Contrasting Effect of Soil Moisture on the Daytime Boundary Layer Under Different Thermodynamic Conditions in Summer Over China

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Abstract The investigation is still lacking concerning the effect of soil moisture (SM) on the evolution of planetary boundary layer (PBL) under different land conditions in a huge domain as large as China. We perform an explicit correlation analysis between daytime PBL height (PBLH) and SM for convective, neutral and stable boundary layer regimes (i.e., CBL, NBL, and SBL), respectively. A negative correlation exists between SM and daytime PBLH for CBL and NBL, exhibiting a spatial pattern of "east strong west weak", albeit a positive correlation for SBL. The standard deviation of PBLH for CBL and NBL exhibits a spatial pattern of "northwest high southeast low". Cloudy, humid, and stable atmosphere result in CBL shoaling. PBLH more correlates with the sensible heat flux (CBL: $r = 0.25$; NBL: $r = 0.33$) over dry areas, but over Northwest China the PBL depends more on meteorology likely owing to the extremely dry soil.

Plain Language Summary The effect of soil moisture (SM) on the evolution of planetary boundary layer (PBL) under different land conditions in China remains elusive. This study explores the correlation between PBL height (PBLH) and SM under different PBL regimes, using the 5-year record of high-resolution summertime soundings across China. The convective boundary layer (CBL) and neutral boundary layer (NBL) heights during daytime are found to negatively correlate with SM. In contrast, the stable boundary layer (SBL) height anticorrelates with SM, likely due to more fluid and moisture intermittent turbulence caused by enhanced SM in SBL. The spatial pattern of the standard deviation of CBL and NBL height exhibits a pronounced “northwest high southeast low” pattern. Our study also reveals more significant impact of sensible heat flux on CBL and SBL regimes over dry areas, compared to over wet areas, indicating that land surface processes are more coupled to the PBL evolution over dry areas. Besides, less cloud, dry and unstable atmosphere favor the development of CBL in wet areas, and PBLH is more dependent on meteorological quantities, but less on SM in dry areas, likely owing to extremely dry soil and bare land over Northwest China.

1. Introduction

As the lowest part of the atmosphere, planetary boundary layer (PBL) is strongly affected by a variety of processes occurring near the surface (Garratt, 1994; Stull, 1988). The exchanges of the momentum, heat, water vapor and air pollutants mainly occur between the Earth’s surface and the PBL (Garratt, 1994; Guo et al., 2016a, 2017; Hong et al., 2006; Hu et al., 2014; Seidel et al., 2010; Zhu et al., 2018). The PBL height (PBLH) is one of the key variables describing the PBL structure (Seibert, 2000), in which the turbulent mixing and dispersion play a decisive role. As such, the PBLH has been extensively used as a key length scale in the parameterization schemes of the vertical diffusion, cloud formation and contaminant deposition (Stevens, 2002; Vogelezang & Hoyt, 1996). Observational studies show that the PBLH exhibits large variability over space and time (Guo, Miao, et al., 2016; J. Liu et al., 2015; Seidel et al., 2012; W. Zhang et al., 2018).

Based on the thermodynamic conditions, the PBL can be classified into the convective boundary layer (CBL), neutral boundary layer (NBL) and stable boundary layer (SBL) (Stull, 1988). The CBL usually prevails at daytime, while the SBL dominates at nighttime. Nevertheless, the SBL and NBL can also form even at
daytime under certain meteorological conditions (e.g., overcast and windy days) and cannot be overlooked (Chen & Houze, 1997; Sivaraman et al., 2013; Stull, 1988). Recently, the PBLH climatology over China has been well characterized using high-resolution radiosonde measurements (Guo, Deng, et al., 2016), and the temporal and spatial variability of PBLH throughout China was further analyzed under the aforementioned three PBL regimes (W. Zhang et al., 2018).

The PBL evolution is found to be subject to changes in a wide range of factors, including solar insolation, synoptic circulation, aerosol, cloud cover, and surface processes (Bianco et al., 2011; Li et al., 2017; Lou et al., 2019; Miao et al., 2017a, 2017b; Su et al., 2018; Zhang et al., 2013; Y. Zhang & Klein, 2010). A recent work, which forms the main basis of our present study, suggested that soil moisture (SM), rather than aerosol caused a reversal in the long-term trend of PBLH in China (Guo et al., 2019). It is well recognized that SM altered surface albedo, soil heat capacity, sensible heat flux (SHF) and latent heat flux (LHF), which in turn affected the evolution of PBL, directly or indirectly (H. Chen & Sun, 2002; Dickinson, 1983; Koster, 2004; W. Zhang et al., 2018). In particular, reduced SM (i.e., dry soil) was closely linked to less surface evaporation, which allowed for more transfer of sensible heat flux (SHF), thereby promoting the growth of PBL (Guo et al., 2019; Mccumber & Pielke, 1981; Pal & Haeffelin, 2016; Pan & Mahrt, 1987; Rihani et al., 2015). Conversely, enhanced SM was found to dramatically inhibit the development of PBL in the wake of extreme flooding (Pal et al., 2020).

Nevertheless, most of the above-mentioned works on the SM effect on daytime PBL ignored the existence of neutral and stable PBL regimes, thereby impairing our understanding of the SM effect under different PBL regimes. Increased SM may lead to the different changes of CBL, NBL and SBL heights even at the same site. Furthermore, the SM–PBL correlation analyses in China are mostly limited to specific regions of interest (e.g., Ma et al., 2019), and the investigate in a huge domain is sorely lacking with regard to the SM impact on the evolution of PBL. China is characterized by complex surface land covers, including bare land, forest, grassland, and cropland. The complex surface land states can lead to the large spatial variability of SM–PBL relationship. Therefore, it is imperative to conduct explicit analysis of SM-PBL relationship in a huge domain as large as China.

The China radiosonde network (CRN) deployed by the China Meteorological Administration (CMA) provides us with an unprecedented opportunity to study the PBLH climatology in China (Guo, Miao, et al., 2016; W. Zhang et al., 2016) and the potential impact of SM on PBL. Therefore, the purpose of the present study is to (1) reveal the daytime PBLH–SM relationships under different PBL regimes throughout China for the summertime of the period 2012–2016; (2) to explore the joint influences of SM and meteorological factors on PBLHs in wet and dry areas across China; (3) to explore the underlying physical mechanism and related land atmosphere feedback processes.

2. Data and Methods

In this study, the PBL is divided into CBL, NBL, and SBL regimes, and the PBLH is calculated separately for all three PBL regimes, based on the high-resolution radiosonde measurements from CRN from 2012 to 2016. The CRN consists of 120 observational sites providing high-resolution (1.2 s) atmospheric sounding observations twice daily: 0800 Beijing time (BJT = UTC + 8) and 2000 BJT. Some additional soundings are made at 1400 BJT in summer (Guo, Miao, et al., 2016). Because of the weak evolution of PBL during transition period, including sunrise and sunset, the subsequent analysis is focused on the data obtained at 1400 BJT. In order to eliminate the influence of precipitation, all the samples with hourly precipitation exceeding 0.1 mm were excluded from further analysis and all radiosonde sites with less than 30 valid sounding profiles were not considered as well. The spatial pattern of radiosonde sites under investigation is shown in Figure S1. Additional, three other meteorological variables were collected, that is, 2-m relative humidity (RH_{2m}), low tropospheric stability (LTS), and total cloud cover (CLD), so as to better understand the factors modulating the PBL development. As an indicator describing the thermodynamic state of the lower troposphere, the LTS was defined as the difference in potential temperature between 700 hPa and the surface (Slingo, 1987).

Condensational heating leads to an increase of potential temperature with height, so the traditional method, which only focuses on temperature gradients, can lead to the result that a convective layer is classified as
neutral or stable. A brief description on how the PBLH is calculated considering both temperature and wind speed for different PBL regimes is presented here for completeness, while the details can be found in our previous work (W. Zhang et al., 2018). Here we only introduce the major steps used to determine the PBL regimes. First of all, the vertical resolution of 1 hPa in the radiosonde measurement has to be resampled to 5 hPa. Then, the near-surface potential temperature difference (PTD) can be derived between the fifth and the second lowest level. The values of PTD, combined with the bulk Richardson number calculated using the original lowest 100 m radiosonde measurements, are used to identify the PBL regimes: (1) if the PTD is higher than 0.1 K and the bulk Richardson number is positive, the PBL analyzed is identified as SBL; (2) if the PTD lies between −0.1 K and 0.1 K, the PBL is thought as NBL; (3) all other PBL cases belong to CBL (Eresmaa et al., 2006). For more details, refer to Supplementary Materials.

Global Land Data Assimilation System data set (GLDAS) is a new generation of reanalysis developed jointly by the National Aeronautics and Space Administration and National Centers for Environmental Prediction (Rodell et al., 2004, http://ldas.gsfc.nasa.gov). The GLDAS data set contains various physical quantities and radiant fluxes that reflect the status of the land surface. Here, the SM, SHF are directly acquired from GLDAS, which coincides with the time of radiosonde measurements (three times per day).

To look into the influences induced by SM and other different meteorological quantities on PBLH, Pearson correlation coefficient and regression lines have been calculated, and Student’s t-test (Student, 1908) was utilized to determine the 95% confidence level. Unless noted otherwise, the analysis concerning the impact of SM on PBL in the following sections refer to the time of 1,400 BJT.

3. Results and Discussion

3.1. Relationship Between SM and PBLH under Different Thermodynamic Conditions

It is well recognized that the SBL and NBL are also found to occur frequently during daytime in summer, albeit the dominance of CBL (e.g., W. Zhang et al., 2018). The PBL regimes have to be considered in order to better elucidate the underlying mechanism how SM impacts on the PBL evolution. Figures 1a–1c shows that both the NBL and CBL heights at 1400 BJT (hereafter called daytime) are negatively correlated with SM. The solar radiation reaching the ground surface tends to peak during daytime, favoring the turbulent mixing of moisture and momentum in the PBL. This in turn is subject to the changes in surface properties such as SM (Stull, 1988), which may account for the strongest negative correlation between daytime PBLH and SM for CBL and NBL.

Interestingly, the SBL heights rise with the increase in SM, likely owing to the fact that the enhanced SM was previously found to come with anomalously strong fluid and moisture turbulence (Shingleton, 2010; Waymire, 2006), and much frequent intermittent turbulence was connected with SBL (Mahrt, 1999), thereby elevating the PBL. In order to remove the uncertainty of the samples, Figures 1d–1f show the violin map of binned CBL, NBL, and SBL heights during daytime as a function of SM, which coincides with the time of radiosonde measurements (three times per day).

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correlation coefficient between PBLH and SM exhibits a pronounced “east strong west weak” pattern for CBL and NBL. Figures 2d–2f show the spatial distribution of the standard deviation. Intriguingly, the spatial pattern of PBLH for PBL regimes is similar to that for the standard deviation of PBLH and SM for each bin. Also given are the linear regression relationships (blue lines) between SM and PBLH and the Pearson correlation coefficient (R). R with asterisks indicates statistically significant trends at a 99% confidence level. CBL, convective boundary layer; NBL, neutral boundary layer; PBL, planetary boundary layer; PBLH, PBL height; SM, soil moisture; SBL, stable boundary layer regimes.

Figure 1. The two-dimensional histogram plots show the relationships between SM and PBLHs at 1400 Beijing time (BJT=UTC+8) in China for (a) CBL, (b) NBL, and (c) SBL regimes. Note the occurrence frequencies smaller than 0.05 is not displayed. Violin plots in the second row present the relationship between SM and PBLHs for (d) CBL, (e) NBL, and (f) SBL regimes at 1400 BJT in China. Each bin has the same number of samples, and the boxplot show the interquartile range (the distance between the bottom and the top of the box), median (the band inside the box), and 95% confidence interval (whiskers above and below the box) of the data. The maximum (the end of the whisker above), minimum (the end of the whisker below), and mean (blue dot) values are shown in each bin as well. Black hollow circles represent outliers. The pink-shaded areas represent the kernel estimations, which indicate the frequency distribution of paired PBLH and SM. The correlation coefficient (R) and regression equation were calculated according to the average values of PBLH and SM for each bin. Also given are the linear regression relationships (blue lines) between SM and PBLH and the Pearson correlation coefficient (R). R with asterisks indicates statistically significant trends at a 99% confidence level. CBL, convective boundary layer; NBL, neutral boundary layer; PBL, planetary boundary layer; PBLH, PBL height; SM, soil moisture; SBL, stable boundary layer regimes.

3.3. Dependence of PBLH on Different Meteorological Factors

The factors influencing the PBL growth are the SM, vegetation, the temperature lapse rate, and the low-level humidity (Findell, 2001). In order to thoroughly demonstrate the roles of meteorological quantities in governing the PBL, we further analyze the relationship between PBLH anomalies and the anomalies of three.
meteorological quantities, including RH$_{2m}$, LTS, and CLD. Defined as the potential temperature difference between 700 hPa and the surface, LTS can indicate the temperature lapse rate. RH$_{2m}$, as a convoluted parameter (temp, pressure, humidity), can indicate the low-level humidity to some extent considering the absence of humidity measurements. Cloud can reduce solar radiation reaching the land surface, and CLD can indicate the amount of cloud. Given the pronounced “east strong west weak” pattern of the correlation coefficient, the dependence of PBLH on meteorology will be analyzed over wet and dry areas, respectively, so as to find the discrepancies of factors influencing the PBLH over different areas. And the spatial distribution of wet and dry sites, which are classified by positive and negative SM anomalies, is shown in Figure S3.

Figures 3a–3c show the combined effects of SM and different meteorological factors on CBL height over wet areas at daytime. Overall, the PBL shoaling occurs as SM increases, which agrees with the results revealed in Figure 2e. Besides, more CLD and high LTS, which means inhibited turbulent mixing and exchange of SHF between the ground surface and PBL, come with decreased PBLH (Figures 3b and 3d). Coincidently, this shallower PBL corresponds to higher RH$_{2m}$ (Figure 3c). Less moisture in the PBL is associated often with lower RH$_{2m}$, which generally facilitates the development of PBL (Dirmeyer et al., 2014; Liu et al., 2004; Stull, 1988). Similarly, over dry areas, the joint impact of meteorology and SM on average varies slightly compared with over wet areas, except for higher sensitivity at extremely LTS and RH$_{2m}$ (Figures 3d–3f). This discrepancy of sensitivity translates to the notation: unstable and dry atmosphere is generally accompanied with anomalously high PBLH over dry areas. Further comparison analysis indicates that the PBLH is most closely associated with SM over wet areas, further confirming the spatial pattern of correlation between SM and PBLH as shown in Figure 2a. It is well known that there is little water vapor in the troposphere over Northwest China where is largely covered by bare land and rather dry soil (Jin et al., 2006). Notably when the lower troposphere is either extremely dry or close to saturation, the occurrence of convection favoring the PBL growth is determined solely by the atmospheric conditions (Findell, 2001).

The joint dependence of NBL height on SM and meteorological factors seems to be basically the same as that of CBL height, regardless of over dry and wet areas (Figure S4). It should be noted that the relative
contribution of SM and meteorological factors to the spatial pattern of PBLH is too complex to be quantified, which needs to be further investigated by model simulations in the future.

3.4. Mechanism of SM Affecting the Evolution of PBL

Figure 4 illustrates the covariation between the anomalies of SHF and PBLH for both wet and dry areas under different thermodynamic regimes at daytime for the summer of 2012–2016. Overall, for CBL and NBL regimes, the PBLH is found to have a stronger positive correlation with SHF (CBL: γ = 2.32 m/Wm⁻²; NBL: γ = 3.41 m/Wm⁻², γ denotes the slope of linear regression between PBLH and SHF) over the dry areas, compared to the wet areas (CBL: γ = 0.99 m/Wm⁻²; NBL: γ = 1.25 m/Wm⁻²). This could be likely associated with the much stronger land-atmosphere coupling over the dry areas and larger LHF in wet areas that tends to suppress the development of PBL through complex physical processes (Pal & Haeffelin, 2016).

Reduced SM is generally linked to enhanced SHF, which in turn favors the growth of PBL for the coupled land-atmosphere system (e.g., CBL and NBL). As shown in Figures 2 and 4, a weak correlation is found between PBLH and SHF for the SBL regime, irrespective of over dry and wet areas. This could be explained by the well-established notion that strong fluid and moisture intermittent turbulence is caused by enhanced SM (Shingleton, 2010; Waymire, 2006), and much frequent intermittent turbulence, instead of SHF, is connected with SBL (Mahrt, 1999). As shown in Figure S5, there exists strong negative association between the anomalies of SM and PBLH for both CBL and NBL, compared with SBL, which corroborates the results revealed in Figures 1 and 2.

Figure 5 schematically shows the mechanism underlying the development of daytime PBL in response to various soil moisture conditions under different PBL regimes. Over dry areas, the PBL tends to be elevated for both CBL and NBL, likely due to the great turbulence mixing caused by strong positive SHF (Figure S6). By contrast, over wet areas, the enhanced PBL occurs for SBL owing to the anomalously strong intermittent disturbance of water vapor. This highlights the importance of considering the soil moisture and PBL regimes when studying daytime PBL and its nationwide variation, which is often ignored in previous studies.
Also noteworthy is that even in dry conditions the potential temperature can show a slight increase with height. Nevertheless, sensible heat fluxes are then large and directed upward counter to the gradient of potential temperature, which will favor the PBL evolution. All those need to be further investigated in the future.

4. Summary and Conclusion

Based on the 5-years (2012–2016) record of high-resolution summertime radiosonde measurements, the relationship between the SM and PBLH in China has been thoroughly examined in the present study. In particular, this study pioneered examination of the effect of SM on the daytime PBLH under different thermal conditions in a huge domain as large as China.

In terms of the impact of atmospheric thermodynamic conditions on the PBL, a strong inverse relationship generally exists between PBLH and SM under the CBL and NBL conditions, which is probably due to the negative feedback between SM and SHF. Conversely, the SBL height have a positive correlation with SM. This is presumably because the intermittent disturbance, rather than SHF, becomes the dominant factor modulating the evolution of SBL. Besides, the overcast condition accounted for most of the SBL events, indicating the important role of cloud in modulating the formation of SBL.

The standard deviation of PBLH for CBL and NBL exhibits a spatial pattern of “northwest high southeast low.” A strong influence that SM exerted on the development of PBL occurs at daytime, showing the
Figure 5. A schematic diagram describing the impacts of soil moisture on the development of PBL under three different PBL regimes: CBL (first row), NBL (second row), and SBL (third row). The left column refers to those over wet soil regime and right column over dry soil regime. The black horizontal solid and dash lines represent the average PBLH and its corresponding PBLH anomalies. The red arrows denote sensible heat flux, blue upward arrows denote latent heat flux, and black arrows denote turbulence. The number of black arrows denote the strength of turbulence, the width of blue and red arrows denotes the magnitude of heat flux, and the hollow arrow in (f) means few occurrences of downward SHF. CBL, convective boundary layer; NBL, neutral boundary layer; PBL, planetary boundary layer; PBLH, PBL height; SBL, stable boundary layer regimes; SHF, sensible heat flux.
pronounced “east strong west weak” spatial pattern of the correlation coefficient between SM and PBLH for CBL and NBL.

Our study has also explored the joint effects of SM and different meteorological factors on PBL over wet and dry areas under different thermodynamic regimes. For both CBL and NBL regimes, the PBL shoaling occurs as SM, CLD, LTS, and RH2m increases. The PBLH seems to be more strongly correlated with meteorological quantities over dry areas, likely owing to the fact that the low levels of the troposphere are extremely dry.

The correlation between SHF and PBLH over wet areas for CBL and NBL regimes seems to be weaker likely due to the stronger LHF in modulating the development of PBL over wet areas. By contrast, there was less apparent relationship between PBLH and SM over dry areas, which could be owing to the dominant effect caused by large LHF rather than small SHF over dry areas.

Although explicit correlation analysis between SM and PBLH has been performed here, it is limited to the instant observations obtained at several times during a day. More importantly, correlation does not imply causation, and the land surface-PBL interactions and development of clouds and convection vary greatly by different timescales. Therefore, process-level understanding of SM affecting the evolution of PBL is warranted in order to gain in-depth insights into the mechanism how soil properties influence PBL, which needs further model simulation in the future in conjunction with temporally continuous observations in specific region of interest.

Data Availability Statement

The high-resolution radiosonde data set is provided by the National Meteorological Information Center (http://data.cma.cn/en/).

References

Bianco, L., Djialalova, I. V., King, C. W., & Wilcak, J. M. (2011). Diurnal evolution and annual variability of boundary-layer height and its correlation to other meteorological variables in California's Central Valley. Boundary-Layer Meteorology, 140, 491–511. https://doi.org/10.1007/s10546-011-9622-4

Chen, S. S., & Houze, R. A. (1997). Diurnal variation and life-cycle of deep convective systems over the tropical Pacific warm pool. The Quarterly Journal of the Royal Meteorological Society, 123(538), 357–388. https://doi.org/10.1002/qj.49712353806

Chen, H., & Sun, Z. (2002). Review of land-atmosphere interaction and land surface model studies. Journal of Nanjing Institute of Meteorology (in Chinese), 29(2), 277–288. https://doi.org/10.1029/2002JD000254

Dickinson, R. E. (1983). Land surface processes and climate-surface albedos and energy Balance. Advances in Geophysics, 25(12), 305–353. https://doi.org/10.1016/S0065-2687(08)60176-4

Dirmeyer, P. A., Wel, J., Bosilovich, M. G., & Mocko, D. M. (2014). Comparing evaporative sources of terrestrial precipitation and their extremes in MERRA using relative entropy. Journal of Hydrometeorology, 15(1), 102–116. https://doi.org/10.1175/Jhm-d-13-051.1

Eresmaa, R., & Järvinen, H. (2006). An observation operator for ground-based GPS slant delays. Tellus A: Dynamic Meteorology and Oceanography, 58(1), 131–140. https://doi.org/10.1111/j.1600-0870.2006.00154.x

Findell, K. L. (2001). Atmospheric controls on soil moisture-boundary layer interactions. 108(D8), (p.172). Massachusetts Institute of Technology. https://doi.org/10.1029/2001JD001515

Garratt, J. R. (1994). The atmospheric boundary layer. Earth-Science Reviews, 37(1), 89–134. https://doi.org/10.1016/0012-6151(94)90074-3

Guo, J., Tian, Y., Zhang, Y., Liu, H., Li, Z., Zhang, W., et al. (2016a). The climatology of planetary boundary layer height in China derived from radiosonde and reanalysis data. Atmospheric Chemistry and Physics, 16, 13309–13319. https://doi.org/10.5194/acp-16-13309-2016

Guo, J., Deng, M., Lee, S.-S., Wang, F., Li, Z., Zhai, P., et al. (2016b). Delaying precipitation and lightning by air pollution over Pearl River Delta. Part I: Observational analyses. Journal of Geophysical Research, 121, 6472–6488. https://doi.org/10.1002/2015JD023257

Guo, J., Li, Y., Cohen, J. B., Li, J., Chen, D., Xu, H., et al. (2019). Shift in the temporal trend of boundary layer height in China using long-term (1979–2016) radiosonde data. Geophysical Research Letters, 46, 6080–6089. https://doi.org/10.1029/2019GL082666

Guo, J., Lou, M., Xiao, Y., Wang, Y., Zeng, Z., Liu, H., et al. (2017). Trans-Pacific transport of dust aerosol originated from East Asia: Insights gained from multiple observations and modelling. Environmental Pollution, 230, 1030–1039. https://doi.org/10.1016/j.envpol.2017.07.062

Hong, S. Y., Noh, Y., & Dudhia, J. (2006). A new vertical diffusion formulation with an explicit treatment of entrainment processes. Monthly Weather Review, 134(9), 2318–2341. https://doi.org/10.1175/MWR3199.1

Hu, X.-M., Ma, Z., Lin, W., Zhang, H., Hu, J., Wang, Y., et al. (2014). Impact of the Loess Plateau on the atmospheric boundary layer structure and air quality in the North China Plain: A case study. The Science of the Total Environment, 499, 228–237. https://doi.org/10.1016/j.scitotenv.2014.08.053

Jin, L., Fu, J., & Chen, F. (2006). Spatial and temporal distribution of water vapor and its relationship with precipitation over Northwest China. Journal of Lanzhou University, 42(1), 1–6

Koster, R. D. (2004). Regions of strong coupling between soil moisture and precipitation. Science, 305(5687), 1138–1140

Li, Z., Guo, J., Ding, A., Liao, H., Liu, J., Sun, Y., et al. (2017). Aerosol and boundary-layer interactions and impact on air quality. National Science Review, 4(6), 810–833. https://doi.org/10.1093/nsr/nwx117

Liu, Y., Gupta, H. V., Sorooshian, S., Bastidas, L. A., & Shuttleworth, W. J. (2004). Exploring parameter sensitivities of the land surface using a locally coupled land-atmosphere model. Journal of Geophysical Research: Atmospheres, 109(D21). https://doi.org/10.1029/2004jd004730
Liu, J., Huang, J., Chen, B., Zhou, T., Yan, H., Jin, H., et al. (2015). Comparisons of PBL heights derived from CALIOP and ECMWF reanalysis data over China. *Journal of Quantitative Spectroscopy & Radiative Transfer*, 153, 102–112. https://doi.org/10.1016/J.JQSR.2014.10.011

Lou, M., Guo, J., Wang, L., Xu, H., Chen, D., Miao, Y., et al. (2019). On the relationship between aerosol and boundary layer height in summer in China under different thermodynamic conditions. *Earth and Space Science*, 6(5), 887–901. https://doi.org/10.1002/2019EA000620

Mahrt, L. (1999). Stratified boundary layers. *Boundary-Layer Meteorology*, 90(3), 375–396. https://doi.org/10.1023/A:1001765729756

Ma, Y., Meng, X., Han, R., et al. (2019). Observational study on the influence of soil moisture on surface energy and atmospheric boundary layer in the Loess Plateau. *Plateau Meteorology*, 4(1), 705–715.

McCumber, M. C., & Pielke, R. A. (1981). Simulation of the effects of surface fluxes of heat and moisture in a mesoscale numerical model: I. Soil layer. *Journal of Geophysical Research*, 86, 9929–9938. https://doi.org/10.1029/JC086iC09p09929

Miao, Y., Guo, J., Liu, S., Liu, H., Li, Z., Zhang, W., et al. (2017a). Classification of summertime synoptic patterns in Beijing and their association with boundary layer structure and aerosol pollution. *Atmospheric Chemistry and Physics*, 17, 3097–3110. https://doi.org/10.5194/acp-17-3097-2017

Miao, Y., Guo, J., Liu, S., Liu, H., Zhang, G., Yan, Y., et al. (2017b). Relay transport of aerosols to Beijing-Tianjin-Hebei region by multi-scale atmospheric circulations. *Atmosphere*, 165, 35–45. doi:10.1016/J.ATMOSENV.2017.06.032

Pal, S., & Haefelin, M. (2016). Forcing mechanisms governing diurnal, seasonal, and interannual variability in the boundary layer depths: Five years of continuous LIDAR observations over a suburban site near Paris. *Journal of Geophysical Research: Atmosphere*, 120, 11936–11956. https://doi.org/10.1002/2015JD023268

Pal, S., Lee, T. R., & Clark, N. E. (2020). The 2019 Mississippi and Missouri River flooding and its impact on atmospheric boundary layer dynamics. *Geophysical Research Letters*, 47, e2019GL086933. https://doi.org/10.1029/2019GL086933

Pan, L. H., & Mahrt, L. (1987). Interaction between soil hydrology and boundary-layer development. *Boundary-Layer Meteorology*, 38(1–2), 185–202. https://doi.org/10.1007/BF00121563

Rihan, J. F., Chow, F. K., & Maxwell, R. M. (2015). Isolating effects of terrain and soil moisture heterogeneity on the atmospheric boundary-layer: Idealized simulations to diagnose land-atmosphere feedbacks. *Journal of Advances in Modelling Earth Systems*, 7, 915–937. https://doi.org/10.1002/2014MS000371

Rodell, M., Houser, P. R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.-J., et al. (2004). The global land data assimilation system. *Bulletin of the American Meteorological Society*, 85(3), 381–394. https://doi.org/10.1175/BAMS-85-3-381

Seibert, P. (2000). Review and intercomparison of operational methods for the determination of the mixing height. *Atmospheric Environment*, 34, 1001–1027. https://doi.org/10.1016/S1352-2310(99)00349-0

Seidel, D. J., Ao, C. O., & Li, K. (2010). Estimating climatological planetary boundary layer heights from radiosonde observations: Comparison of methods and uncertainty analysis. *Journal of Geophysical Research*, 115, D16113. https://doi.org/10.1029/2009JD013800

Seidel, D. J., Zhang, Y., Beljaars, A., Golaz, J.-C., Jacobson, A. R., & Medeiros, B. (2012). Climatology of the planetary boundary layer over the continental United States and Europe. *Journal of Geophysical Research*, 117, D17106. https://doi.org/10.1029/2012JD018143

Shingleton, N. (2010). Coupling a land-surface model to large-eddy simulation to study the nocturnal boundary layer. The University of Utah. Sivaraman, C., McFarlane, S., Chapman, E., Jensen, M., Toto, T., Liu, S., et al. (2013). Planetary boundary layer (PBL) height value added product (VAP): Radiosonde retrievals. Gaithersburg, MD: U.S. Department of Energy.

Slingo, J. (1987). The development and verification of a cloud prediction scheme for the ECMWF model. *The Quarterly Journal of the Royal Meteorological Society*, 113(477), 899–927. https://doi.org/10.1002/qj.49711347710

Stevens, B. (2002). Entrainment in stratocumulus topped mixed layers. *The Quarterly Journal of the Royal Meteorological Society*, 128, 2663–2689. https://doi.org/10.1256/qj.01.202

Student (1908). The probable error of a mean. *Biometrika*, 6, 1–25. https://doi.org/10.2307/2331554

Stull, R. B. (1988). *An introduction to boundary layer meteorology*. Springer Netherlands. https://doi.org/10.1007/978-94-009-3027-8_7

Su, T., Li, Z., & Kahn, R. (2018). Relationships between the planetary boundary layer height and surface pollutants derived from LIDAR observations over China: Regional patterns and influencing factors. *Atmospheric Chemistry and Physics*, 18, 15921–15935. https://doi.org/10.5194/acp-18-15921-2018

Vogezeazang, D. H. F., & Holtslag, A. A. M. (1996). Evaluation and model impacts of alternative boundary-layer height formulations. *Boundary-Layer Meteorology*, 81(3–4), 245–269. https://doi.org/10.1007/BF02303311

Waymire, E. C. (2006). Two highly singular intermittent structures: Rain and turbulence. *Water Resources Research*, 42(6), W06D08. https://doi.org/10.1029/2005WR004492

Zhang, W., Guo, J., Miao, Y., Liu, H., Song, Y., Fang, Z., et al. (2018b). On the summertime planetary boundary layer with different thermodynamic stability in China: A radiosonde perspective. *Journal of Climate*, 31, 1451–1465. https://doi.org/10.1175/JCLI-D-17-0231.1

Zhang, W., Guo, J., Miao, Y., Liu, H., Zhang, Y., Li, Z., et al. (2016). Planetary boundary layer height from CALIOP compared to radiosonde over China. *Atmospheric Chemistry and Physics*, 16, 9951–9963. https://doi.org/10.5194/acp-2016-250

Zhang, Y., & Klein, S. A. (2010). Mechanisms affecting the transition from shallow to deep convection over land: Inferences from observations of the diurnal cycle collected at the ARM Southern Great Plains site. *Journal of the Atmospheric Sciences*, 67(9), 2943–2959. https://doi.org/10.1175/2010JAS3366.1

Zhang, Y., Seidel, D. J., & Zhang, S. (2013). Trends in planetary boundary layer height over Europe. *Journal of Climate*, 26, 10071–10076. https://doi.org/10.1175/JCLI-D-13-00108.1

Zhu, X., Tang, G., Guo, J., Hu, B., Song, T., Wang, L., et al. (2018). Mixing layer height on the North China Plain and meteorological evidence of serious air pollution in southern Hebei. *Atmospheric Chemistry and Physics*, 18, 4897–4910. https://doi.org/10.5194/acp-18-4897-2018

**Reference from the Supporting Information**

Argentinis, S., Viola, A., Sempreviva, A., & Petenko, I. (2005). Summer boundary-layer height at the plateau site of DomeC, Antarctica. *Boundary-Layer Meteorology*, 113(1), 409–422. https://doi.org/10.1007/s10546-004-5843-6

Bonner, W. D. (1968). Climatology of the low level jet. *Monthly Weather Review*, 96(12), 833–850. https://doi.org/10.1175/1520-0493(1968)96<0833-COTLLJ>2.0.CO;2

Garreau, R., & Munfor, R. C. (2005). The low-level jet off the west coast of subtropical South America: Structure and variability. *Monthly Weather Review*, 133(8), 2246–2261. https://doi.org/10.1175/MWR2972.1
Liu, S., & Liang, X.-Z. (2010). Observed diurnal cycle climatology of planetary boundary layer height. *Journal of Climate, 23*(21), 5790-5809. https://doi.org/10.1175/2010JCLI3552.1

Stull, R. B. (1988b). *An introduction to boundary layer meteorology*. Dordrecht. (p.670). Atmospheric Sciences Library Kluwer. https://www.springer.com/gp/book/9789027727688

Sivaraman, C., McFarlane, S., Chapman, E., Jensen, M., Toto, T., Liu, S., & Fischer, M. (2013b). Planetary boundary layer (PBL) height value added product (VAP): Radiosonde retrievals. Gaithersburg, MD, USA. 1–10, U.S. Department of Energy. https://www.arm.gov/publications/tech_reports/doe-sc-arm-tr-132.pdf

Zhang, W., Guo, J., Miao, Y., Liu, H., So, Y., Fang, Z., et al. (2018b). On the summertime planetary boundary layer with different thermodynamic stability in China: A radiosonde perspective. *Journal of Climate, 31*, 1451–1465. https://doi.org/10.1175/JCLI-D-17-0231.1