Article

Understanding the Major Impact of Planetary Boundary Layer Schemes on Simulation of Vertical Wind Structure

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Abstract: The structure and evolution of the atmospheric planetary boundary layer (PBL) plays an important role in the physical and chemical processes of cloud–radiation interaction, vertical mixing and pollutant transport in the atmosphere. The PBL parameterization scheme describes the vertical transport of atmospheric momentum, heat, water vapor and other physical quantities in the boundary layer. The accuracy of wind field simulation and prediction is one of the most significant parameters in the field of atmospheric science and wind energy. Limited by the observation data, there are few studies on wind energy development. A 3D Doppler wind LiDAR (DWL) providing the high-vertical-resolution wind data over the urban complex underlying surface in February 2018 was employed to systematically evaluate the accuracy of vertical wind field simulation for the first time. 11 PBL schemes of the Weather Research and Forecasting Model (WRF) were employed in simulation. The model results were evaluated in groups separated by weather (sunny days, hazy days and windy days), observation height layers of wind field, and various observation wind speeds. Among these factors, the simulation accuracy is most closely related to the observation height layers of wind field. The simulation is fairly accurate at a height of 1000–2000 m, as most of the relative mean biases for wind speed and wind direction are less than 20% and 6% respectively. Below 1000 m, the wind speed and direction biases are about 30–150% $\text{m}\cdot\text{s}^{-1}$ and 6–30%, respectively. Moreover, when the observed wind speed was lower than 5 $\text{m}\cdot\text{s}^{-1}$, the biases were usually large, and the wind speed relative mean bias reaches up to 50–300%. In addition, the accuracy of the simulated wind profile is better in the range of 10–15 $\text{m}\cdot\text{s}^{-1}$ than other speed ranges, and is better above 1000 m than below 1000 m in the boundary layer. We see that the WRF boundary layer schemes have different applicabilities to different weather conditions. The WRF boundary layer schemes have significant differences in wind field simulations, with larger error under the complex topographies. A PBL scheme is not likely to maintain its advantages in the long term under different conditions including altitude and weather conditions.

Keywords: WRF model; simulation; 3D Doppler wind lidar; planetary boundary layer schemes; vertical wind speed; wind direction

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1. Introduction

Wind energy is an inexhaustible source of clean energy. The development of wind power plays an important role in improving the energy infrastructure, protecting the ecological environment, ensuring energy security, and achieving sustainable economic development. The use of wind energy is attracting more and more international attention,

but it is still developing slowly, which is directly related to the instability and intermittence of wind speed. The prediction of boundary layer wind is very worthy of study with respect to the utilization of wind energy. The planetary boundary layer (PBL) is close to the surface underlying the troposphere, and strongly interacts with the atmosphere through turbulent exchanges of mass, energy and momentum in the PBL [1]. PBL parameterizations affect the model performance greatly with respect to vertical eddy diffusivities, surface energy budget, tracer concentrations (e.g., water vapor) and the transport of air pollutants [2–6]. Due to the complexity of the thermodynamic processes associated with radiation, cloud physics, air dynamics, surface friction and anthropogenic sources for water vapor and heat, it is both critical and challenging to reproduce PBL wind structure and predict urban air quality [7].

Many previous studies that have focused on comparing observation data with boundary layer simulations were carried out with the aim of determining whether some kind of PBL schemes were suitable for specific weather conditions or types of terrain, in order to obtain an empirical conclusion to instruct numerical forecasting.

The most commonly used observational data are ground observations. Cup anemometer data were used to compare with vertical wind speed and wind shear, it is predicated that different PBL schemes could be suitable for simulating wind fields under specific stable conditions [8]. Wind speeds above 10 m at ground level were employed to evaluate the sensitivity of the WRF model with various initial condition datasets, noting that nonlocal closure schemes such as YSU and ERA-Interim reanalysis data provide the best estimation of wind speed [9].

Moreover, there some other observation data have been used for verification. Upper air radiosonde was used to study the vertical structure characteristics and time evolution of the atmospheric boundary layer in an arid region of southwestern Algeria [10].

ASAR-retrieved wind field was employed for comparison with a simulated wind structure [11]. Data from 10 stations of the Japan Meteorological Agency's wind profiler network and data acquisition system (WINDAS) were employed to evaluate wind resources in coastal areas. The simulated annual average wind speed has a significant positive bias in the lower part of the PBL, which cannot be improved by alternative PBL schemes [12]. Micro pulse LiDAR estimates were evaluated against simulated PBL heights, which were demonstrate to be underestimated, and it was also found that the nonlocal ACM2 scheme may be good choice [13,14]. Turbulent flux measurements from the FINO1 platform were used in the analysis of different atmospheric stabilities [15].

In this study, we employed high-resolution three-dimensional Doppler wind LiDAR (DWL) observations, which have rarely been used in previous studies, to evaluate simulated atmospheric boundary layer wind fields with 11 different PBL schemes under different weather conditions in Beijing. The objective of this study is to verify the importance of the WRF planetary boundary layer parameterization schemes in wind simulation, and their possible deviation, by means of 3D DWL.

Section 2 describes the DWL data, the PBL schemes and the synoptic characteristics of our case. Section 3 analyzes the PBL wind speed profile, and the horizontal and vertical wind speed and direction, and the Section 4 provides the conclusion.

2. Methodology and Data

2.1. The DWL Observation

Atmospheric turbulence leads to the fluctuation of the refractive index, the movement of the scattering layer and the movement of turbulence block. It can give rise to turbulence scattering caused by the inhomogeneous refractive index of the atmosphere, resulting in the Doppler frequency shift of the returned electromagnetic wave signal. The radial velocity relative to radar can be obtained using Doppler technology. Under certain assumptions, the wind direction, wind speed and vertical motion at the height of echo signal can be estimated by Doppler multi-direction velocity measurement.

The DWL in this study is the Windcube 100 s DWL, manufactured by Leosphere (France) company. It was deployed in the research area of Institute of Atmospheric Physics, Chinese Academy of Sciences (IAP), located at the urbanization area between the north 3rd and 4th ring roads in Beijing. There are buildings around the observation site, such as the single-storey buildings 15 m away, the 2–3 floor office building about 30 m away, gas stations, residential areas and other buildings 80–100 m away from the observation site, and there are also roads, a river, and large green belts, as shown in Figure 1. The red dots in the picture indicates the location of the experiment.

Figure 1. Location of the experimental site in this study.

The DBS scanning mode of vertical observation was adopted. The LiDAR lens transmits four rays at 0° , 90° , 180° and 270° respectively, with a zenith angle of 15° (the angle with vertical direction), and one ray with a vertical direction; thus, the distributions of 3D wind speed and direction at different heights were obtained. The wavelength of the transmitter was $1.5 \mu\text{m}$. Its minimum physical resolution was 25 m. According to the principle of DWL, the blind detection area of the instrument was twice the minimum resolution, so it could only monitor the wind field data above 50 m. DWL has good field observation performance, and it can provide 24 h uninterrupted measurements of meteorological elements such as wind velocity, wind direction, temperature and atmospheric refractive index from 50 m to 3000 m above the surface, with a sampling resolution per 20 s. Following the detection method of Brewster K A [16], the accuracy of the DWL data was verified using the special meteorological observation tower, belonging to the IAP, and the missing DWL data caused by strong noise in the near ground signal were eliminated. The tower is 325 m high, divided into 15 layers, and can provide high-quality observation data for Atmospheric Research and measure wind direction and speed.

2.2. Experimental Design

WRF3.9 was used in this study. We conducted a set of model experiments, corresponding to the 11 PBL schemes discussed in the context. Their abbreviations are YSU, MYJ, GFS, QNSE, MYNN2.5, MYNN3, ACM2, BouLac, UW, Shin-Hong, and GBM (Table 1). These schemes correspond to either local or nonlocal closure.

Local closure estimates the unknown PBL quantities by the physical quantities or gradients, through predicting the turbulence perturbation kinetic energy (TKE) at the same place, while nonlocal closure estimates quantities with many known physical quantities or gradients besides the unknown grid. The K-profile method of first-order closure is employed to address the turbulence closure schemes. YSU and ACM2 are nonlocal schemes, while the others are local schemes.

We set up three nested domains centered at 116.68° E , 39.87° N (Figure 1). The horizontal resolutions were 27, 9 and 3 km, with the domain sizes of 100×94 , 70×67 and 64×55 , respectively. The outermost domain, d01, covered most of China. The second domain, d02, covered the North China Plain and the northwestern mountainous area,

including Beijing city. The third domain is the main research area, and is near the IAP. The atmosphere is divided vertically into 43 layers, including 29 layers below 2 km, and the top layer is at 50 hPa. The physical parameterizations include the Dudhia shortwave radiation scheme, the Rapid Radiative Transfer Model longwave radiation scheme, the Kessler scheme for microphysical processes, and the Grell cumulus convection parameterization scheme. As it is not suitable for this fine resolution, the cumulus convection scheme was only applied in d01 and d02 regions, and was turned off in d03. The model was driven by the NCEP/NCAR reanalysis data and integrated from February 24 to March 2, 2018, with an additional 6 h for spin-up [17]. The model results were output every half an hour.

Table 1. Comparison of 11 planetary boundary layer schemes.

Options	Schemes	Closure Methods	Mixing Processes for Unstable Boundary Layers	Main Features
1	Yonsei University (YSU)	Nonlocal	K-Profile Method, First Order Closed Model	Considers the influence of the entrainment process at the top of the mixed layer on turbulent transport; the height of PBL depends only on the buoyancy profile [18]
2	Mellor-Yamada-Janjic Scheme (MYJ)	Local	Turbulent kinetic energy (TKE) closure scheme, 1.5-order closure model	It was suitable for studying fine PBL structure. The height of PBL was determined by the turbulent energy profile [19]
3	NCEP Global Forecast System (GFS)	Nonlocal	First-order vertical mixing scheme	The height of the PBL was determined by the iterative bulk Richardson method from the surface up integration. The diffusion coefficient above the surface was a cubic function of the height of the PBL, and its coefficient value was obtained by the coupled surface flux [20]
4	Quasi-normal Scale Elimination (QNSE)	Local	TKE Closing Scheme, 1.5 Order Closing Model	The physical process was complex and suitable for the prediction and simulation of the PBL in the stable layer region [21]
5	Mellor-Yamada Nakanishi Niino (MYNN) Level 2.5	Local	TKE Closing Scheme, 1.5 Order Closing Model	Improvement of MYNN3 limits the ratio between the main length scale and TKE [22]
6	Mellor-Yamada Nakanishi Niino (MYNN) Level 3	Local	TKE Closing Scheme, 2 Order Closing Model	Considered the physical process of condensation, the prediction of mixed layer thickness was improved, the TKE magnitude decreased, and the time bias of fog formation and dissipation prediction was reduced [23]
7	Asymmetric Convection Model 2 Scheme (ACM2)	Nonlocal +Local	The upward and downward mixing process were local. First-order Closed Model	The thermal penetration and wind shear of the entrainment layer were considered in the PBL height under unstable conditions. The height of the PBL was determined by the Richardson number [24]
8	Bougeault-Lacarrere Scheme (BouLac)	Local	TKE Closing Scheme, 1.5 Order Closing Model	It could predict the intensity and location of clear-sky turbulence over steep terrain and provide a continuous prediction of turbulent energy intensity [25]
9	University of Washington (TKE) Boundary Layer	Local	TKE Closing Scheme, 1.5 Order Closing Model	The introduction of a water vapor conservation variable and explicit entrainment closure was suitable for the case of the dry convective PBL [26]
10	Shin-Hong Scale-aware	Local	TKE Closing Scheme, 1.5 Order Closing Model	Vertical mixing in a stable PBL and free atmosphere was similar to the YSU scheme, and it could also diagnose TKE and mixed length output [27]
11	Grenier-Bretherton-McCaa	Local	TKE Closing Scheme, 1.5 Order Closing Model	Considered the entrainment process at the top of the PBL, the cloud cover could be well simulated, and the height of the PBL could be calculated according to the grid point heat [28]

Figure 2 illustrates the observed DWL wind data in our case. The PBL wind was weak below a height of 800 m on February 24–25, indicating a stable boundary air. The PBL wind speed increased in the daytime on February 26, and the wind direction above 1000 m height changed from southwest to northwest. The wind slowed again on February 27 and became strong on February 28. At the middle troposphere, according to the MICAPS 4.0 analysis, a cold high pressure was maintained at 500 hPa over northern China, and the low atmosphere was stable. On February 26, a shallow trough passed through Beijing, resulting in haze weather. From 14:00–17:00 UTC (Coordinated Universal Time) on February 28, a

cold front induced an upper gale over Beijing and a gale at the ground at 17:00–20:00 UTC. After a short break with gentle winds, the southwest wind was enhanced at 02:00 UTC on 1 March.

Figure 2. The model topography (left, middle) and the schematic diagram of the DWL (right) deployed in the center of model domain (red point in the left).

Apparently, the PBL wind structures changed substantially under different weather conditions. To clarify the performances of PBL schemes, we evaluated the model results in three weather types, sunny days (24–25 February), hazy days (26–27 February) and windy days (28 February–1 March). The model results at the same height as the DWL vertical observation were compared. Then the model and observation data were grouped depending on the observed wind speeds (i.e., <5, 5–10, 10–15 and >15 m s^{−1}) and six layer heights (30–100, 100–320, 320–1000, 1000–1500, 1500–2000 and >2000 m) to attain a reliable statistical result. Table 2 lists the paired sample sizes in each group. The statistical quantities for evaluation include the model mean bias, correlation coefficient and standard deviation for the wind speeds and directions between the model results (x) and the observations (y) across N layer heights:

Mean Bias

$$MB = \bar{y} - \bar{x} \quad (1)$$

$$\bar{x} = \frac{1}{N} \sum_{i=1}^N x_i \quad \bar{y} = \frac{1}{N} \sum_{i=1}^N y_i \quad (2)$$

Correlation Coefficient

$$CC = \frac{\sum_{i=1}^N (y_i - \bar{y})(x_i - \bar{x})}{\sqrt{\sum_{i=1}^N (y_i - \bar{y})^2 \sum_{i=1}^N (x_i - \bar{x})^2}} \quad (3)$$

Standard Deviation

$$SD = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})^2} \quad (4)$$

Table 2. The DWL sample size in data groups.

Weather Conditions	Obs (m s^{-1})	30–100 m	100–300 m	300–1000 m	1000–1500 m	1500–2000 m	2000–3000 m
Sunny days	0–5	239	342	653	249	87	0
	5–10	1	90	923	719	403	72
	10–15	0	0	56	175	479	748
	>15	0	0	0	34	131	261
Hazy days	0–5	240	420	1056	44	3	0
	5–10	0	0	480	13	96	28
	10–15	0	0	34	270	553	463
	>15	0	0	0	27	142	424
Windy days	0–5	205	257	607	135	86	0
	5–10	34	110	493	314	146	8
	10–15	1	29	224	221	300	210
	>15	0	2	308	357	324	271

3. Results

3.1. PBL Wind Speed Profile

Figure 3 shows the PBL wind speed profiles and the model biases with different PBL schemes. The simulated and observed wind speeds varies greatly with altitude. Compared with Figure 2, most of the PBL schemes captured the evolution of wind speed over the days. Figure 4 shows the variation of simulated and observed wind speed with time at an altitude of about 1010 m. During the whole model period, the mean model biases in wind speeds were positive in the layer at 0–1000 m. All PBL schemes had model biases no greater than $10 \text{ m} \cdot \text{s}^{-1}$. The model layers near the surface were greatly affected by the roughness length of urban boundary layers which are parameterized in the model with uncertainty. The model biases changed with weather conditions. On hazy days (February 26–27), the observed wind speeds were lower than on the clear days, because the stagnant weather conditions and the aerosol radiative feedback both enhanced the PBL stability and also lowered the surface wind speeds [29]. For example, when the wind speed was $5\text{--}10 \text{ m} \cdot \text{s}^{-1}$, the simulated wind speed on the hazy days was $1\text{--}2 \text{ m} \cdot \text{s}^{-1}$ (18–38%) lower than the observed wind speed on each level. On windy days (28 February–1 March), the model bias in wind direction decreased along the height. In the layer of 1000–1500 m, the wind direction bias of PBL schemes were $1.1^\circ\text{--}9.1^\circ$ (0.4–3.4%) (except bias of QNSE was 88° , 33.4%).

Figure 3. The simulated $\text{PM}_{2.5}$ concentrations (red line) and the PBL wind structures in Beijing, February 2018.

Figure 4. The wind field simulations (a–f) with the PBL schemes of YSU, MYJ, QNSE, BouLac, UW and Shin-Hong Schemes and their biases (g–n) against the observations. The sunny, haze and windy days were on 24–25 February, 26–27 February and 28 February to 1 March, respectively.

3.2. Horizontal Wind Component in PBL

Figure 5 presents the model biases in the horizontal wind components at each layer for different horizontal speed levels. Generally, all the PBL schemes had model biases in horizontal wind speed smaller than $2 \text{ m} \cdot \text{s}^{-1}$, and the biases in wind direction were less than 20° . On gentle windy days with observed wind speed less than $5 \text{ m} \cdot \text{s}^{-1}$, the YSU bias reached up to $10 \text{ m} \cdot \text{s}^{-1}$. On sunny days and hazy days, the model biases of YSU were large at 1000–1500 m and 1500–2000 m, where the wind speeds exceeded $15 \text{ m} \cdot \text{s}^{-1}$. QNSE showed the maximum model bias in wind speeds, particularly on haze and windy days. On windy days, the biases in wind direction were about 80° or even more than 100° at heights of 300–1000 m, 1000–1500 m, and 1500–2000 m. Meanwhile, the biases of other PBL schemes were within 20° . The MYJ scheme performed well in the wind speed simulation, but overestimated the wind direction by about 280% below 300 m. At wind speed level

of $5\text{--}10\text{ m}\cdot\text{s}^{-1}$, the biases in wind direction were over 100° for the YSU, GFS, MYNN2.5, MYNN3 and BouLac schemes. The model bias also increased with height, particularly when the observed wind speeds were less than $5\text{ m}\cdot\text{s}^{-1}$. On hazy days, when the wind speed was less than $5\text{ m}\cdot\text{s}^{-1}$, the wind direction biases for these PBL schemes were more than 180° at $1500\text{--}2000\text{ m}$. Table 3 shows the biases of the PBL scheme for a specific height and wind speed interval. At $1000\text{--}1500\text{ m}$ and $1500\text{--}2000\text{ m}$ altitude, the simulated standard deviation was large when the observed wind speeds exceeded $15\text{ m}\cdot\text{s}^{-1}$ or were less than $5\text{ m}\cdot\text{s}^{-1}$. The QNSE schemes gave a reasonable wind speed and direction value on sunny days, but the model results became worse on hazy and windy days. On windy days, the QNSE scheme led to standard deviations of wind directions at $300\text{--}2000\text{ m}$ of up to 80° , or even more than 100° , while the other schemes had biases within 20° . The MYJ scheme well simulated the wind speed, but the variation of wind direction below 300 m reached up to about 280% . The variations of wind directions when using the YSU, GFS, MYNN2.5, MYNN3 and BouLac schemes were over 100° in the wind speed level of $5\text{--}10\text{ m}\cdot\text{s}^{-1}$. On hazy days, for wind speeds less than $5\text{ m}\cdot\text{s}^{-1}$, the simulated standard deviations of wind direction were more than 180° at a height of $1500\text{--}2000\text{ m}$. In Table 3, ①②③④⑤⑥⑦⑧⑨⑩⑪ represent 11 different boundary layer schemes; these are YSU, MYJ, GFS, QNSE, MYNN2.5, MYNN3, ACM2, BouLac, UW, SH, GBM. The figure shows the simulation effect of wind speed and direction in different wind speed segments ($0\text{--}5$, $5\text{--}10$, $10\text{--}15$, greater than 15) under three weather conditions (sunny day, fog, strong wind) at different heights (below 100 , $100\text{--}300$, $300\text{--}1000$, $1000\text{--}1500$, $1500\text{--}2000$, and over 2000 m). For the convenience of comparison, the simulated height is consistent with the horizontal height of the observation point. Therefore, the altitude here represents both the observed altitude and the simulated altitude. Additionally, only schemes with wind speed or direction biases lower than 20% can be shown in the table. According to Table 3, for example, on sunny days, when the height was less than 100 m , and the observed wind speed was less than 5 , the wind speed biases of scheme ③ were less than 20% , and when the wind speed was between 5 and 10 , the wind speed bias of schemes ③ and ⑨ were less than 20% , which indicates that the simulation effects of the PBL schemes were better.

Figure 5. The observed and simulated wind speeds at a height of 1010 m with the PBL schemes of YSU, MYJ, QNSE, BouLac, UW and SH.

Table 3. Under different conditions, the PBL schemes with low biases of wind speed and direction, large correlation coefficients, and close standard deviation on sunny days, hazy days and windy days, and at four wind speeds ranges (0–5, 5–10, 10–15, over 15). The bias of suitable scheme in the table is below 20%. “—” Indicates poor simulation or no data. “All” means all the PBL schemes.

		Wind Speed Simulation			
	Height (m)	Obs ($\text{m}\cdot\text{s}^{-1}$)			
		0–5	5–10	10–15	>15
Sunny days	<100	③	③⑨	—	—
	100–300	①③⑤⑥⑧⑩⑪	①②③④⑤⑥⑧⑨⑩⑪	—	—
	300–1000	⑦	②③④⑨	④	—
	1000–1500	—	③④	①⑤⑥⑧⑨⑩⑪	—
	1500–2000	—	—	⑦⑧⑪	—
	>2000	—	④	All	④
Hazy days	<100	②⑧⑪	—	—	—
	100–300	⑧	All	—	—
	300–1000	⑧	③⑧⑪	①②④⑨⑩	—
	1000–1500	②③	①⑤⑥⑦⑧⑨⑩⑪	②	—
	1500–2000	②③④⑤⑥⑧⑨⑪	①⑥⑦⑩⑪	①④⑤⑥⑦⑧⑨⑩⑪	—
	>2000	—	①②③⑤⑦⑧⑨⑩⑪	①②③⑤⑥⑦⑧⑨⑩⑪	—
Windy days	<100	—	①⑩	①⑤⑥⑩	—
	100–300	—	All	①⑤⑥⑦⑩	①⑨⑩⑪
	300–1000	—	④⑧	②③⑤⑥⑦⑨⑩	⑩
	1000–1500	④⑤⑥	⑤⑥	③⑤⑥⑦⑧⑨⑪	①③⑨⑩
	1500–2000	—	—	③⑦⑧⑨⑪	①③⑨⑩
	>2000	—	—	—	②⑦⑪
		Wind Direction Simulation			
	Height (m)	Obs ($\text{m}\cdot\text{s}^{-1}$)			
		0–5	5–10	10–15	>15
Sunny days	<100	③	①②④	—	—
	100–300	—	①②③⑤⑥⑧⑨⑩⑪	—	—
	300–1000	①②③⑤⑥⑧⑩⑪	All	—	—
	1000–1500	—	④⑤⑧⑨⑪	①②③⑤⑥⑦⑧⑨⑩⑪	①⑤⑥⑧⑨⑩⑪
	1500–2000	①③⑧⑩⑪	—	⑦⑧⑪	①③⑤⑥⑦⑧⑨⑩⑪
	>2000	—	①③⑦⑧⑨⑩⑪	①③⑤⑥⑦⑧⑨⑩⑪	①②③⑤⑥⑧⑨⑩
Hazy days	<100	⑤⑥	—	—	—
	100–300	⑤⑥⑨	①②④⑤⑥⑧	—	—
	300–1000	③⑧⑨	①③④⑤⑥⑦⑧⑨⑩⑪	①②③⑤⑥⑦⑧⑨⑩⑪	—
	1000–1500	①	—	—	—
	1500–2000	—	—	①④⑤⑥⑦⑧⑨⑩⑪	—
	>2000	—	②	①②③⑤⑥⑦⑧⑨⑩⑪	All
Windy days	<100	—	⑨	①④⑨⑩	—
	100–300	—	—	⑨	—
	300–1000	④	⑧	①②③⑤⑥⑦⑧⑨⑩⑪	①⑦⑩
	1000–1500	—	①②③⑤⑥⑦⑧⑨⑩⑪	①②③⑤⑥⑦⑧⑨⑩⑪	②⑤⑥⑦⑧
	1500–2000	①②③⑦⑩⑪	①⑧⑩	③⑧⑩⑪	②③⑤⑥⑦⑧⑨⑪
	>2000	—	①③⑥⑦⑧⑩⑪	④	②⑨⑪

In Figure 6, a comparison is made between the wind field observed near the ground and the simulated wind field with two PBL schemes under the same conditions, with a wind speed of $5\text{--}10 \text{ m}\cdot\text{s}^{-1}$ on sunny days. Figure 7 shows a comparison between different wind speeds and height schemes under three weather conditions. Better results for the scheme simulations are presented. We can see from the chart that the wind direction and

wind speed simulations cover the observation results, but there were still biases, sometimes up to 45° – 60° .

Figure 6. The model biases in wind speed (left, bias less than $2 \text{ m}\cdot\text{s}^{-1}$) and wind direction (right, bias less than 20°) depending on the PBL schemes, the layer heights and the wind speeds on sunny, haze and windy days.

Figure 7. Wind field comparison chart. The observed wind speed is $5\text{--}10 \text{ m}\cdot\text{s}^{-1}$, and the height is $100\text{--}300 \text{ m}$ on the 24th–25th (sunny days).

Obs stands for observation wind field, the GFS scheme simulates the wind field, with wind speed and wind direction bias of $0.68 \text{ m}\cdot\text{s}^{-1}$ and 9.8° , respectively, the BouLac scheme simulates wind field, with wind speed and wind direction biases of $-1.1 \text{ m}\cdot\text{s}^{-1}$, 0.8° .

Figure 8 exhibits the Taylor chart for the model results at different heights and wind speeds when the observed wind speed is at $0\text{--}5 \text{ m}\cdot\text{s}^{-1}$. The Taylor charts show similar characteristics to the other observed wind speeds (i.e., $5\text{--}10$, $10\text{--}15$ and $>15 \text{ m}\cdot\text{s}^{-1}$). The correlation coefficients that failed to pass the significance test with the significance level of 0.05 are not shown in the figure. The horizontal and vertical coordinates represent the ratio of the standard deviation of the simulated value to the standard deviation of the observed value. A ratio of 1 indicates that the standard deviation was perfect. The gray arc represents the isoline with equal distance between each point and the point with a standard deviation of 1. In the left and right columns of the figure, ‘spd’ in the lower left corner stands for the comparison of wind speed between the simulated value and the observed value, and ‘dir’ represents the comparison of wind direction. Obs represents the actual wind speed range of the analysis data in the graph. The cases with coefficients that failed to pass the significance test on the three different kinds of days do not appear in the figures.

Figure 8. Wind field comparison chart, the observed wind field and simulated wind field with several PBL schemes under different conditions. (a) On sunny days, at a height of 300–1000 m, $5 < \text{Obs} < 10 \text{ m}\cdot\text{s}^{-1}$, (b) On hazy days, at a height of 300–1000 m, $10 < \text{Obs} < 15 \text{ m}\cdot\text{s}^{-1}$, (c) On windy days, at a height of 1000–1500 m, $10 < \text{Obs} < 15 \text{ m}\cdot\text{s}^{-1}$.

As can be seen from Figure 8, each wind speed segment could have suitable simulation schemes for each height. Biases and standard deviation should also be considered comprehensively. For example, when the Obs was $5\text{--}10 \text{ m}\cdot\text{s}^{-1}$, the standard deviation at 100–300 m was approximately 20 times higher than the observation standard deviation. The correlation at 300–1000 m was approximately as weak as 0.1–0.2, while at 1000–1500 m, there was the non-pass hypothesis test. On windy days, when Obs was $0\text{--}5 \text{ m}\cdot\text{s}^{-1}$, the simulated value of wind speed was several times the standard deviation of the observed value, and the bias value was greater than 100%.

3.3. Classical PBL Schemes

As is shown in Section 1, many previous studies have indicated that YSU, MYJ, ACM2 showed good simulation results. In this study, the PBL conditions changed with the weather evolution, and they were not always stable or unstable. On windy days, with an observed wind speed of $5\text{--}10 \text{ m}\cdot\text{s}^{-1}$ and at a height greater than 300 m, the YSU bias of wind speed was 50–70%. On sunny days, when the observed wind speed was less than $5 \text{ m}\cdot\text{s}^{-1}$, the MYJ mean bias of wind speed was within the range of 60–290%. A few studies have claimed that the QNSE scheme is suitable in stable conditions, which was also proved in our results. We found that the QNSE scheme performed poorly on windy days, but showed better results on sunny days and hazy days, especially for the observed wind speed exceeding $5 \text{ m}\cdot\text{s}^{-1}$ at layers above 2000 m. The above performances further prove that a scheme cannot be fully suitable for certain weather conditions.

The YSU and MYJ schemes, widely applied in previous studies, also presented good performances in our studies. The YSU scheme may be a good choice under the following conditions: to simulate the surface wind direction for observed wind speeds stronger than $5 \text{ m}\cdot\text{s}^{-1}$, or to simulate the wind direction above 300 m on sunny and hazy days, and perhaps to simulate wind speed below 300 m on windy days. It can also be used to simulate the wind direction above 300 m, the wind speed simulation above 1000 m, the wind speed simulation of over $15 \text{ m}\cdot\text{s}^{-1}$, and the simulation of wind direction at $5\text{--}15 \text{ m}\cdot\text{s}^{-1}$.

The MYJ scheme was considered suitable for the following conditions. For example, to simulate wind speed below 300 m when the wind speed is more than $5 \text{ m}\cdot\text{s}^{-1}$ on sunny days, or to simulate the winds at 300–1000 m, and perhaps to simulate the wind direction when the height is greater than 1000 m, maybe also on windy days when the wind speed is within the range $10\text{--}15 \text{ m}\cdot\text{s}^{-1}$ and the altitude is greater than 2000 m. Additionally, the MYJ scheme is able to well capture both wind speed and direction on hazy days when the wind speed is $10\text{--}15 \text{ m}\cdot\text{s}^{-1}$ at 300–1000 m.

In other words, suitable PBL schemes should be chosen for different conditions. In this case, on sunny days, when Obs was $0\text{--}5 \text{ m}\cdot\text{s}^{-1}$, we found that the wind speed was simulated well at the height 100–300 m, and the wind direction simulation performed well at 300–1000 m. When the Obs was $5\text{--}10 \text{ m}\cdot\text{s}^{-1}$, the wind speed at 100–300 m was better

than at 300–1000 m. When the Obs was $10\text{--}15\text{ m}\cdot\text{s}^{-1}$, the wind speed data were mainly distributed in the upper 1000 m; while little data at 1000–2000 m satisfied the hypothesis test, many data satisfied hypothesis test at heights above 2000 m. At this altitude, schemes 7 and 12 can be used. Wind speeds greater than $15\text{ m}\cdot\text{s}^{-1}$ were mainly distributed at heights above 1500 m, and schemes 2, 4, 7 and 11 could be selected. On hazy days, when the height was above 1000 m, the simulation results of several schemes were better. When the Obs was less than $5\text{ m}\cdot\text{s}^{-1}$ and the height was 1000–1500 m, the wind direction could be simulated with PBL schemes 2 and 3, and the wind speed simulation at 300–1000 m was relatively good. Above 2000 m, the simulation results could not be verified completely due to limited observation data. It turns out that no PBL scheme always shows good performances.

3.4. Vertical Wind Component in PBL

Figure 9 shows the observation and the simulated vertical wind speeds with three PBL schemes according to the observed vertical wind field. On sunny days and hazy days, the simulated wind speed values were 10% of the observation value, and the wind speed was mostly distributed between 0 and 0.5 under the boundary layer, and the wind direction was vertical downward. However, the simulation results show that the wind direction was mainly vertical upward. On the windy days from 28 February to 1 March, there was strong upward turbulence from the surface to the upper air in the vertical direction, and the maximum wind speed was more than $0.5\text{ m}\cdot\text{s}^{-1}$.

Figure 9. Taylor charts of mean bias, correlation coefficients and standard deviations for the model results with 11 PBL schemes. On (a) sunny days, (b) hazy days, and (c) windy days, with the observed wind speed at $0\text{--}5\text{ m}\cdot\text{s}^{-1}$.

The model failed to capture the change in vertical wind speeds (Figure 10), not only as a consequence of the model's uncertainty, but also potentially due to the biases in the

DWL data. It is known that, under a clear sky, the updraft and downdraft of airflow are small. The turbulence echo approached the detection limit of the Doppler LiDAR, which makes an accurate extraction of vertical wind speed difficult.

Figure 10. Comparison of vertical wind speeds between the observations and the simulations using (a) the GFS scheme at 1000–1500 m height on sunny days, (b) the MYNN3 scheme at 300–800 m height on hazy days, and (c) the UW scheme at 1500–2000 m height on windy days.

4. Conclusions

In this study, the accuracy of the vertical wind field simulation for different boundary layer schemes was systematically evaluated using high-resolution wind Doppler LiDAR for the first time, with a typical process simulated by a WRF model in Beijing. The results showed that the wind field was simulated well at a height of 1000–2000 m, as most of the relative mean biases of wind speed and wind direction were less than 20% and 6%, respectively. Below 1000 m, the wind speed and direction biases ranged from about 30% to more than 150% $\text{m}\cdot\text{s}^{-1}$ and 6–30%, respectively. The relative mean bias of the simulated wind profile was up to 50–300% when the wind speed was lower than 5 $\text{m}\cdot\text{s}^{-1}$ in the boundary layer. As the wind speed range was 10–15 $\text{m}\cdot\text{s}^{-1}$, the model results were better than for other speeds, and were better when the height was above 1000 m. The PBL schemes have different capabilities to reproduce the changes of wind speed profiles under different weather conditions. An appropriate PBL scheme is dependent on the weather conditions, and the model biases showed substantial changes at different heights and in different wind speed ranges, and some PBL schemes were not always likely to be suitable for a certain weather condition. The influence of observation height on the assessment was larger than that due to employing the different PBL schemes. This study provides a reference for further improving the development and use of wind energy and the accuracy of complex wind field predictions.

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