover, the retrieval without SNR correction, i.e. ignoring δ_{SNR} in (1), and the spectrum upward edge (V_{edge} in (1)) are also compared with observations of KAZR Doppler velocity and DL cloud base velocity (supplement Fig. S4). The overestimated V_{air} retrieval in the comparison with the two datasets (Fig. S4a, Fig. S4c) indicates SNR broadening correction is necessary for the retrieval algorithm. An interesting finding is that a strong positive correlation between spectrum upward edge and DL observed velocity, although biased due to spectral broadening, is robust evidence to support the retrieval assumption: spectrum upward edge velocity V_{edge} is closely related to the vertical air motion.

5. Preliminary result

The retrieved V_{air} fields can be used to characterize the dynamical structure of low-level oceanic clouds. This is particularly useful to obtain the vertical air motion in shallow convective clouds with precipitation since no such ground-based observations are available. Here a preliminary, conditional sampling of the V_{air} retrievals is presented. Fig. 4 is the vertical air velocity distribution within cloud for the one-year dataset categorized by different Liquid Water Path (LWP) from 0 to 500 gm^{-2}. Height of 0 km represents cloud base and the maximum y-axis is the mean cloud top height in each LWP category. The solid line in the positive (negative) part in Fig. 4 represents the 99% percentile of upward (downward) motion, which can be interpreted as the magnitude that the air velocity can reach. For LWP less than 100 gm^{-2}, there is clearly stronger upward/downward motion near cloud top, which is consistent with the concept that radiative cooling at cloud top drives the convection in stratocumulus. For 100 gm^{-2} < LWP < 300 gm^{-2}, strong negative velocity still exists near cloud top, while stronger upward velocity appears near cloud base and gradually decreases toward cloud top (solid line in Fig. 4b), which indicates that some cumulus are mixed in this category. The dominance of cumulus in category with LWP > 300 gm^{-2} leads to strong upward and downward air motion shown in Fig. 4c.

In much prior research, vertical air velocity retrieved in clouds was limited to nonprecipitating clouds with dBZ less than -17 to satisfy the assumption of using cloud droplets as air motion tracers [*Ghate et al.*, 2010; *Lamer et al.*, 2015]. With the retrieval technique described in this study, improved and more comprehensive observational evidence can be obtained to investigate the air velocity structure and its associated warm cloud characteristics and to improve and validate the parameterization scheme in cloud model.

6. Conclusions

A new warm-cloud air vertical velocity retrieval algorithm is proposed based on KAZR-observed Doppler spectra. The novel aspect is the validation that SNR also contributes to spectral edge broadening besides turbulence and wind shear and should be corrected in order to retrieve non-biased air velocity retrievals. Spectral simulation of cloud-only scenarios is applied to demonstrate the SNR broadening effect, the results suggesting that the SNR broadening term increases with SNR and also depends on the turbulence being simulated. SNR broadening factor in the mixed cloud/drizzle scenario is estimated via numerical simulation with appropriate parameter settings. After correcting all the broadening terms from the spectrum upward edge, air vertical velocity can be retrieved with an uncertainty of 0.2 m/s for SNR smaller than 30.

Case and statistical comparisons are applied to verify the retrieved V_{air}: for one cumulus case verification, the retrieved air motion in cloud is consistent with the independent air velocity retrieval in the sub-cloud layer. The comparison also shows that the retrieval successfully captures the typical upward/downward structure in cumulus clouds. One year of statistical comparisons with KAZR and DL observations shows our velocity retrieval is reliable and the SNR correction is the final piece of the puzzle needed to correct for the traditional bias of the V_{air} retrieval based on lower-bound method. Overall, the verification demonstrates the reliability and accuracy of the retrieval algorithm and provides opportunities for the future applications.

Some preliminary results were presented to investigate the air vertical velocity distribution in cloud with different LWP categories. The results show that cloud with high LWP has strong upward/downward motion, especially near cloud base; clouds with small LWP tends to have strong upward/downward motion near cloud top; which is consistent with the typical characteristics of Sc/Cu structures. This result serves as a hint of more upcoming applications of the V_{air} retrieval to investigate the dynamical and microphysical process and their interplay in warm cloud, and further, to help to improve and develop parameterization scheme in cloud numerical model.

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Figures

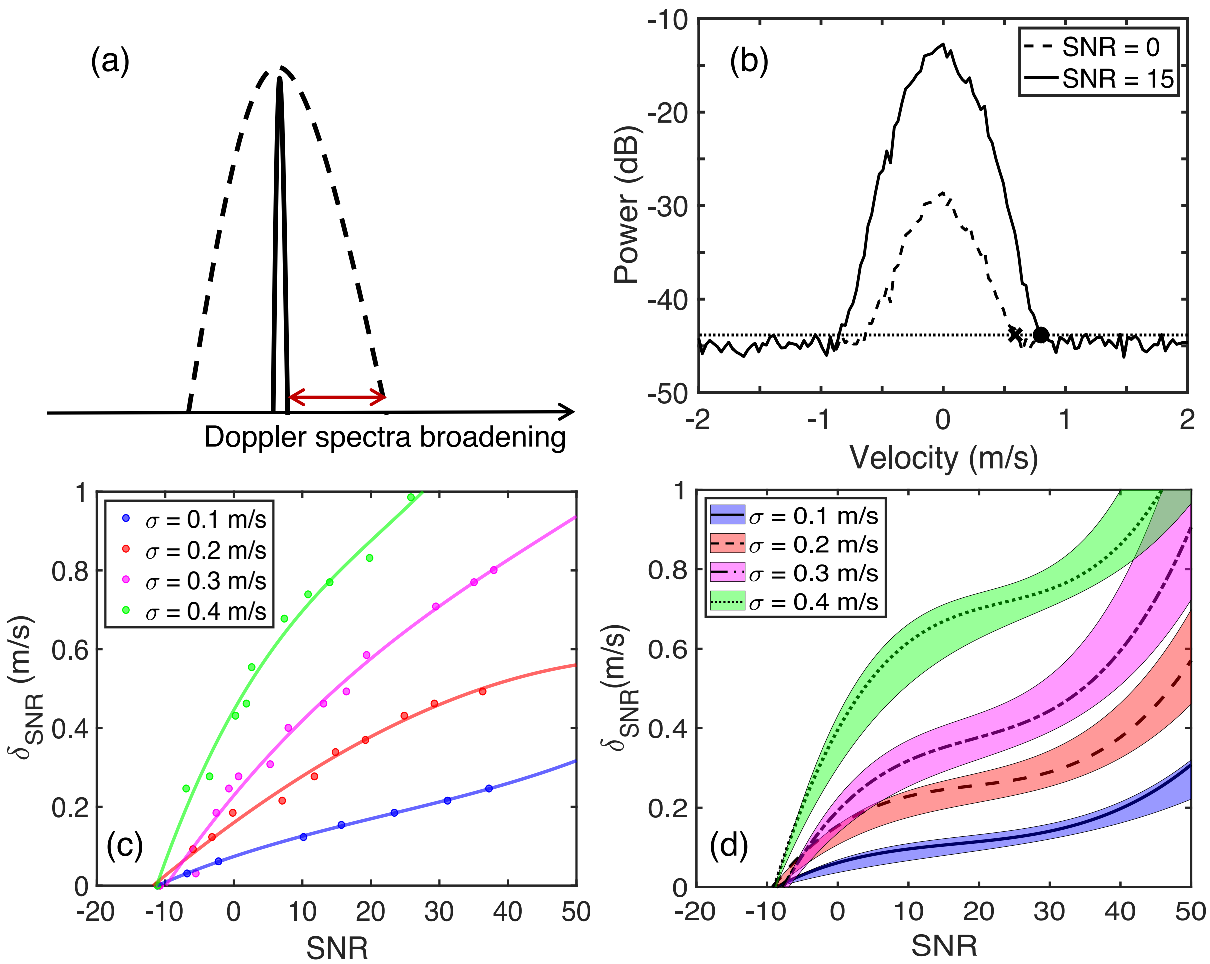

Figure 1: (a) Illustration of Doppler spectrum broadening, solid line represents Doppler spectrum of cloud droplets, dash line represents cloud Doppler spectrum with broadening effect. (b) Generated cloud spectra with SNR equals 0 (dashed line) and 15 (solid line), cross and solid circle indicates upward edge location of two spectra. (c) Cloud-only scenario: SNR broadening factor as a function of SNR for σ of 0.1 m/s (blue), 0.2m/s (red), 0.3m/s (magenta), 0.4m/s (green) respectively. (d) Same as (c) but for cloud drizzle mixing scenario. Solid line, dashed line, dash-dot line and dotted line represents the SNR broadening correction term with σ of 0.1m/s, 0.2m/s, 0.3m/s and 0.4m/s, the shading area indicates uncertainty.

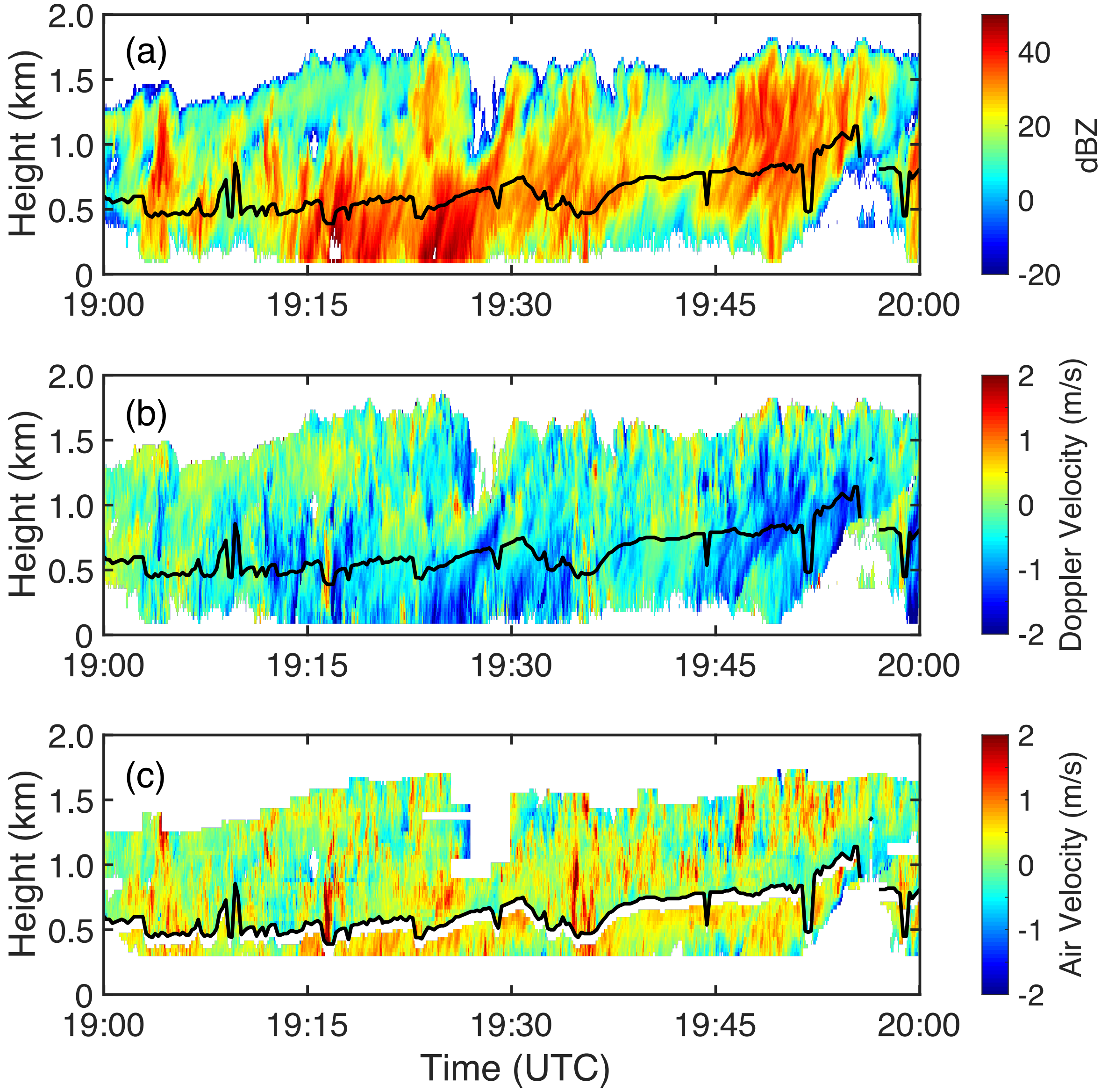

Figure 2: (a) Reflectivity (b) Doppler velocity from KAZR and (c) combined air velocity retrieval on 20170618 at ENA site. Black line represents cloud base determined by ceilometer. In (c), air velocity above cloud base are retrieved form the proposed technique, below cloud base are independent retrieval based on Radar-Lidar technique. Positive velocity represents upward motion.

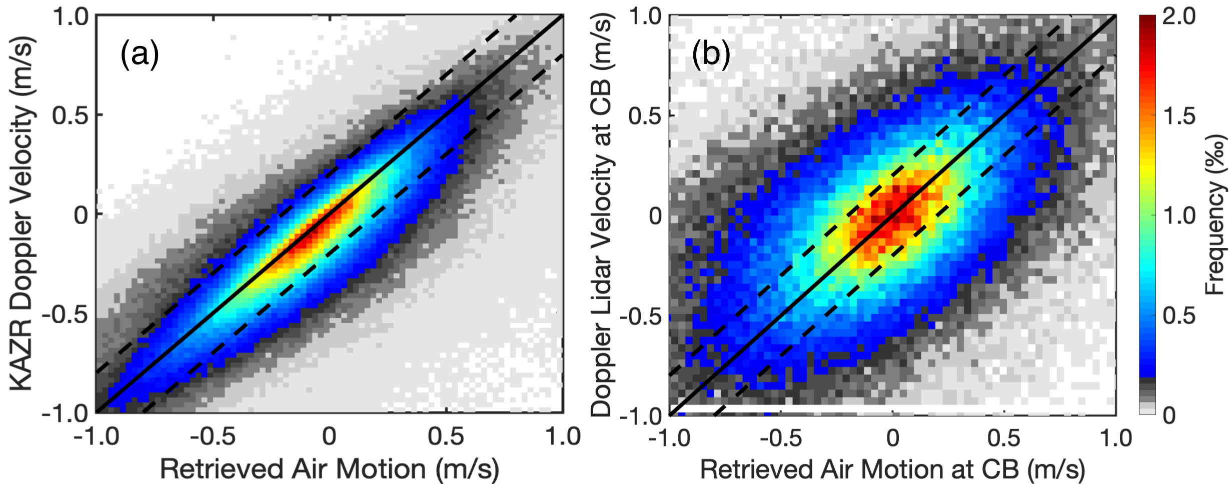

Figure 3: (a)Comparison between air velocity retrieval and in-cloud Doppler velocity from KAZR for drizzle-free cloud (dBZ <-20). (b) Comparison between air velocity retrieval and Doppler Velocity from DL at Cloud Base. The color indicates the occurrences frequency per range bin normalized by the total observable number represented by permillage. Solid line is the one-to-one line and the dashed line represents the retrieval uncertainty.

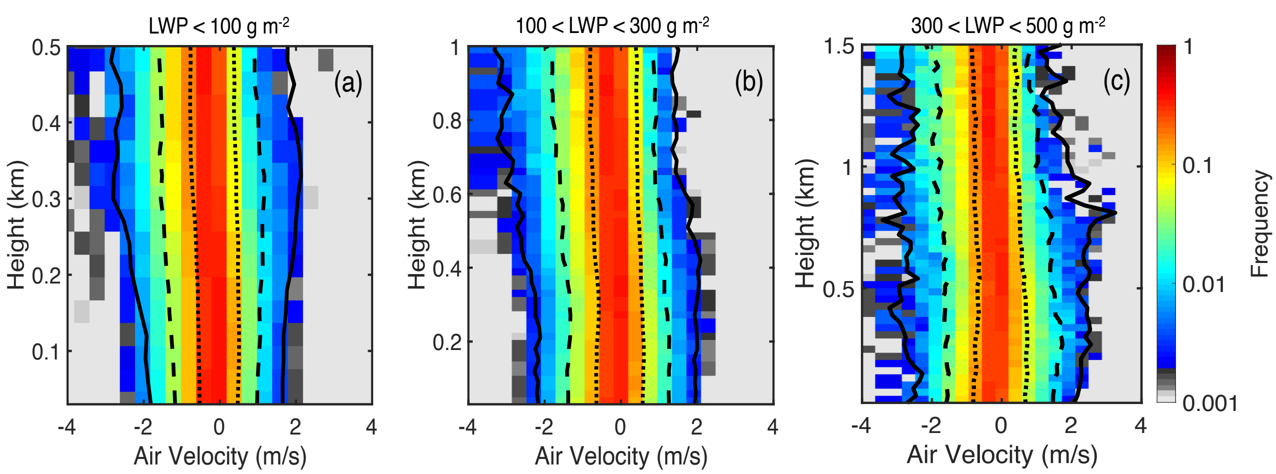

Figure 4: Air velocity distribution for (a) LWP smaller than 100 g m^{-2}, (b) 100 g m^{-2} < LWP < 300 gm^{-2}, and (c) 300 g m^{-2} < LWP < 500 gm^{-2}. The color represents the occurrences frequency per range bin normalized horizontally. Solid line, dashed line and dot line represents 99%, 95% and 75% percentile of upward (positive velocity) and downward (negative velocity) air motion respectively.