

Aerosol and Air Quality Research

# Investigation of Coastal Atmospheric Boundary Layer and Particle by Unmanned Aerial Vehicle under Different Land-sea Temperature

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# ABSTRACT

During summer daytime, the surface  $PM_{2.5}$  concentration tends to rise briefly in the west coast of Bohai Sea, which might be related to the thermal internal boundary layer (TIBL) formed by the land-sea thermal interaction. In this study, we investigated the relationship between land-sea air temperature and pollutant concentration in summer over a coastal region of northern China using an unmanned aerial vehicle (UAV)-measurement platform to obtain vertical meteorological data and pollutant concentration. In midday, when only considered onshore winds, PM2.5 concentration was significantly higher than that in not considered onshore winds, meanwhile the high positive correlation between land-sea temperature difference and particle concentration was identified. It can be seen from the UAV observed profiles that the TIBLs were formed at the bottom of the atmospheric layer in the daytime with height values in the range of 44-97 m, resulting from the impact of onshore winds caused by land-sea thermal difference. This land-sea thermal difference influences the atmospheric boundary layer (ABL) and TIBL structures, also the PM<sub>2.5</sub> concentration diffusion. We found that larger land-sea temperature difference could induce lower coastal ABL height and larger potential temperature vertical gradients below TIBL, even delaying the stable layer establishment. When TIBL and ABL heights increased, as a result, the height of the maximum PM<sub>2.5</sub> concentration also increased. In addition, TIBL could lead to an increase in surface PM2.5 concentration lasting for 2 hours during the daytime. Our results establish the relationship between land-sea temperature difference and particle diffusion, and have an important role in coastal air quality forecast.

Keywords: Atmospheric boundary layer, Particle matter, Thermal internal boundary layer, Unmanned aerial vehicle, Land-sea temperature

# **1 INTRODUCTION**

Atmospheric boundary layer (ABL) is the lowest part of the Earth's atmosphere and is directly affected by the surface. The height of ABL varies from several hundred meters to several thousand meters and the vertical variation of temperature, humidity, and wind in ABL play an important role in the formation of weather phenomena and transportation of air pollutants (Stull, 1988;



Received: May 8, 2022 Revised: August 5, 2022 Accepted: August 9, 2022

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Publisher:

Taiwan Association for Aerosol Research ISSN: 1680-8584 print ISSN: 2071-1409 online

(c) Copyright: The Author(s). This is an open access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are cited. Garratt, 1994; Guo *et al.*, 2014; Xu *et al.*, 2019). Coastal regions serve the interface between sea and land. The variation of coastal boundary layers directly reflects the interaction between sea and land. Numerous studies have suggested that onshore/offshore wind caused by the land-sea thermal difference strongly affect coastal boundary layers (Angevine *et al.*, 2006; Grachev *et al.*, 2018).

In summer, the variation in the structure and dynamics of coastal ABL is affected by the onshore wind, as it blows the stable air from the sea to the land during daytime. As a result of the surface heating and aerodynamic roughness changing intensifying the turbulence, a convective thermal internal boundary layer (TIBL) in the lowest atmospheric layer is induced at coastal areas (Garratt, 1990; Prabha et al., 2002; Davis et al., 2021; Martins et al., 2021). The high-water vapor mixing ratios often observed within TIBL indicate that incoming marine air is mixed inside of it (Talbot et al., 2007). Meanwhile, the height of the coastal ABL displays an abnormal decrease when TIBL is formed (Huang et al., 2016b). The height of TIBL is generally observed to be less than 0.2 km to more than 1.0 km and is affected by many factors (Bastin et al., 2005; Fan et al., 2008; Rani et al., 2010). In general, the height of TIBL is related to the distance from the sea and the land-sea temperature difference (Gryning and Batchvarova, 1990; Calmet and Mestayer, 2016). There are seasonal variations in TIBL height. In the Indian east coastal region, seasonal variation of TIBL height is relatively weak, with maximum TIBL height occurring during winter and minimum height during summer (Reddy et al., 2021). The TIBL can impact coastal pollution dispersion, which results in high concentrations of air pollutants near the surface (Lin et al., 2001; Boyouk et al., 2011; Augustin et al., 2020; Aslam et al., 2021; Yang et al., 2022). The growth of a TIBL could bring ozone-rich air aloft under onshore wind conditions into the layer, subsequently increasing the surface ozone concentrations farther inland (Lin et al., 2007). Generally, the particle concentration is anti-correlated with ABL height, but the average concentrations of PM<sub>2.5</sub> and PM<sub>10</sub> increase with increasing boundary layer height when a TIBL is formed (Wei et al., 2018). These studies show the establishment and variation of TIBL in coastal areas, as well as the impact of TIBL on air pollutants. However, due to limitation of observation means, these prior studies mostly are the research of single or several cases. Besides, the low vertical resolution limited to analysis the low part of ABL. Meanwhile, in situ vertical PM2.5 concentration observation in a TIBL is still lacking.

Nowadays, many observation methods have been used to study the ABL, such as ground weather stations, weather balloons, remote sensing, and satellite systems (Luo et al., 2014; Kral et al., 2018; Wang et al., 2021). These observation methods have their advantages and disadvantages. For example, lidar data has good continuity and high detection height, but the curvature of the Earth, obstructions of buildings, and interference from other phenomena make it difficult for lidar to sense the lowest part of ABL (LaDue et al., 2010). Recently, unmanned aircraft vehicles (UAV) have become a rapidly emerging technology that can address the limitation of other measurements in ABL research (Knuth et al., 2013; Cassano, 2014; Guimarães et al., 2019, 2020). Research suggests that UAVs can provide reliable atmospheric data that can complement and even supplement conventional low-height sampling of a coast (Cook et al., 2013). These studies demonstrate that UAVs can be well applied to the observation of atmospheric data and air pollutants in the ABL, providing more direct data. However, UAV-based vertical observations of coastal boundary layer meteorological variables and pollutants are still scarce. Meanwhile, there has been no UAV-based research on TIBL. UAVs can provide higher vertical resolution of meteorological variables and pollutants under coastal boundary layer when TIBL is formed, to better study the difference in TIBLs under the different conditions of onshore winds.

In this study, a UAV platform involved meteorological and PM<sub>2.5</sub> observation instruments was used to investigate the influence of land-sea air temperature on variation of coastal ABL and pollutants in Tianjin, China. First, the relationships of land-sea air temperature and surface particle concentration under different conditions were analyzed. Second, the mean profiles of meteorological variables were displayed and analyzed. Third, we analyzed the difference of UAV measured profiles during daytime and around sunset to explain the impact of difference land-sea air temperature on the ABL and TIBL. Moreover, the variation of vertical and surface PM<sub>2.5</sub> concentration over coastal regions influenced by TIBL was also discussed.



# **2 MATERIALS AND METHODS**

#### 2.1 UAV Platform and Ground-based Observations

The UAV measurements involved meteorological and PM2.5 observation instruments vertically takeoff and landed at fixed site within the lower troposphere (1000 m) in Tianjin, China located 3 km from the coastline of the Bohai Sea. As illustrated in Fig. 1, the UAV platform was outfitted with two parts of miniaturized sensors, including meteorological and PM<sub>2.5</sub> measurement sensors. The six-axis rotor UAV has a wingspan of ~1.6 m and weight of 2.5 kg. The takeoff weight, including instrument payloads, is ~15 kg. Air temperature, Relative humidity (RH), atmospheric pressure, wind speed, and wind direction were measured by a combined meteorological sensor (CAWS-UAV2000) that was mounted at the top of the UAV. TEMO pDR-1500, which was mounted on the bottom part of the UAV, was deployed to measure the PM2.5 mass concentration (Han et al., 2018). All the instruments used on the UAV are summarized in Table 1. To assure the quality and reliability of the measurements, all the instruments were examined closely and calibrated before and after the field campaign. Meanwhile, only ascending profiles were used to analyze. Furthermore, TEMO pDR-1500 and RP1405F were deployed together to continuously measure PM<sub>2.5</sub> mass concentration on the ground and the observed concentration were compared (See Supplementary Material Fig. S1). The linear regression was fitted indicated that TEMO pDR-1500 could be applied in the vertical observation.



Fig. 1. UAV platform.

Table 1.	Summary	of instruments an	d associated	parameters use	d on the UAV
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Parameters	Instrument	Range	Resolution	Unit	Accuracy	Time interval (s)
Temperature	CAWS-UAV2000	-90-50	0.01	°C	0.2	1
RH		0–100	0.1	%	3	1
Atmospheric pressure		300-1100	0.1	hPa	1	1
Wind speed		0–40	0.1	m s <sup>-1</sup>	0.5ª	5
					1 <sup>b</sup>	
Wind direction		0–360	0.1	0	5ª	5
					2 <sup>b</sup>	
PM <sub>2.5</sub>	TEMO pDR-1500	0–400	0.001	mg m <sup>−3</sup>	0.005	1
PM <sub>2.5</sub>	TEMO RP1405F	0–1000	0.0001	mg m <sup>−3</sup>	0.002 <sup>c</sup>	360
					0.001 <sup>d</sup>	

<sup>a</sup> when wind speed is less than 5 m s<sup>-1</sup>.

<sup>b</sup> when wind speed is more than 5 m s<sup>-1</sup>.

<sup>c</sup> 1-hour averaged.

<sup>d</sup> 24-hour averaged.



The hourly concentrations of surface PM<sub>10</sub>, PM<sub>2.5</sub>, sulfur dioxide (SO<sub>2</sub>), nitrogen dioxide (NO<sub>2</sub>), carbon monoxide (CO), and ozone (O<sub>3</sub>) in major cities are available from the Ministry of Ecology and Environment of the People's Republic of China (http://www.mee.gov.cn/). The hourly surface meteorological data were obtained from the China Meteorological Data Service System (http://data.cma.cn/). These data were used to analyze the diurnal variation of surface pollutant concentrations and meteorological variables. An aerosol lidar (WUXI CAS Photonics Co., Ltd., China) was employed to obtain the continuous backscattering profiles and extinction coefficient.

### 2.2 Field Campaign

The UAV was launched in the Binhai new area meteorological Science Park (117.80°E, 39.17°N). Nearly half of the underlying surface in this area is covered by vegetation or bare land. The southeast side is a road with less traffic on it. No major exhaust emission sources are found in and around the experimental field. As shown in Fig. 2, the experimental field is located on the eastern edge of Tianjin. The UAV's takeoff site is ~3 km northwest of the Bohai Sea. Since the experimental site is in the north of the "C" type coastal bay of Bohai Sea, the onshore wind direction can be defined as 45 to 225° in this study. Due to the external observation drive (especially the external battery) of UAV, the campaign only conducted in fine and cloudy days. The measurement campaign lasted from 1 to 21 July 2019, during which 59 flights were conducted. On a given day, the UAV was scheduled to be launched at 05:00, 08:00, 14:00, 17:00, 20:00, and 22:00 Beijing time (BJT). The actual observation times during UAV flights were strictly coordinated with the air force to avoid potential collisions with other aircraft. During the measurement campaign, the times of sunrise and sunset were approximately 05:00 and 19:30 BJT, respectively. In this study, we defined "morning time" as time before 08:00 BJT, "day time" as time between 8:00 to 20:00 BJT (included 8:00), "midday" as time between 10:00 to 15:00 (included 10:00 and 15:00) and "evening time" as time after 20:00 BJT (included 20:00) in a day. The maximum flight height was  $\sim$ 1000 m and the UAV was launched to ascend/descend at a speed of  $\sim$ 2 m s<sup>-1</sup>; it needed ~20 min to complete a flight mission. The aerosol lidar was located in the Binhai new area weather bureau (117.72°E, 39°N), approximately 8 km to the west coast of the Bohai Sea. It is located ~19 km southwest of the UAV experimental field. These two places have similar geographical and meteorological conditions. The combined measured data of UAV and aerosol lidar can reflect the vertical characteristics of coastal ABLs. Two coastal meteorological observation stations in Hangu (117.77°E, 39.24°N) and Tanggu (117.72°E, 39.04°N) were named Met\_H and Met\_T, respectively. They were selected to study the diurnal variations of surface meteorological variables near UAV and lidar observation locations. One maritime meteorological observation station (Marine, 119.2°E, 39.11°N) was also selected to compare the differences of surface meteorological variables between sea and land. Two coastal air quality observation stations in Hangu (117.76°E, 39.16°N) and Tanggu (117.71°E, 39.03°N) were named AQ\_H and AQ\_T, respectively. They were selected to provide continuous measurements of surface PM<sub>2.5</sub> concentration variation.



**Fig. 2.** (left) Map of North China with the location of the study area; (right) locations of the UAV experimental field and lidar site (black dots), meteorological ground stations (blue squares), and air quality stations (red triangles).



#### 2.3 The Determination of the Boundary Layer Height

In this study, we used the potential temperature gradient to analyze the variation of ABL in a UAV experimental field. The potential temperature is calculated using

$$\theta = T(p_0/p)^{0.286} \tag{1}$$

where T is the temperature measured by the UAV in K,  $p_0$  is the reference pressure of 1013.25 hPa, and p is the pressure as measured by the UAV. The gradient of potential temperature ( $\theta$ ) was calculated by the difference in  $\theta$  between two layers divided by the difference of height between these two layers. The level of the maximum vertical gradient of potential temperature can be seen as the height of ABL (Oke, 1988; Stull, 1988; Sorbjan, 2007). In addition, the gradient of potential temperature can also be used to judge the atmospheric stratification characteristic. The stable layer is defined as a gradient greater than 0, the near-neutral layer is defined as a gradient near to 0, and with a gradient smaller than 0, it is deemed an unstable layer. When the wind direction is onshore wind, the top of unstable layer can be seen as TIBL top (Garratt, 1990; Kallstrand and Smedman, 1997; Miller *et al.*, 2003).

### **3 RESULTS AND DISCUSSIONS**

#### 3.1 Land-sea Temperature Difference and Surface Particle Concentration

Tianjin is located in the land and sea junction area; the land and sea thermal difference has an important influence on the diffusion of surface pollutants. Sea breeze events are usually identified during May to September in Tianjin, and June–July is the period of sea breeze most frequently occurrence (Lu *et al.*, 2008; Qiu and Fan, 2013), and the sea breeze usually occurs 5–6 h after sunrise (Huang *et al.*, 2016a). Meanwhile, onshore winds occur more frequently than sea breeze events. Therefore, we selected May to August 2019 to analyze the impact of onshore winds on pollutants. Fig. 3 shows the PM<sub>2.5</sub> concentration distribution in Tianjin under different conditions. Compared to Fig. 3(a), PM<sub>2.5</sub> decreased in some stations in Fig. 3(b). It is mainly due to the high boundary layer height which is conducive to PM<sub>2.5</sub> diffusion in Midday. In Fig. 3(c), when only onshore winds were considered, PM<sub>2.5</sub> concentration was higher than that in Fig. 3(b), and the values in coastal areas were significantly higher than those in inland areas. When onshore winds were not considered, PM<sub>2.5</sub> concentration was lower than that in Fig. 3(b). In coastal areas, PM<sub>2.5</sub> concentration significantly increased, when only considered onshore winds, which was also shown by Hao *et al.* (2017). This suggests that onshore winds increased coastal PM<sub>2.5</sub> concentrations in midday.

The variation of PM<sub>2.5</sub> concentrations in coastal areas are also linked to the land-sea air temperature difference that may lead to onshore winds. Fig. 4 shows the relationship between land-sea air temperature difference and surface particle concentrations in AQ H under difference conditions during May to August 2019. The land-sea air temperature difference refers to the 2-m air temperature difference between Met H and Mairne. As shown in Fig. 4, compared to Fig. 4(a), the positive correlations between land-sea air temperature difference and PM10 or PM2.5 concentration were significantly increased in AQ\_H (coastal site) when considered values in the midday (Fig. 4(b)). In Fig. 2, compared to UAV site, AQ H and Met H is closer to inland, so we only consider east wind and southeast wind are represented as onshore wind for Met\_H. The correlation coefficients were further increased when only considered values by the onshore wind during the midday in Fig. 4(c). In the midday, east and southeast wind at Met\_H could account for 40% in all of wind directions. If onshore wind was not considered, the correlation coefficients between land-sea air temperature difference and particulate matter concentration were lower than 0.4. Due to the influence of these onshore winds, the correlation coefficients in Figs. 4(b-c) were significantly higher than those in Fig. 4(d). This phenomenon means that the onshore winds brought marine air mass to the coastal areas, thus affected the formation and diffusion of coastal particulate matter concentration.

Fig. 5 shows the hourly variation of averaged PM<sub>2.5</sub> concentration in Met\_H when considered non-onshore wind (nOW) days and only considered onshore wind (OW) days, from May to August. In Fig. 5, the averaged PM<sub>2.5</sub> concentration peaked around 08:00 BJT in two lines due to the low ABL height and human activities. However, the minimum value occurred around 18:00 and 20:00





**Fig. 3.** Distribution of PM<sub>2.5</sub> concentration in Tianjin. Different time and wind direction was selected: (ALL-ALL, a) all the time with all the wind directions, (Midday-ALL, b) midday with all the wind directions, (Midday-Onshore, c) midday with onshore-wind (Southeast and East in Hangu station), and (Midday-non-Onshore, d) midday without onshore-wind.

in nOW and OW. Meanwhile, in OW, the  $PM_{2.5}$  concentration showed an increasing trend after 13:00, where  $PM_{2.5}$  concentration increased by 5% and 7% at 14:00 and 15:00, respectively, compared to 13:00. When the  $PM_{2.5}$  concentration increased, the land-sea temperature difference reached the maximum of the day. The establishment of the TIBL is mainly caused by the thermal differences between sea and land, which makes the variation of thermal difference could affect the structural characteristics of TIBL, then affect the diffusion of pollutants.

#### 3.2 The Observed Mean Profiles of Meteorological Data by UAV

Through analyzing the vertical variation of meteorological data by UAV observation, the influence of onshore winds could be recognized. As shown in Fig. 6, the temperature decreased as height increased with a gradient of about  $-0.07^{\circ}C$   $100 \cdot m^{-1}$  under 200 m, and about  $-0.2^{\circ}C$   $100 \cdot m^{-1}$  above 200 m in the morning and evening. While in the daytime, the temperature decreased as height increased, with a gradient of about  $-0.6^{\circ}C$   $100 \cdot m^{-1}$  under 200 m and about  $-0.4^{\circ}C$   $100 \cdot m^{-1}$  above 200 m. At morning and evening, the temperature gradient under 200 m was obviously smaller than that above 200 m, while it was opposite during the day. The mean RH varied between 60-80% and showed a vertical decreasing trend. But, in the morning and evening, the mean RH increased above 600 m, while a high RH layer existed in the daytime under 100 m.

The mean wind speed profiles at different times were similar. The mean maximum wind speed of about 6 m s<sup>-1</sup> occurred at around 200 m. The standard deviation of the wind speed was relatively small below 200 m and more than  $\pm$  2 m s<sup>-1</sup> most of the time above 200 m. However, the height of mean maximum wind speed in the daytime was relative lower. The mean gradient of the potential temperature was about 7 K km<sup>-1</sup> in morning and evening under 200 m, and about 9 K km<sup>-1</sup> above



**Fig. 4.** Scatter plots of observed surface PM<sub>10</sub> (black square) and PM<sub>2.5</sub> (red circle) concentration versus land-sea air temperature difference in Hangu. R<sub>10</sub> and R<sub>2.5</sub> represented the correlation coefficients between land-sea air temperature difference and PM<sub>10</sub> and PM<sub>2.5</sub> concentration, respectively. Different time and wind direction was selected as Fig. 3. The calculation method of correlation coefficient (R) can be seen in supplementary material.



**Fig. 5.** Diurnal variations in averaged  $PM_{2.5}$  concentration in Met\_H in non-onshore wind directions (nOW, red) and onshore wind (OW, blue) with the variation of averaged land-sea temperature difference (black), from May to August.



**Fig. 6.** Mean profiles of temperature, RH, wind speed, and potential temperature (blue solid line) including their standard deviations (blue shadow) based on UAV flights (a) in the Morning and Evening, and (b) in the Daytime.

100

80

0

0 2

٥

40

60

n

20

24

28

32

36

200 m. In the daytime, as shown in Fig. 6, the potential temperature gradient was also smaller under 200 m than that above and 200 m, then the mean value of potential temperature decreased with height under 100 m, indicating that the lowest troposphere is unstable.

8 10

6

0

297 300 303 306 309

From the average profiles, no matter in the daytime or at other times, there is a transition layer around 200–300 m. In Fig. 7, the dominant wind direction is southeast below 300 m, while the southeast and east wind could contribute 52% in the daytime. Meanwhile, the southeast and east directions represent onshore winds for the location of UAV experimental field. Therefore, in the mean profiles, difference in meteorological data between below and above 200–300 m is mainly impacted by the air mass from the sea.

#### 3.3 The Impact of Onshore Wind on the Coastal ABL and Formation of the TIBL

During the daytime, most wind direction profiles were onshore winds below 200–300 m, indicating that the lower atmosphere was affected by the air mass from the ocean. As a result, in the influence of the stable air mass from the sea during the daytime, an unstable layer formed at the bottom of ABL, which is known as a TIBL (Prabha *et al.*, 2002; Nazir *et al.*, 2005; Wei *et al.*, 2018).

From Fig. 5, the land-sea air temperature difference was largest around 14:00-15:00, which corresponds to the surface PM<sub>2.5</sub> concentration increased. Therefore, the UAV measured at 14:00-15:00 of different days were selected to analyze the effects of land-sea temperature difference. Some important boundary conditions for the individual UAV measured time were presented in Table 2. To analyze the coastal ABL structure in the daytime, Fig. 8 shows the UAV measured profiles at 14:00-15:00 of different days. From the profile of the potential temperature, different degrees of the unstable layer have been found for these days, with a maximum absolute gradient of -29 K km<sup>-1</sup> on 3 July and minimum absolute gradient of -10 K km<sup>-1</sup> on 13 July. These unstable layers varied in height but were all less than 100 m. According to the wind direction in UAV site, the wind directions of these days were onshore wind. This indicates that the unstable layer was a TIBL. Meanwhile, the ABL heights also varied differently, with a maximum height of 290 m on 13 July and minimum height of 68 m on 4 July. These ABL heights were significantly lower than daytime inland ABL heights (Seidel *et al.*, 2012; Zhao *et al.*, 2019). The coastal ABL height was found significantly decreased when TIBL formed under the influence of onshore winds, which



**Fig. 7.** Wind frequencies of different heights (a  $\leq$  300 m; b > 300 m) measured by UAV.

Table 2 Meteorologica	l boundary conditions	of the experiment times
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Time (BJT)	15:00 3 July	15:00 4 July	15:00 5 July	15:00 10 July	14:00 13 July
ΔT (°C)*	5.9	10	4.4	2.4	3.6
Wind direction <sup>**</sup>	S	S	E	SE	SE
TIBL height (m)	44	47	93	86	97
Potential temperature gradient of unstable layer (K km <sup>-1</sup> )	-29	-24	-14	-15	-10
ABL height (m)	136	68	151	279	290

 $^{*}\Delta T$  is the difference in air temperature between Met\_H and Marine.

\*\*Wind direction is the 10-m wind direction in UAV site.

caused the low ABL height during the daytime. The absolute gradients of the unstable layer on 3 and 4 July were larger than other days; and the thickness of the near-neutral layer above the unstable layer was relatively small on 3 and 4 July and larger than 100 m on other days. These differences between 3 and 4 July and the rest are not limited to the potential temperature profile. On the RH profile, the values in the TIBL were significantly higher than those in the upper atmosphere on 3 and 4 July. However, these feature was not pronounced on other days, when RH increased with height. It can be seen from the wind direction profile that, the wind directions were onshore winds in the near-surface layer and some even in the whole atmosphere.

Under the impact of the onshore wind, the difference of land-sea air temperature led to the difference of meteorological variables variation in the coastal ABL. Compared to other days, the ABL heights on 3 and 4 July were much lower. As seen in Table 2, the higher the land-sea air temperature difference, the lower the height of ABL. In addition, when the land-sea air temperature difference was large, the potential temperature gradient within the TIBL layer was also relatively large. On 3 and 4 July, when the land-sea air temperature difference was large, the potential temperature difference was small, they were -15 and -10 K km<sup>-1</sup>, respectively.

The onshore wind not only formed a TIBL during the daytime at the coast, which decreased the boundary layer height, but also delayed the formation of a stable boundary layer around sunset. Fig. 9 gives the difference of measured ABL profiles between onshore wind and non-onshore wind from 17:00–18:00. At 17:00 on 8 July and 18:00 on 21 July without onshore wind, a stable



**Fig. 8.** UAV measured potential temperature, temperature, RH, wind speed, wind direction, and PM<sub>2.5</sub> concentration profiles at 15:00 BJT on 3 July (black lines), at 15:00 BJT on 4 July (blue line), at 15:00 BJT on 5 July (red lines), at 15:00 BJT on 10 July (green lines), and at 14:00 BJT on 13 July (purple lines). And the black dots are the ABL top of each time.



**Fig. 9.** UAV measured potential temperature, temperature, and wind direction profiles at 17:00 BJT on 1 July (black lines), at 17:00 BJT on 8 July (blue line), at 17:00 BJT on 14 July (red lines), at 18:00 BJT on 3 July (orange lines), at 18:00 BJT on 18 July (green lines), and at 18:00 BJT on 21 July (purple lines).

boundary layer was found at the lowest atmosphere. This indicates that the profile observed at 17:00 on 8 July and 18:00 on 21 July essentially maintained the ABL structure of the coastal land. Under the influence of the onshore wind, at 17:00 on 1 July and 18:00 on 3 July, the lowest atmosphere was still an unstable layer, while at 17:00 on 14 July and 18:00 on 18 July it was a near-neutral layer. The differences between the two kinds of structures in the lowest atmosphere might be due to the land-sea temperature difference. The land-sea air temperature differences at 17:00 on 1 July and 18:00 on 3 July were about 4.1 and 6°C, respectively, significantly greater than those at 17:00 on 14 July and 18:00 on 18 July with a value of about 2°C. As solar radiation weakens before sunset, a stable boundary layer will form from the ground, while the influence of the onshore wind. This is mainly because cooler air from the onshore wind mixes with warmer air from the coast, which causes aloft atmosphere layer cooler and increases potential temperature gradient, resulting in the lowest stable atmosphere on the coast to be more unstable.



#### 3.4 The Impact of TIBL on the Coastal Air Pollutant

The variation of vertical  $PM_{2.5}$  concentration along the coast may be affected by two factors; namely, the influence of horizontal transmission at different heights and the influence of boundary layer structure, such as a TIBL, etc. Therefore, in the same period of different days, the pollutant concentration profiles had some differences. In Fig. 8, on the PM<sub>2.5</sub> profile, the values in the TIBL increased as height increased. This vertical PM<sub>2.5</sub> concentration gradient was largest on 4 July might due to the lowest TIBL height compared to other onshore wind days. TIBLs were formed by the thermal differences between land and sea and the pollutants compressed between the top of TIBL and top of ABL were also affected by the thermal differences between land and sea. Fig. 10 shows the relationship between the PM<sub>2.5</sub> concentration gradient (0–100 m) and ABL height observed by UAV in the daytime under the influence of land-sea air temperature difference. As seen in Fig. 10, the higher the land-sea temperature difference, the higher the PM<sub>2.5</sub> concentration gradient and the lower the ABL height. In daytime, PM2.5 concentration increase with height under the influence of the upward movement. Meanwhile, TIBL acts as a cap that prevents air mass mixing between the atmosphere below and above TIBL. As a result, PM<sub>2.5</sub> was compressed in the near-neutral layer between the TIBL and ABL top. The higher land-sea temperature difference led to the lower ABL height, which meant the thinner near-neutral layer, so that the PM2.5 concentration was compressed in this thinner layer, which in turn led to the rapid increased of PM<sub>2.5</sub> concentration and formation of a higher PM<sub>2.5</sub> concentration gradient.

Fig. 11 shows the UAV measured profiles at different times on 4 July to display the continuous the influence of land-sea air temperature difference on the TIBL and PM2.5. From around sunrise to before sunset, a lofted inversion layer existed above the near-surface layer. Meanwhile, the near-surface atmospheric layer was carried over from the stable layer to the unstable layer. It is worth noting that the near-neutral layer above the surface unstable layer was relatively thin compared to those in the daytime atmospheric layer as seen in Fig. 8. The diurnal variations in wind direction indicated that during the daytime of 4 July, the near-surface atmosphere was affected by onshore wind. A TIBL was formed near the coastal surface during the daytime under the effect of the onshore wind. The diffusion of particulate matter was affected by a TIBL. The PM<sub>2.5</sub> concentration profiles were similar at 15:00, 17:00, and 18:00 with maximum values at 74, 103, and 155 m, which were higher than the top of the TIBL (47, 63, and 67 m), respectively. From 15:00 to 18:00, the characteristics of the coastal atmosphere gradually changed to those of the continental atmosphere, which made the height of the TIBL and near-neutral layer bottom increase. Meanwhile, the thickness of the near-neutral layer also deepened continuously. The concentration of PM<sub>2.5</sub> in the mixed layer was affected by the rising movement and reached its maximum near the top of the mixed layer, which made the height of the peak PM<sub>2.5</sub> concentration increase. While







**Fig. 11.** UAV measured potential temperature, wind direction, and PM<sub>2.5</sub> concentration profiles at 05:00 BJT (black lines), at 15:00 BJT (blue line), at 17:00 BJT (red lines), at 18:00 BJT (orange lines), at 20:00 BJT (green lines), and at 22:00 BJT (purple lines) on 4 July.

in the stable layer during the evening (22:00) and before sunrise (5:00), the  $PM_{2.5}$  concentration decreased first and then increased with height.

The diurnal variation of ABL height has strongly impact on the diurnal cycle of surface PM<sub>2.5</sub> concentration. Generally, the surface PM<sub>2.5</sub> concentration is found to anti-correlate with ABL height (Miao et al., 2018; Pan et al., 2019). In Fig. 10, the negative correlation between land-sea temperature difference and ABL height indicated that the larger the land-sea temperature difference was, the larger the surface particle concentration might be, which has been proved in Fig. 4. This variation was mainly caused by the formation of TIBL. To illustrate the influence of the formation of the TIBL on the surface pollutants, we display the variation of aerosol backscattering observed by lidar, wind direction and PM<sub>2.5</sub> concentration on 4 July in Fig. 12. By analyzing the vertical backscattering coefficient variation by lidar, the position where a sudden change occurs can be defined as the top of the ABL at the lidar location (Talbot et al., 2007; Tang et al., 2015). As shown in Fig. 12(a), under the influence of onshore wind, the boundary layer collapsed obviously in the afternoon which was similar to the variation of atmospheric layer in Fig. 11. If the wind blew from the sea and a ABL turning point exists below 500 m during the daytime, at the height of this point, as indicated by lidar, a TIBL is formed (Wei et al., 2018). This indicated the formation of TIBL is very common over coastal areas (Boyouk et al., 2011; De Tomasi et al., 2011; Huang et al., 2016b; Augustin et al., 2020). It is worth noting that the height of TIBL by lidar was relatively higher than that by UAV. This is mainly because the distance of lidar to the sea was greater than the UAV, which led to higher TIBL and ABL height. Meanwhile, the establishment of TIBL would increase the coastal surface pollutant concentrations. In Fig. 12(b), the wind direction turned southeast at 13:00 and 14:00 for Met\_H and Met\_T, respectively. The presence of east and southeast wind at coastal observation stations indicates that the wind is from the sea. As a result, the coastal stations on 4 July were under the influence of onshore winds from the afternoon, implying the formation of a TIBL. In Fig. 12(c), like the variation in Fig. 5, the PM<sub>2.5</sub> concentration increased significantly around sunrise and started to decline after 9:00, when the boundary layer height started to rise at both stations. The PM<sub>2.5</sub> concentration began to increase (about 31% and 35%, respectively) at 13:00 and 14:00 when the wind direction turned to southeast, respectively. After two hours of continuous increased, the concentration decreased again. This short time of increased surface PM<sub>2.5</sub> concentration was also found in a previous study (Boyouk et al., 2011). As seen in Fig. 11, from 15:00 to 18:00, the heights of the TIBL and ABL increased, which led to the surface PM<sub>2.5</sub> concentrations decreasing as seen in Fig. 12(c).

### **4 DISCUSSION**

As TIBLs are formed by onshore wind, the land-sea temperature difference has an important influence on the coastal TIBL and ABL structures. A large number of studies have been reported on the formation factors of TIBL and its relationship with pollutant concentration in coastal areas. However, these studies mostly concentrated on the structure of TIBL and the influence of TIBL





**Fig. 12.** (a) Time-height section of the lidar backscattering coefficient  $(km^{-1} Sr^{-1})$  variation. Layer transitions determined by the inflexion point method are superimposed on the lidar backscattering coefficient variation map. Both ABL top (black circles) and TIBL top (red circles) areas are represented. (b) Diurnal variations of the Wind and (c) PM<sub>2.5</sub> concentration in Hangu (red) and Tanggu (black) on 4 July are also showed.

formation on the pollutant, the relationship between the formation factors of TIBL and pollutant concentration has not been well established. In this study, we found the positive correlations between land-sea air temperature difference and coastal particle concentration. This phenomenon is mainly because when the air temperature differences between land and sea are larger, the air mass of the sea is more stable than that of the land, which makes the potential temperature gradient formed in the TIBL larger and the height of TIBL and coastal ABL lower which increased the particle concentrations.

Onshore wind not only carry the stable air of the sea, which leads to the formation of coastal TIBL, but also carried the polluted air mass from the sea, included those originated from the sea, such as emissions of shipping and offshore oil drilling platforms, or transported from land to the sea (Zhang et al., 2013; Zhang et al., 2014; Zhang et al., 2016; Han et al., 2019). When background wind opposes to the onshore wind, the convergence in coastal areas often leads to pollutant accumulation, resulting in higher pollutant concentrations (Kallos et al., 1993; Papanastasiou and Melas, 2009). Hao et al. (2017) analyzed the influence of sea breeze on the air pollutants in Tianjin and found the pollutants concentration increased slightly in the front of sea breeze front. Based on the satellite Aerosol Optical Depth (AOD) observation, air pollutant concentration is higher over the ocean in Bohai Bay than those in coastal sites. These relatively high levels of pollutants may be carried to the coastal areas when sea breezes occur. However, the large number of sediments located in the Bohai Sea which might result in overestimated AOD over the sea (Xia et al., 2013; Zhang et al., 2016; Shen et al., 2019). Meanwhile, the collected PM<sub>2.5</sub> concentrations in Bohai also proved that the higher values in Bohai Sea than those in coastal zone (Han et al., 2019). In addition, the high humidity from the sea may lead to the increase of pollutant concentration through heterogeneous processes in coastal areas (Liu et al., 2007; Sarwar et al., 2012), the modeling study of the influence of sea salt by the heterogeneous reactions showed these sea salt related heterogeneous reactions accounted for approximately 10% and 50%, for the total surface sulfate and nitrate concentrations in south coastal China (Li et al., 2018). However, the correlation



coefficients between RH and particulate matter concentration were lower than 0.2 under the same conditions as Fig. 4 in this study, while only a strong negative correlation between  $PM_{10}$  and RH with value about -0.41 occurred at midday by the onshore wind (See Supplementary Material Fig. S2). This indicates that heterogeneous reaction or aerosol hygroscopic increase might be less correlated with the variation of coastal  $PM_{2.5}$  concentration in the daytime.

In fact, the influence of onshore winds on the coastal pollutants might be the combination of the above reasons. More studies are needed to improve our understanding of the role of TIBL in the coastal area over northern China in the future. Particularly, modeling research will be used to obtain the different factors influencing the variation of pollutant concentrations when a TIBL is formed in spring and summer.

# **5 CONCLUSION**

To investigate the relationship between land-sea air temperature and pollutant concentration in summer, an ABL measurement campaign was conducted using UAVs within the lower troposphere (1000 m) in Tianjin, China, located 3 km from the coastline of the Bohai Sea. In this study, an UAV platform involved meteorological and  $PM_{2.5}$  observation instruments was used to study the influence of land-sea air temperature on the variation of coastal ABL and TIBL. Simultaneously, the variation of a TIBL and its impact on the variation of PM<sub>2.5</sub> concentration was also analyzed.

In midday, when only considered onshore winds, PM<sub>2.5</sub> concentration was significantly higher than that in not considered onshore winds, and the values in coastal areas were higher than those in inland areas. The positive correlations between land-sea air temperature difference and particle concentration were significantly increased when considered values in the midday. This trend was much significantly increased when only considered the values under the onshore wind in midday. From the UAV measured mean profiles, the variation of vertical meteorological variables showed that a transition layer exited around 200–300 m. During the daytime, the wind direction profiles indicated that the lower atmosphere (below 200-300 m) was affected by onshore winds. The heterogeneous thermal condition between land and sea caused a TIBL in coastal area. The degree of land-sea temperature difference might lead to the difference in thickness of near-neutral layers above the TIBL; the higher the land-sea temperature difference, the lower the height of the nearneutral layer, that is, the lower the ABL height. When the land-sea temperature difference was large, the potential temperature gradient within the TIBL layer was also relatively large. The onshore wind not only formed a TIBL during the daytime at the coast but also delayed the formation of a stable boundary layer before sunset: the higher the land-sea temperature difference, the more the lowest atmospheric layer tended to be unstable, later establishing a stable layer before sunset.

The influence of the TIBL on the PM<sub>2.5</sub> concentration can be expressed in two ways. First, the TIBL might influence the vertical diffusion of particulate matter in the ABL. When the land-sea temperature difference decreased, TIBL and ABL heights increased, and, as a result, the height of the maximum PM<sub>2.5</sub> concentration also increased. Meanwhile, by analyzing the daytime PM<sub>2.5</sub> concentration gradient below 100 m under the onshore wind, a positive correlation was found between the PM<sub>2.5</sub> concentration gradient and land-sea temperature difference. Second, the formation of TIBL has strong impact on the surface PM<sub>2.5</sub> concentration. A TIBL can trap the pollutants emitted from the ground, leading to an increase in surface PM<sub>2.5</sub> concentration. Ultimately, the surface PM<sub>2.5</sub> concentration on 4 July increased significantly in the afternoon and then decreased slowly with the impact of TIBL and ABL height increased.

A TIBL is a special atmospheric layer caused by the onshore wind in coastal areas. Additionally, the degree of the land-sea temperature difference might be an important factor influencing the TIBL structure. Furthermore, the variation of TIBL structures affects the dispersion of particulate matter in coastal areas. In the future, more studies will be conducted to further verify and explore the influence mechanism of land-sea temperature difference on TIBL and particulate matter diffusion in coastal areas.

# ACKNOWLEDGMENT

This research was supported by the National Natural Science Foundation of China (Nos. 41771242



and 42130513) and Scientific Research Project of Tianjin Meteorological Bureau (202114zdxm01). The authors also thank the anonymous reviewers for their constructive comments in improving this work.

# SUPPLEMENTARY MATERIAL

Supplementary material for this article can be found in the online version at https://doi.org/ 10.4209/aaqr.220206

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