# Retrieval of the Convective Clouds Turbulence Structure Using High-Resolution Vertically Pointed Doppler Radar Data

Pinsky, Mark; Khain, Alexander; Krasnov, Oleg A.; Khain, Pavel

**DOI**
10.1109/IGARSS53475.2024.10642343

**Publication date**
2024

**Document Version**
Final published version

**Citation (APA)**
Pinsky, M., Khain, A., Krasnov, O. A., & Khain, P. (2024). *Retrieval of the Convective Clouds Turbulence Structure Using High-Resolution Vertically Pointed Doppler Radar Data*. 511-514. Paper presented at 2024 IEEE International Geoscience and Remote Sensing Symposium, IGARSS 2024, Athens, Greece. https://doi.org/10.1109/IGARSS53475.2024.10642343

IGARSS 2024 - 2024 IEEE International Geoscience and Remote Sensing Symposium | 979-8-3503-6032-5/24/$31.00 ©2024 IEEE | DOI: 10.1109/IGARSS53475.2024.10642343

# RETRIEVAL OF THE CONVECTIVE CLOUDS TURBULENCE STRUCTURE USING HIGH-RESOLUTION VERTICALLY POINTED DOPPLER RADAR DATA

*Mark Pinsky, Alexander Khain*∗ *Oleg A. Krasnov* *Pavel Khain*

The Hebrew University of Jerusalem, Department of Atmospheric Sciences, Israel

Delft University of Technology Microwave Sensing, Signals and Systems, Delft, the Netherlands

The Israel Meteorological Surface, Israel

## ABSTRACT

The high-resolution vertically pointed Doppler FMCW radar PARSAX was used for the investigation of turbulence in isolated convective clouds. The radar measures reflectivity, the mean Doppler velocity, and the spectrum width in clouds that are crossing the radar beam due to horizontal wind. The measured spectrum width is used to separate the air velocity from the sedimentation velocity of cloud drops in every reflecting volume. The transverse structure functions and the vertical velocity spectra were estimated for convective clouds which have different evolution stages and cloud top heights. The slopes of these structure functions and spectra, characterizing the kinetic energy transfer, were obtained. Three layers with different regimes of cascade energy transfer were found with an increase in the height. The first layer with a spectra slope of $-1$ was observed in the atmospheric boundary layer up to the height of 2 km. A layer with a classic Kolmogorov slope of -5/3 was observed above this layer, at a height of $2\ldots5$ km. At the upper part of the cloud appears a layer that tends to the Bolgiano-Obukhov slope of -11/5 generated by buoyancy forces influencing that part of the cloud. The measured spectra also made it possible to non-rigorously estimate the profiles of the turbulence kinetic energy, turbulent dissipation rate, and associated with velocity fluctuations turbulent diffusion coefficient.

***Index Terms***— Cu clouds, turbulence, Doppler radar

## 1. MEASURED DATA AND THEIR PROCESSING

The TU Delft PARSAX radar is an S-band polarimetric FMCW software-defined radar research platform [1] that has been working continuously in the high-resolution (3.3m) Doppler atmospheric vertical profiler mode throughout the past decade.

Four convective clouds of different cloud top heights were observed over Delft, Netherlands, on 18/6/2021, UTC 14:19 -17:30, when they were crossing the radar beam due to horizontal wind. The PARSAX radar measured the vertical profiles of reflectivity, the mean Doppler velocity, and the spectrum width in the clouds and rain every 0.512 seconds. The High-Resolution Integrated Forecast System (HRES-IFS) weather forecast model data were used to determine wind, temperature, dew point, and relative humidity during the period of clouds' existence. A strong wind reaching the speed of 20 m/s took place above the height of 1 km. The vertical profiles of temperature indicate that the atmosphere including the atmospheric boundary layer (ABL) was stable concerning dry processes, with the vertical temperature gradients of about $-7^\circ/km$. The relative humidity was high at lower heights, ranging a few kilometers. The BL was stably stratified. The high values of the cloud base height were related to the fact that these clouds precipitated intensively. The latent heat release in large clouds occurred at altitudes higher than in the small Cu clouds.

The set of analyzed clouds includes the small Cu at the dissipating stage, the medium convective cloud at the mature stage, the large Cu cloud at the decaying stage, and the very large convective cloud consisting of two sub-clouds, one of them being at the deceleration stage and the other at the developing stage. All the clouds produced precipitation. The strong wind shear led to the significant slope of the precipitation reflectivity lines below 2000 m.

The preliminary processing of the measured data consisted of two stages. The first stage is the localization of the extended time-height zones where radar signals are strong enough and reliable for further data processing. As a result, the clouds are represented by solid sections having continuous borders. These borders are shown with red lines in Fig. 1 for one of the analyzed clouds.

At the second stage of the preliminary processing, we interpret the time-height signal variations and introduce a certain correction of the mean Doppler velocity. We assume that in these cases Doppler signals are formed by the drizzle and raindrops with size obeying the two-parametric Marshall-Palmer DSD $N(D) = N_0\Lambda\exp(-\Lambda D)$, where $\Lambda$ is the slope

∗This research was supported by The Israel Science Foundation (grants 2027/17; 2635/20; 1449/22)..

parameter of the distribution, and $N_0$ is the drizzle/rain drops concentration. We suppose that parameters $N_0$ and $\Lambda$ are constant within each resolution volume that is determined by the radar's range resolution $\Delta z = 3.3m$ and by its antenna's beamwidth $\Delta\theta = 0.052$ rad while being different in different volumes.

The mean Doppler velocity measured by the radar in each resolution volume is the sum of two components: the vertical air velocity and the mean sedimentation velocity of drizzle/raindrops, which may have the same order of magnitudes. The second component is determined by the DSD parameters. We used the simultaneously measured Doppler spectrum width approach [2] to separate the air velocity from the mean Doppler velocity. For the correction algorithm, an analytical relationship between the mean falling velocity of drizzle/raindrops and their diameter has been applied. The results of this correction show that it leads to a significant velocities increase in updraft areas, compared to similar areas in the mean Doppler velocity fields (see Figs. 1, bottom panel).

Turbulence is characterized by parameters and functions associated with the spatial fluctuations of velocity. However, a vertically pointed Doppler radar provides only a time series of signals, which have to be converted into a space domain using the hypothesis of frozen turbulence. It assumes that the turbulent fluctuations cross the radar beam at the mean wind velocity without significant changes. This velocity of the horizontal transfer was taken from the HRES-IFS model. Spatial and time variations of the measured vertical velocity are related to each other as $w(t) = w\left(x - t\sqrt{U^2 + V^2}\right)$, where $U$ and $V$ are the model components of horizontal wind velocity. The resulting horizontal resolution of measurements $\delta_x = \max\left\{\Delta t\sqrt{U^2(z) + V^2(z)}, z \times \Delta\theta\right\}$ is determined by the maximum of these two dependent on height $z$.

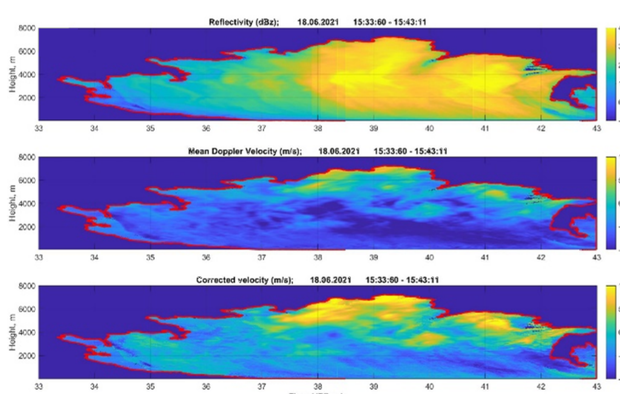


**Fig. 1**. An example of the fields of radar reflectivity, the measured and corrected mean vertical velocities, obtained for the case of a secluded large convective cloud. The red contours mark the boundaries of data for further analysis.

## 2. ANALYSIS OF TURBULENT STRUCTURE FUNCTIONS

A vertically pointing Doppler radar can measure the transverse structure function $D_{NN}(r) = \left\langle [w(x) - w(x+r)]^2 \right\rangle$ using the frozen turbulence hypothesis, since the radar beam is perpendicular to the motion of the cloud with the horizontal wind. In the case of homogeneous and isotropic turbulence, the longitudinal and the transverse structure functions within the turbulence inertial subrange are proportional to $r^{2/3}$. It is typical for the Kolmogorov type of energy cascade where the largest vortexes are divided into smaller ones, and this division continues down to millimeter-sized vortexes, whose kinetic energy is transferred to heat. The measured turbulence is anisotropic due to the impact of both the horizontal ground surface leading to a stratified boundary layer, and the buoyancy force acting in the vertical direction during the cloud development. For weakly anisotropic turbulence, the transverse and longitudinal structure functions have the same slopes that characterize the turbulent energy cascade. If the transverse structure functions are approximated by the power law of $D_{NN}(r) = D_0 r^{\eta}$, the energy spectra are also approximated by a power law $F(k) = F_0 k^{\mu}$. The power exponents are related as $\mu = -(\eta + 1)$.

The vertical profiles of these slopes were calculated using the corrected fields of the vertical velocity (Fig. 1, bottom panel). For this purpose, at every height, we cut out a horizontal segment long enough to estimate the averaged transverse structure function over this segment and then fit it using the power function. The vertical profiles of $D_{NN}(r)$ and $F_{NN}(k)$ slopes, obtained for the analyzed secluded convective clouds, allow us to draw important conclusions about the existence of three different regimes in turbulent energy transfer, following each other as the height increases. The profiles were measured both inside and under the convective clouds.

For the small Cu, the slope agrees with the classical Kolmogorov's 2/3 $D_{NN}(r)$ slope (the -5/3 slope of the energy spectra). This slope is associated with hydrodynamic instability of turbulent vortices, leading to their breaking into smaller ones. In the larger convective clouds, all three regimes are seen. The first regime corresponding to the structure-function slope below $2/3$ is observed in the ABL up to the height of 2 km. This slope can be associated with the spectral slope $-1$, obtained in several studies. We believe that this slope is related to the stable stratification of the ABL. Above altitudes of 2 km, the change of slopes takes place reaching the value $2/3$ (the $-5/3$ slope of the energy spectra) and continues increasing up to a slope equal to $6/5$. The corresponding spectra obey the so called Bolgiano-Obukhov slope, which is equal to $-11/5$. The slope of this type is usually related to buoyancy-generated convection turbulence. Unlike turbulence initiated by hydrodynamic instability, buoyancy forces contribute energy to all the scales belonging to the inertial sub-range of turbulence. The strongest effect of buoyancy forces on cloud dynamics is observed in updraft zones.

## 3. ANALYSIS OF ENERGETIC SPECTRA

To estimate the spectra, we use the field of corrected measured vertical velocity to calculate the averaged periodogram. A set of wave numbers is obtained from a set of frequencies using the frozen turbulence hypothesis. The averaging is carried out using several velocity series corresponding to several horizontal segments taken from the neighboring height levels. The way we choose segments for averaging allows us to keep the vertical resolution high enough (below 40 m), using the advantages of a very high (3.3m) radar measurements resolution. The averaged periodogram provides a very good estimate of the spectrum, since it does not distort the spectrum shape, i.e., does not introduce a bias while generating only small random errors. It allows us to estimate the spectrum slope which is a very important characteristic of turbulence. An example of spectrum estimation is shown in log-log coordinates in Fig.2 as the blue line. The horizontal section contains white noise within the range of the largest wave numbers. This section appears due to averaging Doppler signals in the horizontal direction, while the length of this section increases with height. We did not use the corresponding wave numbers range (e.g. 0.03-0.055 $\mathrm{m}^{-1}$ in Fig.2) for processing the spectrum.

We approximate the estimated spectra by a power dependence corresponding to the turbulent law $F(k) = F_0 k^{\mu}$. An example of approximation taken at the height of 3.5 km is shown in Fig.2 with the straight red line. We compared the slope of the approximated spectrum with Kolmogorov $-5/3$ and Bolgiano-Obukhov $-11/5$ slopes, also shown in Fig.2. In this particular case, the slope is closer to $-11/5$.

**Profiles of the spectral slope.** The first turbulence parameter to be estimated using the spectrum approximation was the spectrum slope $\mu(z)$ in log–log coordinates. The profiles of this parameter were evaluated using the approximated structure functions. The two types of estimations might lead to slightly different results since estimation using structure function is based on data falling within the turbulence inertial subrange (the corresponding spatial scales generally do not exceed 200 m). At the same time, estimations of spectra slopes based on the averaged periodogram approximations use scales from 100 m up to 1000 m. We have not found a scale of a distinct separation between large-scale convective motions and turbulent motions and, therefore, could not calculate the external scale of turbulence. These estimations also allow us to estimate the slopes of the structure functions $\eta = -(\mu + 1)$.

The vertical profiles of slopes, obtained in the secluded large convective cloud are shown in Fig. 3. In general, a good agreement between the two types of independent estimations (using $D_{NN}(r)$ and $F_{NN}(k)$) is observed. We see the existence of three different regimes of energy transfer in the wave numbers space, both inside and below the cumulus clouds. This fact confirms the high reliability of the conclusions since both methods are independent. However, the slopes of the structure function, estimated using the spectra approximation are, as a rule, slightly lower than that estimated from the structure functions fitting. This fact can be explained by the difference in spatial scale intervals used for estimations.

**Non-rigorously estimate the profiles of some turbulent parameters.** The vertical profiles of a few turbulent parameters such as the turbulence kinetic energy (TKE), turbulent dissipation rate, and turbulent diffusion coefficient have been estimated using the parameters of fitted spectra. These estimations include large *a priori* uncertainties, e.g. in the external turbulent scale, which has to be set to a reasonable value. All our estimations are based entirely on the measurements

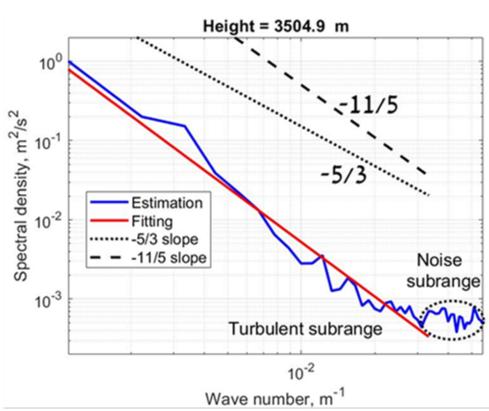


**Fig. 2**. An example of spectral density estimation (blue) and its approximation (red), calculated for the large convective cloud at the height of 3500 m. The Kolmogorov $-5/3$ and Bolgiano-Obukhov $-11/5$ slopes are also shown.

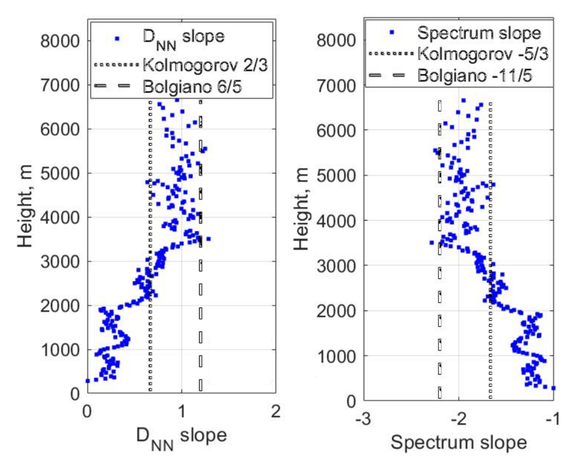


**Fig. 3**. An example of vertical profiles of $D_{NN}(r)$ and $F(k)$ slopes, obtained using $F(k)$ fitting in the secluded large convective cloud that is shown in Fig. 1.

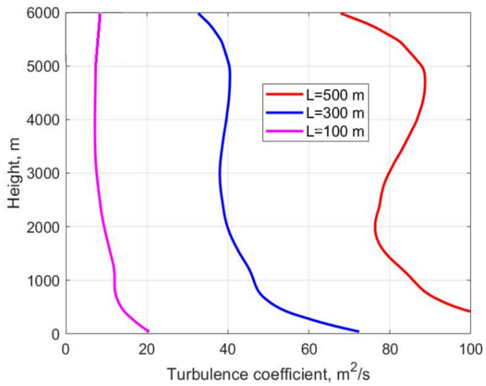


**Fig. 4**. An example of vertical profiles of the turbulent diffusion coefficient, evaluated using the estimated spectra in the secluded large convective cloud that are shown in Fig. 1.

of the vertical velocity component, which nevertheless allows us to draw some physical conclusions. The parameters essentially depend on the external turbulent scale that is associated with the size of vortices arising as a result of the instability of cloud convection. Several studies determined it in convective clouds as 1/15- 1/10 of the cloud size. Applying this approach, in analyzed cases the external scale changes from 100 m for the small Cu to 500 m for the very large convective cloud. Thus, three values of the external turbulent scales (100, 300, 500 m) have been used for turbulence parameters evaluation.

The profiles of TKE show two maxima: one in the ABL, and the other near cloud tops. The maximum of TKE at the cloud top level was previously found in 10-m resolution LES [4]. The maximum below 2 km can be attributed to the intensive turbulence production in the ABL due to the strong wind shear. The similar maxima in the turbulent dissipation rate profiles also can be explained by wind shears near the ground surface, and by the buoyancy at high levels, respectively. The values of the turbulent dissipation rate increase with the cloud size increasing, being for the small and the medium clouds in reasonable agreement with estimations obtained from observations and numerical LES. The profiles of the turbulent diffusion coefficient for three external turbulence scales are presented in Fig. 4 and are in good agreement with values expected for convective clouds. At the same time, the LES shows that such a profile in Cu monotonically increases with height reaching the maximum at the cloud top. Fig. 4 shows that such maximum near cloud top takes place only at the external turbulence scale of 100 m. As expected, the turbulent coefficients in larger clouds are higher than those in the small Cu, being still quite close to the medium clouds. The magnitudes of the turbulent coefficients do not contradict the general expectations concerning the intensity of turbulence in convective clouds and agree well with those obtained for the case of small Cu in LES with a 10 m resolution [4].

## 4. CONCLUSIONS

A high-resolution vertically pointing Doppler FMCW radar PARSAX was used to study the turbulence in isolated convective clouds. The high-sensitivity radar continuously observes the hydrometeors moving through the vertically directed antenna's beam with the horizontal wind, providing profiles of reflectivity, the mean Doppler velocity, and the spectrum width every 0.512 seconds with a height resolution of 3.3 m. The measured spectrum width was used to separate the air velocity from the sedimentation velocity of drizzle drops and raindrops in each reflecting volume using the proposed algorithm that is based on the assumption of Marshall-Palmer DSD for drizzle and raindrops. Four convective clouds of different sizes, evolution stages, and cloud top heights were investigated using the radar and HRES-IFS weather forecast model data. The transverse structure functions and the measured spectra of vertical velocity were estimated to obtain their slopes that characterize the turbulence. Three different regimes of a cascade energy transfer were found, following each other with increasing altitude above the ground. The first one corresponds to the spectra slope $-1$ and was observed in the BL, below 2 km. It agrees with typical values for the stably stratified BL. Higher, at $2-3$ km above the cloud base, a transfer to the classical Kolmogorov slope of $-5/3$ was found, which with further height increasing approaches the Bolgiano-Obukhov slope of $-11/5$. We attribute this last regime to the effect of high buoyancy forces contributing to the generation of turbulence within a wide range of scales. The agreement of the turbulent parameters with earlier data and assumptions indicates that the method applied in this study is reliable, and data of a single vertically pointing Doppler radar can be used for retrieval of important parameters of cloud turbulence.

## 5. REFERENCES

[1] O.A. Krasnov, L.P. Ligthart, Z. Li, P. Lys, and F. van der Zwan, ”The PARSAX - full polarimetric FMCW radar with dual-orthogonal signals,” *2008 European Radar Conference*, pp. 84-87, 2008.

[2] D. Atlas, R.C. Srivastava, and R.S. Sekhon, ”Doppler Radar Characteristics of Precipitation at Vertical Incidence,” *Rev. Geop. Space Phys*, vol. 11, pp. 1-35, 1973.

[3] M. Pinsky, O.A. Krasnov, H.W.J. Russchenberg and A. Khain, ”An investigation of turbulent structure of cloud-capped mixed layer by means of a Doppler radar,” *J. Appl. Met. Clim.*, vol.49, pp.1170-1190, 2010.

[4] M. Pinsky and A. Khain, ”Convective and turbulent motions in non-precipitating Cu. Part III: Characteristics of turbulence motions,” *J. Atmos. Sci.*, vol.80, pp.457-471, 2023.