Response to Reviewers' comments

Dear Editors and Reviewers:

Thank you for your letter and for the Reviewers' comments concerning our manuscript entitled "Turbulence parameters in the troposphere–lower stratosphere observed by Beijing MST radar" (ID: remotesensing-1551879). Those comments are all valuable and very helpful for revising and improving our paper, and they also provided important guidance for us to improve our research. We appreciate for Editors and Reviewers' warm work earnestly. We have studied each comment carefully and have made required corrections. We hope that the present modification would meet with approval. The main corrections in the paper and the responds to the Reviewer's comments are as follows:

Reviewer 1

Reviewer's comment on the manuscript:

Investigations of the altitude profile of turbulence parameters and their variations provide an essential input in understanding the development of clouds and precipitation, the coupling between troposphere- lower stratosphere, dynamic processes of various spatial scales in the atmosphere. In the present time the relevant research by using MST radar data to analyze the seasonal and diurnal variation features of turbulence parameters has been limited to just a few regions, owing to the MST radar can support the weather and climate forecasting models

The manuscript is aimed on the investigation of statistical features of turbulence parameters at different atmospheric layers. The results are based on data observed by Beijing's MST radar from 2012 to 2014 by using the spectral width method to calculate the turbulence energy dissipation rate and vertical turbulence diffusion coefficient. Authors have analyzed in detail the seasonal and annual variations of the turbulence energy dissipation rate and vertical turbulence diffusion coefficient at different heights. The comparison between the atmospheric turbulence parameters and atmospheric stability was also carried out.

The manuscript is well organized and written. It provides new results which are important for the studies of turbulence in the troposphere - lower stratosphere system and for weather and climate forecasting models. The manuscript meets the criteria for the publication in the Remote Sensing in a full measure.

I recommend the manuscript for a publication in the present form.

Response:

We are very grateful for your review and affirmation of our work.

Response to Reviewer 2

Comments and Suggestions for Authors

The paper discusses the distributions of the turbulence energy dissipation rate and the vertical turbulence diffusion coefficient over Beijing, from the Doppler radar observations made in 2012-2014. The data interpretation is based on the spectral method.

The paper in its current form is very much like a technical report. In order to decide whether it is worth publishing, we have to understand which of the authors' points would be interesting to the journal audience. Are these the turbulence parameters in the specific area or some conclusions that can be valid in other areas? Or the methods that can be applied in other areas?

So my opinion is that the paper needs more discussion of the methods and their physical basics. To this end, the authors must provide the answers to the following questions:

1. What are the physical assumptions behind the applied methods? How can we be sure that these assumptions hold? The methods

2. How do we know that the turbulence under consideration is really isotropic Kolmogorov turbulence? The authors say that "most current research on radar-based turbulent parameters is based on the Kolmogorov assumption of isotropic turbulence in the inertial range [4-6]". Unfortunately, references [4-6] cannot support this statement: they are classical theoretical works. Two of these works [5,6] are different

publications/editions of the same book by Tatarskii.

We sincerely thank the reviewer for providing valuable comments and suggestions for further improvement of the paper. In the revised version of the manuscript, all the above suggestions have been incorporated as well as the specific comments of the reviewer.

Questions:

"……we have to understand which of the authors' points would be interesting to the journal audience. Are these the turbulence parameters in the specific area or some conclusions that can be valid in other areas? Or the methods that can be applied in other areas?

Response: Thank you very much for your comments and questions, which let us realize that we haven't stated the value of this paper clear and direct.

Firstly, this paper's investigation and results contribute to a better understanding of the turbulence characteristics and micro-scale atmospheric dynamics in the troposphere and stratosphere at mid-latitude based on the high spatio-temporal resolution MST radar remote sensing data. Since observing turbulence in the troposphere and stratosphere is not easy and lacks device and methods， the characteristics of turbulence parameters revealed by the MST radar are of great value. There are limited MST radars around the world, the results of the turbulence parameters obtained from the Beijing MST radar are representative. Relevant studies have been conducted on calculating turbulence parameters in the troposphere–lower stratosphere at different latitudes by using atmospheric radars, and we have made a non-exhaustive list of the existing results in this paper, as shown in Table 1.

Table 1. Turbulence parameters in the troposphere–lower stratosphere from different radars.

Station	Altitude (range resolution)	Turbulence parameter	Citation

PANSY (69.00°S, 39.35°E)	1.5–19 km (150 m)	log(ε) −5 to −3 m^2 s^{-3}	Khoma et al. 2019 [1]
MARRSY (69.03°N, 16.04°E)	5–17 km (300 m)	log(ε): −7 to −2 m^2 s^{-3} median ε 1.13×10^{-4} to 2.50×10^{-4} m^2 s^{-3}	Li et al. 2016 [2]
Harrow (42.04°N, 82.89°W)	1.5–11 km (500 m)	log(ε): −4 to −2 m^2 s^{-3}	Kantha and Hocking 2011 [3]
MU (35°N, 136°E)	Troposphere 5–20 km (150 m)	log(K_z) 0 m^2 s^{-1} log(K_z) −0.7 to 0.3 m^2 s^{-1}	Fukao et al. 1994 [4] Yamanaka et al. 1994, Kurosaki et al. 1996 [5,6]
VBG (34°46'48"N, 120°33'36"W)	2–21 km (150 m)	median log(ε): −3.7 (8 km) to −3.1 m^2 s^{-3} (2/21 km)	Nastrom and Eaton 2005 [7]
WSMR (32°N, 106°W)	5–20 km (150 m)	median/mean log(ε): −3.5 to −2.5 m^2 s^{-3}	Nastrom and Eaton 1997 [8,9]
ARIES ST (28.4°N, 79.5°E)	3–12 km (150 m)	mean log(ε): −3 to −2 m^2 s^{-3}	Jaiswal et al. 2020 [10]
Gadanki (13.5°N, 79.2°E)	7.5–21 km (150 m)	median log(ε): −4 to −3 m^2 s^{-3}	Rao et al. 2001 [11,12]
Tirupati (13.47°N, 79.1°E)	4–19 km (150 m)	log(ε): −6 to −3 m^2 s^{-3}	Rao et al. 1997 [13]
Pune (UHF) (18°32'N, 73°51'E)	1.05–10.35 km (300 m)	mean log(ε): −6.4 to −3 m^2 s^{-3}	Singh et al. 2008 [14]

Conclusions such as the seasonal variation characteristics are different in troposphere and stratosphere, and the turbulence intensity in the lower-stratosphere is the main impact factor for the turbulence parameters et al. provide new results in the troposphere-
90 lower stratosphere research field. These conclusions can be verified if it is valid in other areas by using other MST radars, ST radars and radiosondes. The results are also important for weather and climate forecasting models. For example, the vertical turbulence diffusion coefficient profiles are needed in the models.

95 On the other hand, the method we used to calculate turbulence parameters can be applied to wind profiler radars, which have the same detection principles but uses shorter electromagnetic waves. The analysis method, such as comparing the atmospheric turbulence parameters and atmospheric stability to reveal the influence

factors of the turbulence parameters, is essential and can be applied to wind profilers to better understand the turbulence characteristics in the boundary layer and troposphere.

All those as described above would be interesting to the journal audience.

The answers to two specific questions are as following:

Q1. What are the physical assumptions behind the applied methods? How can we be sure that these assumptions hold the methods?

Response:

This question mainly includes two points: physical assumptions of spectral method and the relationship between turbulence intensity and turbulence parameters.

1.1 Physical assumptions of spectral method — All the scatter is due to turbulence.

1.1.1 The radar echo power spectrum broadened by turbulence

Radar echo is the backscattering result of all scattering cells in the radar sampling space. For a given range library, due to coherent integration and incoherent integration of the radar, the random motion of the scattering cells is shown as the random distribution of its Doppler velocity near the mean wind speed. That is, the Doppler spectrum of the radar is broadened. The Doppler spectral width contains atmospheric turbulence information and can be used to calculate the macro parameters of turbulence.

The present study shows that the spectrum width σ_o in the radar power spectrum has a turbulent contribution σ_t (standard deviation of radial wind speed) and non-turbulent contribution σ_u, such as beam broadening σ_b(Fig7.7, Fukao 2014 [15]) and shear broadening σ_s(Fig7.8, Fukao 2014 [15]), under the condition of no interference signal:

$$\sigma_o^2 = \sigma_t^2 + \sigma_u^2 = \sigma_t^2 + \sigma_s^2 + \sigma_b^2 + \sigma^2 \quad (1)$$

where σ^2 refers to the influence of other factors, such as gravity waves, which will also cause the spectral width to increase in the total acquisition time of the radar (Fig7.9, Fukao 2014 [15]).

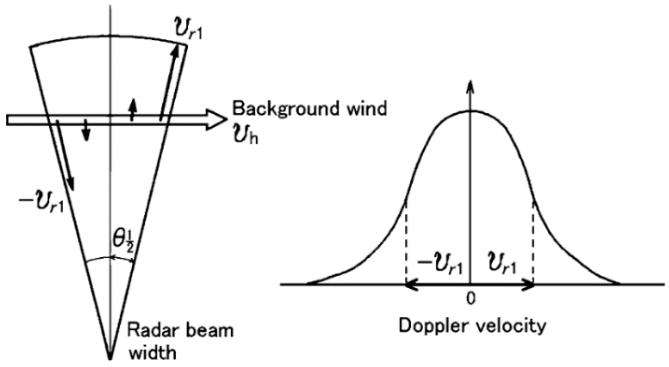


Fig. 7.7 Conceptual diagram of the broadening of the spectrum width due to the antenna beam pattern

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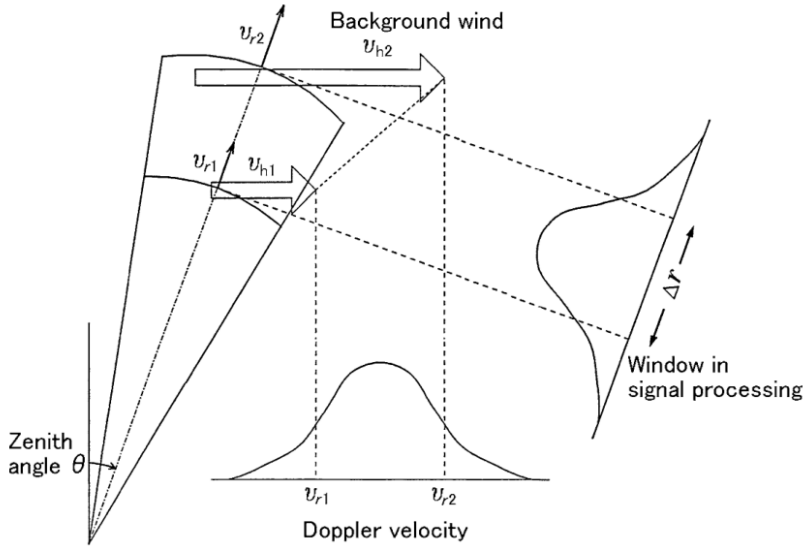


Fig. 7.8 Conceptual diagram of the broadening of the spectrum width due to horizontal shear

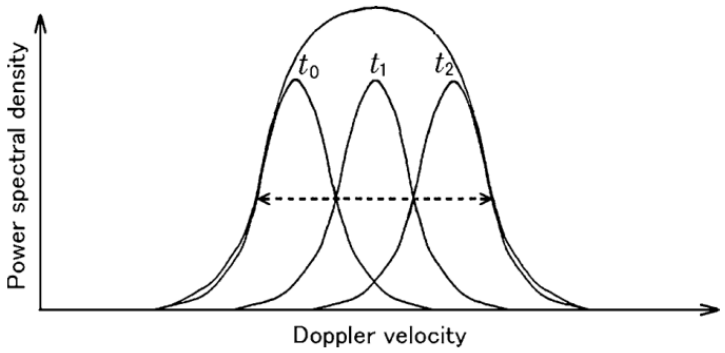


Fig. 7.9 Conceptual diagram of the broadening of spectrum width due to time changes of the wind of gravity waves within the beam. The width of the composite Doppler spectrum obtained after incoherent integrations is indicated by the *dashed line*

(Fukao 2014 [15])

A more detailed discussion of the contributions of the observed spectral width and the formulas for calculation can be found in Hocking 1983, 1985 [16] [17]; Nastrom 1997 [18]; Dehghan and Hocking (2011) [19]; Fukao. 2014 [15].

1.1.2 Turbulent scattering and specular reflection

Of course, all the above mentioned are radar signals obtained by turbulent scattering. In fact, in reality, radar is often affected by specular reflection (Fresnel scattering), and the oblique beam is less affected by specular reflection than the vertical beam. Therefore, spectral width data of oblique beam is selected in this paper. For a more detailed discussion of the relevant theories of Fresnel scattering, see the work of Gage et al.(1982) [20].

1.2 The relationship between turbulence intensity and turbulence parameters

If the turbulence detected is isotropic (i.e. the reviewer's second question), σ_t^2 (radial wind speed variance) represents the turbulence intensity. For the isotropic Kolmogorov turbulence, the relation between the turbulent energy dissipation rate ε and σ_t^2 is as follows (Hocking, 1983 [16]; Weinstock, 1981) [21]:

$$\varepsilon = \mathrm{c}_1 \sigma_t^2 N, \tag{2}$$

where c_1 is a constant and N is the B–V frequency (s^{-1}). For a stably stratified

atmosphere, σ_t^2 has the following relationship with ε (Weinstock, 1981 [21]): $\varepsilon = A^{-\frac{3}{2}} N \sigma_t^2$, where A is the Kolmogorov constant, taking A = 1.6, $c_1 \approx 0.49$. $N^2 = g\frac{dln(\theta)}{dz}$, and the potential temperature θ can be calculated by the equation $\theta = T\left(\frac{1000}{P}\right)^{0.286}$, where T is the temperature (K) and P is atmospheric pressure (hPa).

Kz is closely related to ε (Fukao et al., 1994 [4]; Nastrom and Eaton, 1997 [9]; Rao et al., 2001 [11]). The equation is as follows:

$$K_z = c_2 \varepsilon N^{-2} = c_1 c_2 N^{-1} \sigma_t^2, \quad (3)$$

where ε is the dissipation rate of turbulent energy, N is the B–V frequency, and c_2 is a constant. In this paper, c_2 = 0.3 (Fukao et al., 1994[4]).

The specific derivation of the formula for the relationship between turbulence intensity and turbulence parameters can be seen in the work of Hocking, 1983[16]; Weinstock, 1981[21]; Fukao et al., 1994[4]; Nastrom and Eaton, 1997[18]; Rao et al., 2001[11,12] et al.

The modified content revised version(clean) for Q1 is as follows:

Line N0:170-175 (Section2.2, Page No:5 of 18) Radar echo is the backscattering result of all scattering cells in the radar sampling space. For a given range bin, due to coherent integration and incoherent integration of the radar, the random motion of the scattering cells is shown as the random distribution of its Doppler velocity near the mean wind speed. That is, the Doppler spectrum of the radar is broadened. The Doppler spectral width contains atmospheric turbulence information and can be used to calculate the parameters of turbulence.

Q2. How do we know that the turbulence under consideration is really isotropic Kolmogorov turbulence? The authors say that "most current research on radar-based turbulent parameters is based on the Kolmogorov assumption of isotropic turbulence in the inertial range [4-6]". Unfortunately, references [4-6] cannot support this statement: they are classical theoretical works. Two of these works

[5,6] are different publications/editions of the same book by Tatarskii.

Response:

As considered by the reviewers, spectral method is based on the physical assumption that atmospheric scatterers are isotropic turbulence. The detection principle of atmospheric radar is that the irregular body of atmospheric refraction index has scattering effect on the electromagnetic wave emitted by radar, and the turbulence scale detected by atmospheric radar is half of the electromagnetic wave length of radar, which is called Bragg scale. Therefore, the frequency (wavelength) of electromagnetic wave emitted by radar should be selected according to the actual situation of the atmosphere. The distribution characteristics of turbulence scale at each height are shown in the figure below (Hocking 1985) [17]. In order to detect isotropic Kolmogorov turbulence at different heights, atmospheric radar needs to select different wavebands. For MST radar, electromagnetic wave in VHF band should be selected. The Beijing MST radar emits electromagnetic waves with a wavelength of 6m, so it can be assumed that the turbulence considered in this paper (troposphere-lower stratosphere) is indeed isotropic Kolmogorov turbulence.

The modified content in the revised version(clean) for Q2 is as follows:

Line 45-51 (Section1, Page No:1 of 18) Due to the distribution characteristics of turbulence scale at each height [3], atmospheric radar needs to select different wavebands to detect isotropic Kolmogorov turbulence at different heights. For MST radar, electromagnetic wave in VHF band should be selected. The Beijing MST radar emits electromagnetic waves with a wavelength of 6m, so it can be assumed that the turbulence considered in this paper (troposphere-lower stratosphere) is indeed isotropic Kolmogorov turbulence.

Thank you for your suggestion for the **"most current research on radar-based turbulent parameters is based on the Kolmogorov assumption of isotropic turbulence in the inertial range [4-6]"**. Such references do not allow readers to clearly

understand this statements. Therefore, in the revised version, our references include not only classical theory, but also the theory of radar-based turbulent parameters. And as considered by reviewer, two of these works [5,6] only need to cite the former.

The modified content in the revised version(clean) is as follows:

Line No:43-45 (Section1, Page No:1 of 18) The atmospheric radar echo signal contains turbulence information. Most current research on radar-based turbulent parameters is based on the Kolmogorov assumption of isotropic turbulence in the inertial range [4-6].

[4] Hocking, W.K. Measurement of turbulent energy-dissipation rates in the middle atmosphere by radar techniques - a review. Radio Sci. 1985, 20, 1403-1422, doi:10.1029/RS020i006p01403.

[5] Batchelor, G.K. The theory of homogeneous turbulence; Cambridge university press: 1953.

[6] Tatarski, V.I. Wave propagation in a turbulent medium; Courier Dover Publications: 1961.

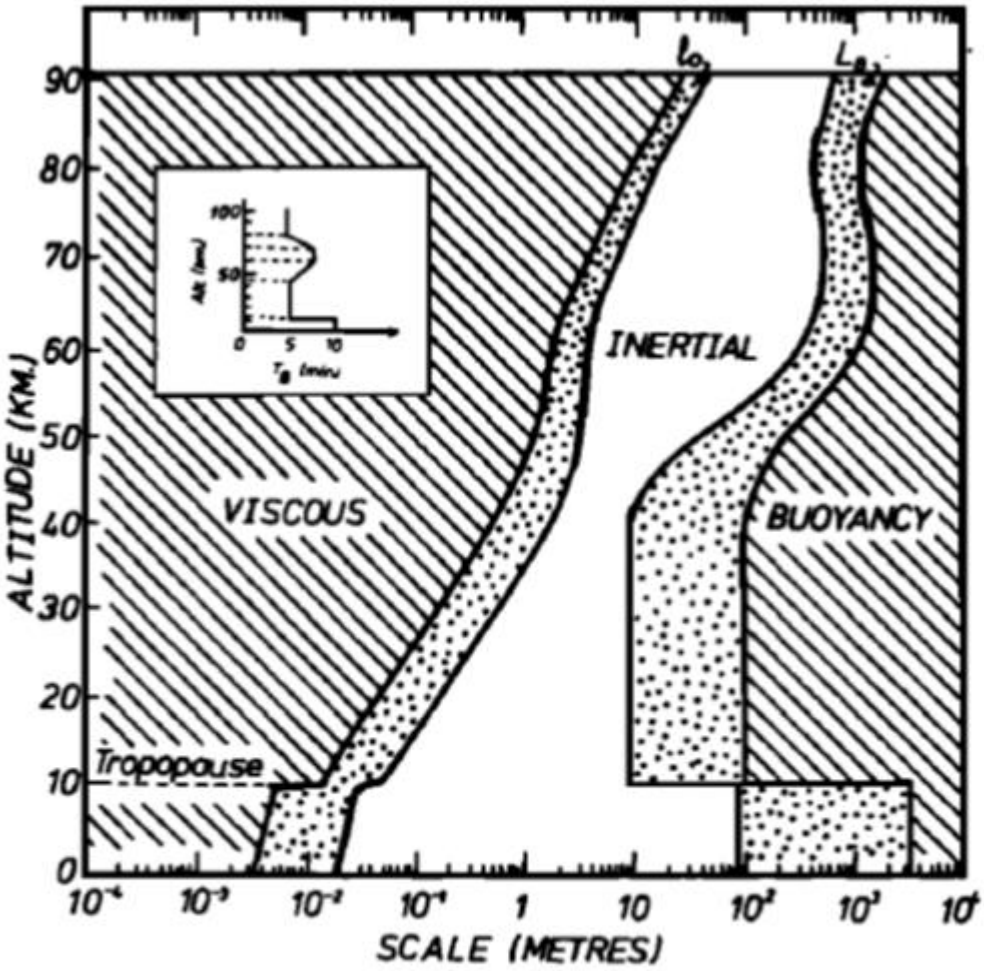


Fig. 1. Typical inner and inertial range/buoyancy range transition scales (ℓ_0 and L_B respectively) for turbulence in the atmosphere.

Hocking 1985 [17]

The details of the revision to the manuscript

Thank you very much for your professional questions and suggestions. According to the suggestions of reviewers, the original text has been modified as described above. Please see " remotesensing-1551879-version2-clean.pdf" for the revised manuscript.

Reference

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