Investigation of the Impact of Complex Terrain on the Structure of Planetary Boundary Layer Using Vehicle-based Wind Lidar

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Abstract: This study investigates the Planetary Boundary Layer (PBL) dynamics over Taiwan's complex terrain using vehicle-based wind lidar. Results reveal significant spatial variability in aerosol distribution and wind patterns within the PBL, highlighting the influence of terrain on atmospheric dynamics. The LES simulations demonstrate the presence of mountainous terrain leads to significant convection occurring in both upper and lower boundary layers, promoting vertical mixing within the basin.

1. Introduction

The temporal and spatial distributions of PBL over complex terrain are important for the prediction of regional air quality. Model simulations indicated the gradient of PBL height which is associated with the sea-breeze front is enhanced by the topography [1].

Taiwan is an island located in the subtropical region off the southeastern coast of China. The terrain of Taiwan is dominated by the nearly north-south-orientated Central Mountain Range with an average height of 2,500 m. The west side of Taiwan is flanked by gently sloping plains and small hills. The precipitous topography complicates the plain-to-mountain flow patterns of local circulations such as the land-sea breeze and mountain-valley breeze, both are highly affected by the surface obstacles and land-use in the PBL. The flow significantly influences the vertical exchange related to valley and slope flow circulations [2].

Studying the PBL by radiosondes or ground-based lidars is limited over complex terrain because of the operational constraints and relatively large spatial variance of PBL. To deeply investigate the influence of complex terrain on the PBL and the regional circulation in Central Taiwan, vehicle-based Doppler wind lidar was operated to measure the spatial distribution of aerosols and winds.

2. METHODOLOGY

2.1 Doppler Wind Lidar

To investigate the spatial distribution of the PBL, a coherent Doppler lidar (CDL, jointly developed by Ocean Univ. of China and Leice Transient Technology Co., Ltd.) was mounted on a pickup truck to measure the wind profiles at distances from 50 m up to 6 km.

Figure 1. Wind Lidar mounted on a pickup trunk.

2.2 Motion Correction

The recorded radial velocity needs to be corrected with the relative velocity along the laser beam direction between the vehicle and the atmosphere, where the moving platform motion will add to the measured LOS velocity in the moving coordinate system. The analysis regarding the uncertainties and the motion-induced errors can be found in Zhai et al. [2]. The motion-corrected CDL wind was validated with radiosondes co-launched at TianZhong. The vehicle's movement path and speed are shown in Figure **2**b. The vertical wind profiles measured by the moving CDL and radiosondes are shown in Figure 3. The motion-corrected wind profiles are in close alignment with radiosonde measurements.

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Table 1. Specification of Leice Wind Print S-4000.

Model	Doppler Wind Lidar
Detection range	40m – 4000m (up to 6 km)
Data update	Up to 0.25s (fastest)
Range resolution	15m/30m/60m (configurable)
Wind speed accuracy	0.1 m/s
Wind speed range	0 – 70 m/s
Wind direction accuracy	0.1°
Power supply	AC 220V/50Hz or DC 12V/24V
Power consumption	200W
	500W when cooling at 40 °C
Operating temperature	-30 °C to +50 °C
Operating humidity	0 – 100%

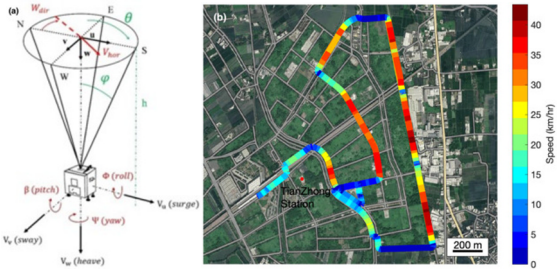

Figure 2. (a) Schematic diagrams of moving DBS scan system. (b) The moving path and speed of the vehicle-based lidar.

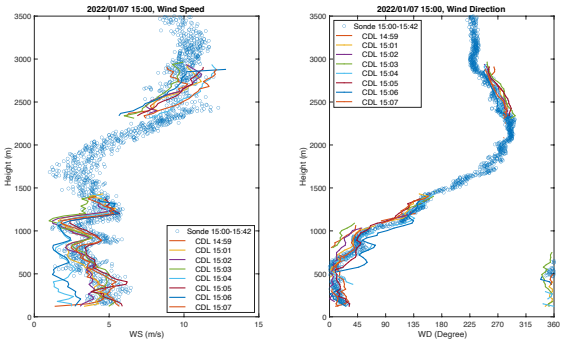

Figure 3. Motion-corrected CDL wind profiles vs. co-launched radiosonde profiles.

2.3 Large Eddy Simulation (LES)

A large eddy simulation (LES) model PALM developed by Hannover Univ. [3] was executed for this study to investigate the possible influence of topography on the structure of the boundary layer.

PALM was developed as a turbulence-resolving large-eddy simulation (LES) model specifically designed to run on massively parallel computer architectures. Meanwhile, turbulence closure based on the Reynolds-averaged Navier-Stokes (RANS) equations has been added so that PALM can run not only in turbulence-resolving mode but also in RANS mode, in which the entire turbulence spectrum is parameterized.

2.4 Study Areas

The Taichung Basin (Figure 4a) is selected as the study area to investigate the possible influence of complex terrain (Mt. Dadu) on the structure of the PBL by the vehicle-based CDL. Figure 5 shows a typical diurnal variation of the PBL measured in the Taichung Basin (CSMU). It can be noticed that the winds in the upper and lower PBL are in opposite directions, which is likely due to the return flow from mountainous areas. In comparison, the flat Yulin-Chiayi Plain (Figure 4b) is selected as the control group.

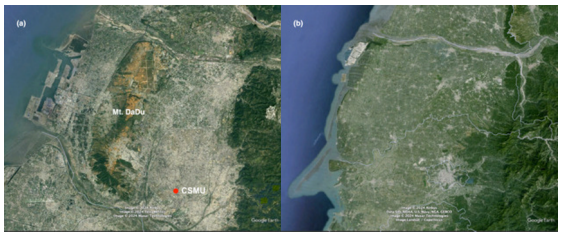

Figure 4. The topographic maps of (a) Taichung Basin and (b) Yulin-Chiayi Plain.

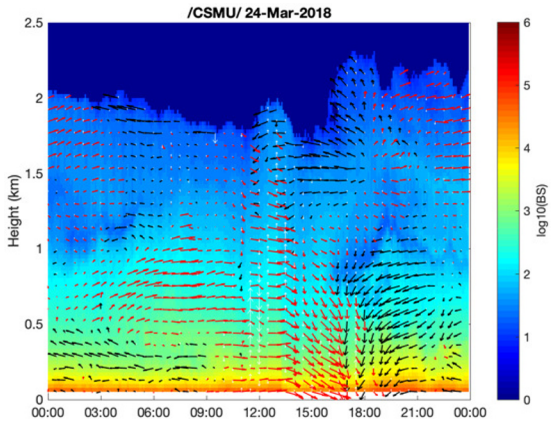

Figure 5. The time-height evaluation of aerosol backscatters and wind arrows measured at Taichung Basin (CSMU) on 2018/3/24. Red and black arrows represent eastward and westward winds, respectively.

3. Results

3.1 Moving Measurements

The PBL cross-sections observed by the moving CDL over the Taichung Basin and Yulin-Chiayi Plain indicated significant differences in the PBL structure. Figure 6 shows the spatial variability of the PBL aerosol distribution observed at noontime on Nov. 11th, 2021. The mixing layer near the coastal area appears shallower comparing the inland region.

Figure 7 shows the spatial distribution of aerosol and wind observed at noon on Dec. 16th, 2021. Two distinct aerosol layers can be noticed

at the bottom and top of the PBL on the western side of Mt. Dadu, near the coastal area. In contrast, only one aerosol layer is present within the PBL on the eastern side of the plateau, inside the Taichung Basin. On the western side of the plateau, winds mainly originate from the NNW direction, with wind speeds gradually decreasing from the ground up to the top of the PBL. Conversely, on the eastern side, wind direction shifts from NNW to West at the bottom of the PBL, indicating the presence of the wind tunnel along the river (mouth is towards the west). Wind shear is identified within the middle of the PBL in this region.

Figure 6. East-to-west cross-section of aerosol profile measured by vehicle-based lidar on Nov. 11th, 2021.

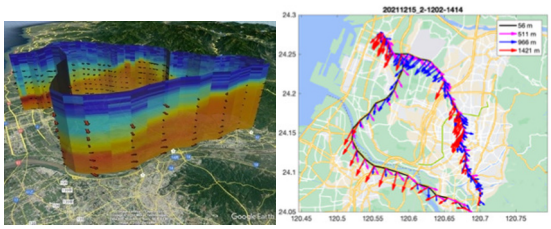

Figure 7. The cross-section of aerosols and winds along the path measured on Dec. 15th, 2021.

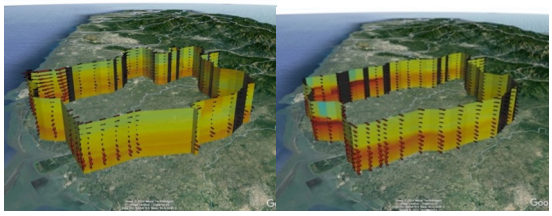

Figure 8. The cross-section of aerosols and winds measured on Jan. 12th and Jan. 13th, 2022.

However, the boundary layer over the Yulin-Chiayi Plain (Figure 8) shows no significant variation from east to west, with noticeable stratification. The wind shears might be owing to the return flow of the local circulation. These observations emphasize the complex spatial heterogeneity of the PBL influenced by topographical features and local wind patterns.

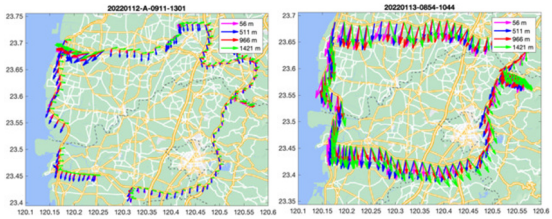

Figure 9. Same as Figure 8, the wind profiles along the path of the moving CDL.

3.2 Large Eddy Simulation (LES)

The LES model PALM is used to investigate the influence of topography on the structure of the boundary layer with/without topography. Our basic settings of the model are westerly (sea breeze) at the bottom 0-500 m and easterly (land breeze) at the top 500-1100 m. The prevailing westerly winds are above 1100 m with temperature inversions of 2 K and 4 K at 500 m and 1100 m, respectively.

Table 2. LES Setup

Property	Specification
Number of grid points	800x288x80
Horizontal resolution	50 m
Vertical resolution	30 m
Size of the model domain	40000x14400x2400 m
Prognostic variables	$u, v, w, E, \Theta, s_1, s_2$
Sensible heat flux	0
Inversion height	500 m and 1100 m
Inversion strength	2 K

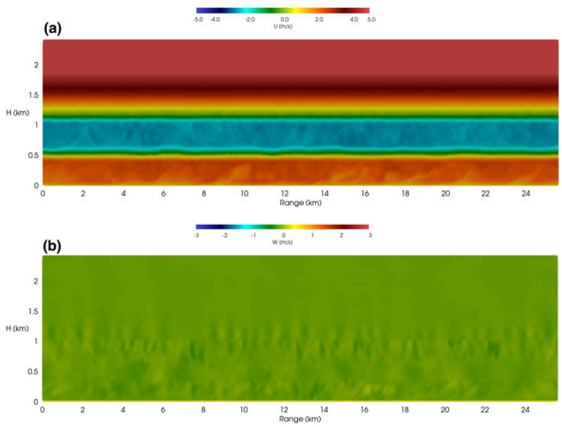

Figure 10. PALM LES Simulation with flat topography (no terrain). (a) U and (b) W are the zonal and vertical wind speeds, respectively.

Figure 10 is a simulation result for flat terrain. The zonal wind (U) shows that in the absence of terrain, the structure of the wind field maintains a stably stratified flow from west to east with almost no change. The vertical wind field (W) also shows that no significant convection occurs.

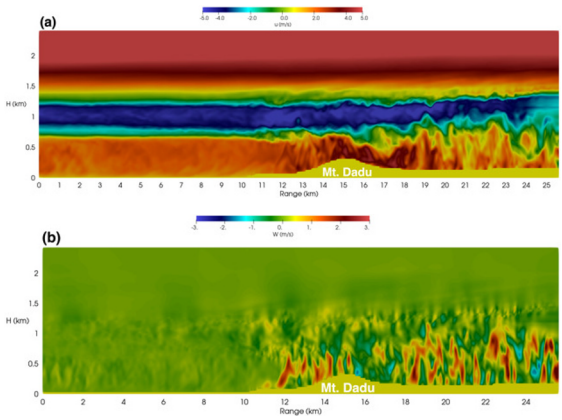

Figure 11. Same as Figure 10 but with actual terrain.

Figure 11 is a simulation result with the actual topography of Mt. Dadu. The zonal wind shows that the bottom wind field continues to rise after passing through the Mt. Dadu and the upper easterly belt is getting thinner. The vertical wind shows that significant convection occurs in the upper and lower wind fields in the basin resulting in vertical mixing of the upper and lower layers.

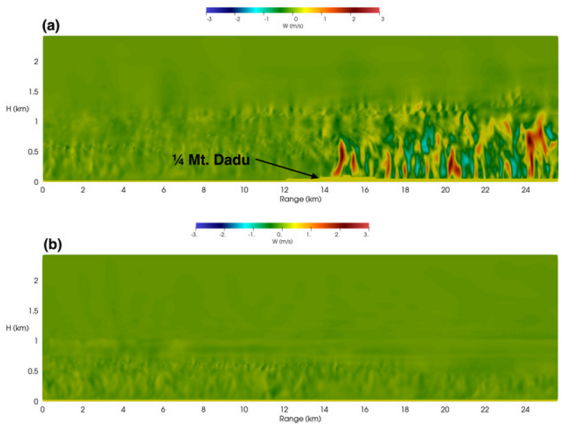

Figure 12. Same as Figure 11b but with terrain height set to (a) ¼ of the actual terrain or (b) 1 m.

To figure out how sensitive the changes of PBL structure are to the topography. Figure 12 shows the LES simulations but with terrain height set to ¼ of the actual terrain or 1 m. It can be noticed even a hill with a maximum height lower than 100 m can cause significant changes up to the top of the PBL.

These LES results are consistent with our moving-lidar measurements, more model adjustments are needed to match the observations inside and outside the basin.

4. CONCLUSIONS

The vertical and horizontal distribution of aerosols and winds are successfully observed by vehicle-based lidar. The vertical structure of aerosols is associated with the wind shear.

Our moving lidar measurements reveal significant spatial variability in aerosol distribution and wind patterns within the PBL over Mt. Dadu and the surrounding areas. The wind shear is identified within the middle of the PBL on the eastern side, indicating complex wind interactions in this region. Over the Yulin-Chiayi Plain, there is minimal variation in the boundary layer from east to west, with noticeable stratification persisting.

The LES simulations demonstrate distinct differences in wind patterns and convection dynamics between flat terrain and regions with topographical features like Mt. Dadu. The flat terrain causes steady and stratified wind flows with minimal convection. The presence of mountainous terrain leads to complex interactions. The zonal wind shows changes in airflow, with ascending motion at the mountain base and thinning easterly winds aloft. Moreover, significant convection occurs in both upper and lower boundary layers, promoting vertical mixing within the basin.

It is evident from this study that the complex terrain can have a substantial impact on wind behavior and PBL evolution.

5. Acknowledgments

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6. References

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