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Atmospheric Chemistry and Physics
Discussions

Interactive comment on "Intermittent turbulence contributes to vertical diffusion of $PM_{2.5}$ in the North China Plain" *by* Wei Wei et al.

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Dear reviewer, We really appreciate your revealing questions and comments. Some key points about the intermittent turbulence in the SBL that you have brought up with are helpful to improve this work. We also thankful for the useful references you suggested. We did our best to respond to these comments one by one. We hope the reviewer would approve of our following response.

Normally, intermittent turbulence is associated with the stable boundary layer (SBL). That is, turbulence strength varies when the background stratification is generally stable. When the stratification is totally wiped out by strong turbulent mixing for a relatively long period, the relatively strong turbulent mixing is not considered as part of a time se-

ries of intermittent turbulent mixing anymore. In this study, a period of strong turbulent mixing occurred at the end of all the three cases and each of them lasted for nearly a day. If the authors think the strong turbulent mixing period in each case is part of the time series of intermittent turbulence, this is definitely not what intermittent turbulence in the traditional definition.

Response: We really appreciate your questions. As your comments note, intermittent turbulence in the SBL is manifested by sporadic bursts lasting from tens of seconds to several minutes. In this study, turbulence during TSs is much stronger than that of CSs and after checking through all of the raw time series, we find that vertical wind speed during TSs is characterized by episodic and intermittent events. The primary reason of the seemingly continuous turbulence during TSs in Fig.2 is that the 10-Hz observed turbulence is confined to a narrow plot and the weak events are covered by the relatively stronger fluctuations, which makes it look like continuous. For space reasons, here we take three examples to illustrate the details of intermittent turbulence during the TSs, one for Case-1 and the other two for Case-2. Meanwhile, the intrinsic mode functions (IMFs) from the empirical mode decomposition are given. As shown in the following Figure 1, the raw time series of vertical wind speed are not fully-developed and continuous. On the contrary, the strength of turbulence is variable. The stronger turbulence can last several minutes and frequently happens within each time series (marked by shaded areas). And this characteristic is more obvious in the high frequent IMFs (i.e. from IMF1 to IMF8). These results show that the relatively stronger turbulence during TSs happens intermittently but not continuously. Some previous observations also confirmed that intermittent bursts of turbulence and mixing can also occur multiple times (Poulos, et al., 2002). We suppose that the intermittent turbulence during TSs in Fig. 2 is just covered by the frequently happened bursts.

Figure 1 Three examples of IMFs and 30-min vertical wind speed from TSs. The shaded areas mark the relatively strong intermittent "burst".

Meanwhile, we use some other indexes, including kurtosis and FI (Flux Intermittency defined by Mahrt, 1998), to verify the behavior of intermittency. The normalized probability density function of fully-developed turbulence should be Gaussian but intermittency would modify its shape. Therefore, kurtosis (K=(ãĂŰu'ãĂŮˆ4) ÌĚ/σˆ4) that characterizes the variation of probability distribution could be introduced as an intermittency index (Vindel et al., 2008). Another useful index for intermittency is FI, which is shorthand for flux intermittency proposed by Mahrt (1998) and has been applied in many works (e.g. Ha et al., 2007). FI is defined as σ_F/|F|, where σ_F is the standard deviation of the averaged friction velocity and |F| is the absolute value of friction velocity. Considering the limited scale in the SBL, σ_F is based on 1-min values of friction velocity and |F| is 30-min averaged. Figure 2 presents Kurtosis and FI, compared with simultaneous PM2.5 concentration and IF. It can be seen that the values of Kurtosis and FI are much larger during TSs, which is consistent with the development of PM2.5 concentration and IF values. All of the parameters confirm that, the relatively stronger turbulence during TSs is intermittent but not fully-developed. Besides, it should be noticed that the small values of turbulence during CSs are mainly due to the extremely weak turbulent fluctuation. Considering that the objective of this work is not the comparison between different methods, we just applied the arbitrary-order HSA technique into this study. According to Huang et al. (1998), this method is intuitive, direct, and adaptive, with a posteriori-defined basis, from the decomposition method, based on and derived from the data, which makes it suitable for the analysis of nonlinear and non-stationary turbulence signals in the ABL. Detailed discussion on the methodology is given in the supplement. The results of Kurtosis and FI have been added to verify the conclusion as in: “In order to validate the results of IF, another two parameters to indicate the intermittency of turbulence were developed using the same data: one is kurtosis (Vindel et al., 2008) and the other is FI (Mahrt, 1998; Ha et al., 2007). The results of both kurtosis and FI are consistent with those of IF (see Figure S7).” (page 13, line25, lines 3-6)

Figure 2 Comparison of (a) – (b) PM2.5 concentration, (c) – (d) IF, (e) – (f) Kurtosis, and (g) – (h) FI by Mahrt (1998). Left panel is for Case-1 and right panel is for Case-2.

Physically, intermittent turbulent mixing in the SBL can be generated by intermittent strengthening wind shear, which can be associated with low level jets (LLJs) as pointed by the authors in the paper. However, this mechanism is not new; Banta et al. (2003, JAS; 2006, QJ; 2007 JAS) have investigated relationships between LLJs and turbulent mixing extensively.

Response: Yes, a series of works have focused on the relationship between the LLJs and intermittent turbulence, which is a widely-accepted mechanism. Based on this mechanism, we further attempted to reveal the effect of intermittent turbulent mixing on the dispersion of PM2.5 from a viewpoint of small-scale turbulent structure. As far as we know, there is few works aiming on this topic and we hope this study could provide a different new angle to think about the possible reasons for the dispersion of near surface PM2.5. We are also thankful for your useful references. These works enhanced our understanding on the LLJs and intermittent turbulence and we cited these works in the revision. “The reasons for intermittent turbulence in the ABL have not yet been well understood. Some potential causes include gravity waves (Sorbjan and Czerwinska, 2013; Strang and Fernado, 2001), solitary waves (Terradellas et al., 2005), horizontal meandering of the mean wind field (Anfossi et al., 2005), and low-level jets (LLJs, Marht, 2014; Banta et al., 2007; 2006; 2003).” (page 15, lines 2-5)

In addition, from the title of the paper, it seems that the authors would address the role of intermittent turbulent mixing to the vertical dispersion (not diffusion, diffusion is for molecular movements) of PM2.5. However, the observation indicates that the intermittent turbulent mixing during the high PM2.5 period is not strong enough to disperse PM2.5 and the significant reduction of PM2.5 is observed at the end of each event when strong mixing arrives. Then what is the significance of intermittent turbulence during the stable period? What is the significance of the new intermittent turbulence index introduced here in comparison with simple parameters such as wind speed if wind shear is the key physical process for dispersing PM2.5?

Response: Thank you so much for your comments. The title is changed into “Intermittent turbulence contributes to vertical dispersion of PM2.5 in the North China Plain: cases from Tianjin" in the revision. And we have checked through the paper to rewrite "diffusion" with "dispersion". We are sorry for the ambiguity. Actually, the turbulence during TSs belongs to intermittent regime while the CS can be considered as a more stable regime and the turbulence is largely suppressed. The turbulence during CSs is too weak with mean u* and TKE less than 0.3 m/s and 0.5 m2/s2 respectively, and z/L during the nighttime is much larger than 1, which could be sorted as the extremely stable regime or radiation regime (as in Mahrt, 2014). On the other hand, the turbulence of the TS is relatively stronger but not strong enough. These are two totally different stratification conditions. In order to reveal the distinction of different stages and the corresponding turbulence, an index (IF) was proposed. According the theory of arbitrary-order HSA, the larger deviation of scaling exponent ξ(q) represents stronger intermittency of turbulence. At this point, the turbulence during TSs is intermittent, according to the distribution of IF (Fig.6). On the contrary, the values of IF during CSs are near zero, which is mainly attributed to extremely weak fluctuation (u_* less than 0.3 m/s). To avoid ambiguity, the time with u_*<0.3 m/s is colored as grey in Fig.6. As mentioned in the first response above, the results of other indexes (i.e. kurtosis and FI) also confirm the conclusion in this study, that is, the turbulence during TSs is intermittent and the associated intermittent turbulent mixing facilitates the dispersion of PM2.5 near the surface. We emphasized this in the revision: "The results show that the turbulence is very weak during the cumulative stage due to the suppression by strongly stratified layers; while for the stage of dispersion, the turbulence is highly intermittent and not locally generated." (page 1 lines 20-22) "Any of these mechanisms would destroy the statistical symmetries stored in the fully developed turbulence, resulting in deviations from K41's q/3 and a set of concave curves in which the degree of the discrepancy of concave curves manifests the strength of turbulent intermittency." (page 11 lines 21-22 and page 12 lines1-2) "The Hilbert-based exponent scaling function ξ(q) shows great deviations from K41's theoretical result of q/3 by a set of concave curves, indicating that the enhanced turbulence in the ABL when entering the TS is intermittent rather

than continuous or fully developed." (page 17 lines 18-20)

Furthermore, because the stable boundary layer is known to be associated with weak winds when wind direction variations can be significant, how does wind advection contribute to the temporal variation of PM2.5 besides vertical dispersion of PM2.5 by turbulent mixing? Where is the high PM2.5 source?

Response: Thank you for your questions. PM2.5 pollution in Tianjin and its neighboring cities (i.e., Beijing) has received great attention and a series of works have studied the impacts of synoptic and local circulation (Zhang et al., 2017; Miao et al., 2017; Ye et al., 2016; Zhang et al., 2012; Zheng et al., 2015a; Jiang et al., 2015). Here we summary their main conclusions. Tianjin is located in one of the most polluted city clusters (the so-called Beijing-Tianjin-Hebei region, BTH region) and surrounded by Hebei, western Shandong and northern Henan, several most severely polluted provinces in Northern China (see map in Figure 3). Therefore, southerly flows from the polluted areas would deteriorate the air quality in Tianjin (Zhang et al., 2017; Miao et al., 2017; Zheng et al., 2015a; Jiang et al., 2015). Tianjin features a four-season climate and is under the influence of the Siberian anticyclone in winter. The strong north-westerly wind from the Siberian anticyclone in winter is helpful to the advection of air pollutants. Therefore, the clean days are associated with the high-pressure centers northwest of the polluted region. In order to summarize the circulation mechanism, Fig.2 also illustrates the wind vector during these two cases. Please see page 7 line 14-20: "For Case-1, wind at lower levels mainly comes from the south-east during the CS, while the dominant wind direction turns into west when it comes to the TS. Although the wind direction for Case-2 is seemingly unsteady in Fig. 2, the statistical the rose diagrams (see Figure S8) confirm a similar result, with south-easterly flows dominating the CS and westers for the TS. This wind-direction pattern is in agreement with previous works (Zhang et al., 2017; Miao et al., 2017; Zheng et al., 2015a; Jiang et al., 2015). They found that south-easterly wind can bring the aerosols emitted by the surrounding cities to this region while the clean hours are normally characterized by strong high-pressure centers northwest of the polluted region in winter." Some works (Zhang et al., 2017; Wang et al., 2014) have revealed that reginal transport and local emission both play an important role in air quality in the BTH region. One work by Zhang et al., (2017) focusing on the primary PM2.5 found that in Tianjin, primary PM2.5 mainly originated from local emission before heavy pollution events; when it comes to polluted periods, the contribution from non-local region increased and amount of pollutants were transported from Shandong, Henan, even Jiangsu and Anhui via the low-level southerly flows. In addition, some works (Zheng et al., 2015a; Chan and Yao, 2008) have pointed out that if a large-area pollution event occurred in densely distributed mega-cities (as in BTH region), air pollution might not be eliminated solely by advection considering that the up-wind flows are polluted as well. Based on these solid results by previous works, this work tries to reveal the effects of the vertical transport of intermittent turbulence which is a relatively new and different view so far. "However, in the region with densely distributed mega-cities (as in the case of Tianjin), because the upwind flows is polluted, mere advection may not be enough to disperse pollutants, thus resulting in persistent air pollution events (Zheng et al., 2015a; Chan and Yao, 2008)." (page 7 lines 20-22)

Figure 3 Map of Tianjin and its surrounding cities.

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Please also note the supplement to this comment:
https://www.atmos-chem-phys-discuss.net/acp-2018-121/acp-2018-121-AC2-supplement.pdf

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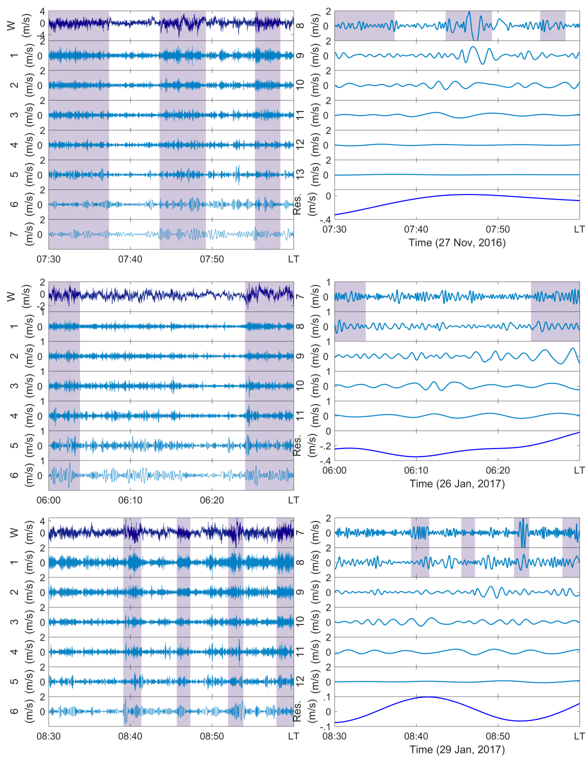

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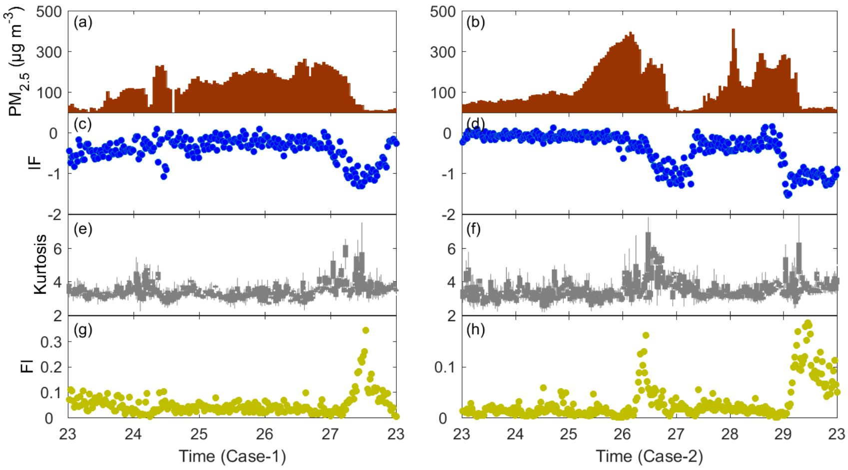

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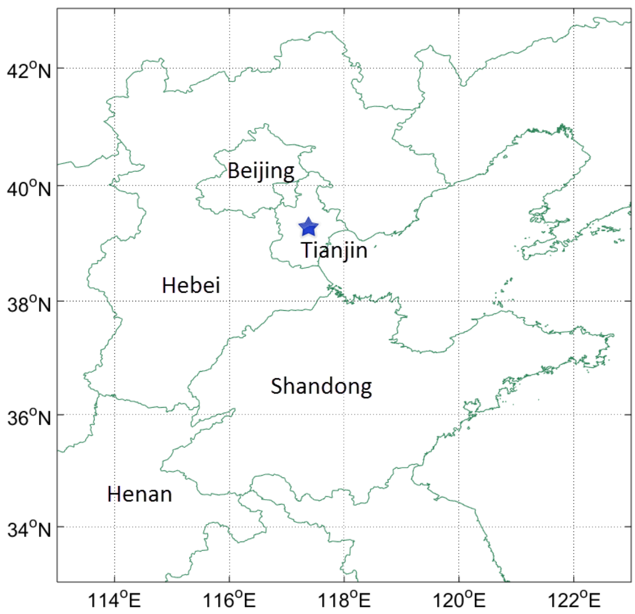

Fig. 3. Map of Tianjin and its surrounding cities.