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RELATIONSHIP BETWEEN ENTRAINMENT RATE AND SUMMER MONSOON DYNAMICS IN THE EASTERN NORTHWEST MONSOON TRANSITION REGION

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Abstract: The entrainment rate refers to the ratio of the surrounding air mass to the air mass involved in the rising unit distance, including turbulent entrainment and dynamic entrainment. It is applied to the boundary layer parameterization of convective clouds, numerical model improvement, and observation of cloud droplet spectrum dispersion and tropical cyclone studies. Using the high-altitude intensive observation data at 07:00 and 19:00 every day from May to September 2006 to September 2016 in the monsoon transition zone in the northwestern part of Minqin, Yuzhong, Pingliang, Yinchuan, and Yan'an, combined with the daily observation data on the ground, calculate the entrainment rate at different heights, and obtain the relationship between entrainment rate and height, monsoon precipitation and monsoon in different regions. The results show that: ① The entrainment rate is directly proportional to air temperature and saturated water vapor pressure, but inversely proportional to relative humidity. The relative humidity threshold of clouds is 65%. The higher the relative humidity threshold, the lower the cloud heights of different magnitudes of precipitation, and the cloud heights increase with the increase of rainfall. ② There are obvious early-night changes and regional differences in the entrainment rate: from the surface to 3 km, at 07 o'clock is significantly smaller than at 19 o'clock, the near-surface layer weakens with increasing altitude, and increases with altitude above 500 m; from small to large is the monsoon affected area, monsoon swing area and non-monsoon area, there is no obvious regional difference above 3 km. ③ The entrainment rate is closely related to the intensity and nature of precipitation: the entrainment rate decreases with the increase of rain intensity from near the ground to below 600m, but increases with the increase of rain intensity from 500m to 2-3 km; Stable precipitation below has strong entrainment, while convective precipitation above has strong entrainment. Convective precipitation has high saturated water vapor pressure and strong entrainment, while stable precipitation has high saturated water vapor density and rich water vapor but weak entrainment. ④ The relationship between the entrainment rate and the monsoon and its duration: the entrainment rate weakens from no monsoon to monsoon presence, and the maximum height of the strongest entrainment also decreases. There is no obvious difference in the duration of the entrainment rate between the non-monsoon area and the monsoon-affected area. Only in the monsoon swing area, the longer the duration near the surface, the smaller the entrainment rate, and the opposite is true at 1-2 km high. ⑤ The relationship between the entrainment rate and the Asian-Pacific Oscillation (APO) monsoon intensity index shows that: at 07:00, the near-surface layer increases with height, and above 800 m, it weakens with height, and the correlation between monsoon intensity and entrainment rate is not obvious; at 19:00, the near-surface It increases with altitude, and weakens with altitude above 300 m, and the stronger the monsoon, the smaller the entrainment rate. The entrainment rate decreases as the boundary layer height decreases.
Keywords: Entrainment rate; Summer monsoon; Dynamic relationship; Monsoon transition zone; Northwestern and eastern

1 INTRODUCTION

The entrainment rate is an important parameter in the convective parameterization scheme, which affects the transport of matter and energy in convective clouds, and plays a positive role in improving the cloud parameterization scheme in large-scale models, improving precipitation forecast and improving the effect of rainfall enhancement. In the foreign AP1000 nuclear power technology, the entrainment rate is used to determine whether the core is exposed [1], and Stanfield et al. [2] used the carbon monoxide (CO) measurement of the microwave detector and the tropospheric emission spectrometer on the Aura satellite to estimate the entrainment rate, and compared with CloudSat and CALIPSO The deep convection cases determined by the observations are correlated, CO is regarded as a conserved quantity on the time scale of convective transport, and the entrainment rate is derived by using a simple plume model, and the observed value of the entrainment rate is correlated with the convective height, the relative humidity of the environment and The relationship between the Convective Available Potential Energy (CAPE) of atmospheric infrared sounder data. Han et al[3] used the continuity equation of the liquid film in the ring fog flow to estimate the droplet entrainment rate in 349 experiments. Drueke et al. [4] used large eddy simulation to evaluate the entrainment rate of shallow cumulus, and proposed a cumulus entrainment recovery algorithm based on the Turbulent Kinetic Energy (TKE) similarity theory. The method is only estimated based on the environment and under-cloud conditions, and the first numerical verification of the three inversion methods is carried out by conducting observation system simulation experiments on a series of continental and ocean shallow water cumulus convection conditions. These simulations considered a wide range of shallow cumulus environments and variations in numerical configurations.

Lu Chunsong et al[5-7] used the mixing ratio of dry air and adiabatic clouds at a certain height to estimate the entrainment rate, taking into account the adiabatic growth and entrainment mixing process of cloud blocks. Guo Xiaohao[8,9] used the

TOGA-COARE (Tropical Ocean Global Atmosphere Coupled Ocean-Atmosphere Response Experiment) project deep convective cloud aircraft observation data, and applied the mixing ratio method to estimate the entrainment of convective clouds at different distances from ambient air to convective clouds. rate, indicating that the entrainment rate of deep convective clouds is related to the temperature and humidity of the ambient air, and higher humidity and lower temperature often correspond to a larger entrainment rate; The simulation shows that the entrainment rate decreases with height above the cloud base, and increases with height near the cloud top, but the higher the cloud top height is, the less obvious the entrainment rate increases near the cloud top. Khairoutdinov et al[10] found through simulation that the entrainment rate in cumulus congestus is smaller than that in shallow cumulus, and they found that the minimum entrainment rate is about 0.1 km- 1. De Rooy et al[11] calculated the entrainment rate in marine cumulus using the large eddy model, and the results showed that the entrainment rate decreased from 1.5 km- 1 to 0. 1 km- 1 below the height of 2 km, while at Above 2 km altitude, it is roughly kept at about 0. 1 km- 1. Jensen et al. [12] used an iterative method to calculate the entrainment rate according to the relationship between the equivalent potential temperature inside and outside the cloud and the entrainment rate at different heights: first assume that the entrainment rate is 0.1% km-1, and then The value of the entrainment rate is increased by an increment of 0. 1% km- 1 until the neutral buoyancy stratification of the air mass is similar to the observed cloud base height, and the entrainment rate value at this time is taken as the estimated value. Cheng et al. [13] also studied the entrainment rate at 5 m scale in 186 shallow cumulus clouds in the southern Great Plains of the United States in 2015, and showed that the average entrainment rate of the 186 cloud clusters was systematic from the cloud edge to the cloud center. decrease. Wan Rong et al[14] passed

Mesoscale MAPS (Mesoscale Analysis and Process System) torrential rain business model and cloud model nesting experiment, found that the entrainment coefficient has a certain relationship with the height of cloud development and precipitation intensity, which provides help for the prediction of county-level rainfall enhancement potential. Luo Shi et al. [15] used the explicit mixed bubble model (Extended Metra Potential Method, EMPM) to assume that the ambient air entrained into the cloud has different relative humidity, and explored the effect of dry air with different relative humidity being entrained into the cloud through sensitivity experiments. After the cloud, the impact on the cloud droplet spectrum and its microphysical quantities shows that the entrainment mixing process has an important impact on the cloud droplet spectrum, inhibits the formation of precipitation in the cloud, and weakens the development of convection. The entrainment rate in the above research focuses on the improvement of the numerical model, and mostly uses the data of aircraft cloud penetration, which has certain difficulties in practical application. In this paper, using the conventional radiosonde observation data at intervals of 10 m at 07:00 and 19:00 every day in the eastern non-monsoon affected area, monsoon swing area, and monsoon affected area in the eastern part of Northwest China, we explore the temporal variation of entrainment rates in different areas and at different heights, and further conclude that Relationship between entrainment rate and monsoon precipitation and summer monsoon.

2 APPLICATION DATA AND CALCULATION METHOD

Using a total of 5 stations in the non-monsoon area (Minqin) in the east of Northwest China, to the monsoon swing area (Yuzhong, Pingliang, and Yinchuan) and the monsoon-affected area (Yan'an) every day from May to September 2006-2016 at 07:00 and 19:00 The entrainment rate at different heights was calculated based on the high-altitude intensive observation data at a height of 10 m, combined with the daily observation data on the ground.

The entrainment rate is a parameter describing the entrainment strength, which refers to the rising unit distance. Humid air is a mixture of dry air and water vapor. In the atmosphere, the change of water vapor is obvious as the height rises. Therefore, the mass of saturated water vapor microgroups is used to replace M in this paper. The specific calculation is as follows:

T=t+273.16, t is temperature, P is air pressure, when t≥0, it is the state equation of ideal gas. The properties of general gases are very close to ideal gases under the conditions of not too high pressure and not too low temperature. Therefore, real gases are often treated as ideal gases.

According to the ideal gas state equation, that is, the equation describing the change law of the ideal gas state:

$$pV=mRT/M=nRT$$

In the formula: p is the gas pressure (Pa); V is the gas volume (m3); m is the saturated water vapor mass; n is the amount of gas substance (mol); T is the absolute temperature (K); R is the gas constant (proportion constant) [J/(mol K)]. Thus the constant in the volume V=T×constant/P is nR. In the equation of state represented by moles, R is a constant of proportionality. For any ideal gas, R is constant, which is (8.31441±0.00026) J/(mol·K). If mass is used to represent the state equation, pV=mrT, r is related to the gas type at this time, r is the gas constant/average molar mass of the gas, r=R/M, and M is the average molar mass of the gas. Constant=m×R/M.

3 DETERMINATION OF CLOUD AREA (RELATIVE HUMIDITY THRESHOLD METHOD)

Entrainment rate indicates the material and energy exchange between cloud and ambient air at the boundary of cumulus clouds. In this paper, encrypted sounding data is used to calculate the entrainment rate, and the relative humidity method is used to distinguish whether there are clouds. Sun Li et al. [16] analyzed and studied the humidity measurement error of radiosondes and concluded that under the condition of high temperature in the lower troposphere, the humidity measurement results are more accurate, and the identification of cloud layers is more reliable. Low humidity basically satisfies this condition, so it is relatively reliable to use relative humidity to judge cloud cover.

Calculate the cloudy threshold when the relative humidity is greater than 70%[17] The cloud thickness of different magnitudes of precipitation in the five stations from May to September, and the cloud thickness increases with the increase of rainfall: the light rain at 07 hours is 0.1-3.6 km, Moderate rain at 4.4-6.1 km, heavy rain at 4.9-8.2 km; 19:00 was lower and thinner than 07:00, light rain at 0-1.6 km, moderate rain at 0.7-5.7 km, heavy rain at 3.6-5.4 km. Minqin in the arid area was thicker and higher, while Yan'an in the semi-humid area was thinner and lower. At 19:00 Minqin and Yuzhong, there was no obvious difference in cloud thickness between moderate rain and heavy torrential rain.

The main research areas of this paper are the non-monsoon area, the monsoon swing area and the monsoon-affected area. The above-mentioned relative humidity greater than 70% is not suitable for cloudy thresholds. Further, 5 stations 5 are calculated from 70%, 65% and 60%. -September, the cloud heights of different levels of precipitation at each relative humidity threshold were used to determine the optimal threshold. The greater the relative humidity threshold, the lower the cloud height of different magnitudes of precipitation, and the cloud height increases with the increase of rainfall: when the relative humidity threshold is 70%, there is no cloud at 19:00, which is obviously inappropriate; the threshold is at When the threshold is 65%, light rain clouds appear at 1.55-3.25 km, moderate rain cloud height is 6.24 km, and heavy rain is 6.35 km; when the threshold is 60%, light rain clouds appear at 0.74-3.85 km, moderate rain and heavy rain cloud heights are the same is 6.95 km, but there is no difference. Based on the above analysis, it is more appropriate to set the relative humidity threshold above 65% with clouds.

4 RESULTS ANALYSIS

4.1 Changes with Altitude

During the monsoon period (May-September), the saturated water vapor pressure at 07:00 is significantly lower than that at 19:00, and at 07:00, the area below 2 km near the surface layer is classified into non-monsoon area, monsoon-influenced area, and monsoon swing area from large to small, and the area below 400 m increases with height., the above decreases with height. At 19:00, the area below 2.3 km near the surface layer is classified into non-monsoon area, monsoon oscillating area and monsoon affected area from large to small, and the difference between the monsoon affected area and monsoon oscillating area is less than 1 Pa as the altitude decreases. The non-monsoon area is larger below the height h of the near-surface layer, and the monsoon-affected area is larger above the h height, where h=2 km (07 o'clock) or h=3 km (19 o'clock), but the difference between the three areas above 3 km is less than 0.5 hPa, There is no change to the region. Since the entrainment rate tends to 0 above 3 km, there is no regional change. This paper focuses on the analysis of the entrainment rate change below 3 km. The calculation results of the entrainment rate are no rain, light rain, Height-by-height averages of moderate and heavy rain. The entrainment rate at 19:00 was greater than that at 07:00, and at 07:00, the entrainment rate increased from below 500 m to the ground with increasing altitude, from small to large, it was the monsoon-influenced area, non-monsoon area to monsoon swing area; above 500 m, the entrainment rate weakened with increasing altitude, From small to large, it is monsoon affected area, monsoon swing area to non-monsoon area; at 19:00, the entrainment rate increases from below 100 m to ground entrainment rate, from small to large, it is monsoon swing area, monsoon affected area to non-monsoon area, 100 m Contrary to the above, the entrainment rate decreases with increasing height, and the area from small to large is consistent with 07 o'clock.

4.2 Precipitation Changes during the Monsoon Period

4.2.1 Precipitation of different magnitudes

Taking the relative humidity of 65% as the cloudy threshold, the cloud height in different monsoon regions increases with the increase of rainfall: at 07:00, the light rain is 2.95-5.65 km, the moderate rain is 5.65-7.25 km, and the heavy rain is 5.24 -8.24 km; At 19:00 it was lower and thinner than at 07:00, with light rain at 2.55-3.35 km, moderate rain at 2.55-6.55 km, and heavy rain at 4.05-5.45 km. The non-monsoon area is thicker and higher, and the monsoon-affected area is thinner and lower. At 19:00, there is no obvious difference in cloud thickness between moderate rain and heavy torrential rain in Minqin and Yuzhong.

The saturated water vapor pressure gradually decreases from no rain, light rain, moderate rain and heavy to heavy rain, and decreases with the increase of altitude, and is less than 0.2 hPa at 10 km. The saturated water vapor density increases with the increase of rainfall, and is 10.2 g/m3 in the near-surface moderate rain and heavy to heavy rain, and decreases with the increase of altitude, and is 3.5 g/m3 at 10 km.

The entrainment rate at 19 o'clock is significantly greater than that at 07 o'clock, and the entrainment rate decreases with the increase of height, and the weakening is more obvious at 19 o'clock than that at 07 o'clock. There is no change in rain intensity above 3 km, and the entrainment rate decreases from 1.0 × 10-6 m - 1 tends to 0. At 07:00, the entrainment rate of the non-monsoon area, monsoon swing area, and monsoon-influenced area increases with the increase of rain intensity from the ground to below 600, 800, and 400 m, respectively, and the entrainment rate increases with the increase of rain intensity at above 1.85, 2.65, and 2.55 km, respectively. rate weakens and tends to be 1.0 × 10-6 m- 1 at 3 km. At 19:00, the entrainment rate in the non-monsoon area and the monsoon swing area below 50 m below the surface layer increased with the increase of rain intensity, and the entrainment rate in the above three areas all decreased with the increase of rain intensity. The entrainment rate in different regions weakens gradually from the non-monsoon region, the monsoon swing region to the monsoon-affected region.

Compare the relationship between different magnitudes of precipitation and the entrainment rate below 3 km: the entrainment rate below 3 km near the surface is inversely proportional to the rain intensity, the greater the rain intensity, the smaller the entrainment, and the entrainment rate increases with height in the near-surface, the above weakens with altitude.

Temperature: at 07:00, the range from low to high below 2km is moderate rain, light rain, heavy to heavy rain, and no rain; The height is light rain, no rain, moderate rain, heavy to heavy rain, and the height above 3.2 km increases with the increase of rainfall. At 19:00, from low to high below 0.6 km, heavy to heavy rain, moderate rain, light rain, and no rain; 0.6-2.0 km, moderate rain, heavy to heavy rain, light rain, and no rain; 2.0-2.6 km, moderate rain, light rain, heavy rain From heavy rain to no rain, 2.6-3.6 km is moderate rain, light rain, no rain, heavy to heavy rain, and the height above 3.6 km increases with the increase of rainfall.

Relative humidity: 1 000 m at 07:00, decreases with height below 200 m at 19:00, and increases with height above to the maximum humidity height. At 07:00, the relative humidity increased with the increase of rainfall, and the relative humidity of no rain, light rain, moderate rain and heavy to heavy rain below 50 m near the ground was 63%, 76%, 82% and 88% respectively; the humidity increased with the increase of height, but there is a large value center for light rain and heavy rain at 2.6 km, and moderate rain at 3.3 km, and the humidity decreases with the increase of altitude. At 19:00, the humidity increases with the increase of rainfall. The relative humidity of no rain, light rain, moderate rain and heavy to heavy rain below 50 m near the ground is 36%, 58%, 72% and 80%, respectively, and the humidity increases with the increase of height, the maximum humidity values of no rain, light rain, moderate rain and heavy to heavy rain are 50%, 68%, 72% and 85% respectively, and the altitudes are 2.2, 2.3, 2.3 and 1.8 km respectively. Small, tends to decrease to less than 25% above 10 km.

From the non-monsoon affected area, the monsoon swing area to the monsoon affected area, the temperature decreases and the humidity increases; while the relative humidity increases with the increase of rainfall, increases with the increase of altitude below 2-3 km, and decreases with the increase of altitude. Small, the temperature is lower and the humidity is higher at 07:00 than at 19:00. The higher the temperature, the greater the saturated water vapor pressure, the lower the relative humidity, and the greater the entrainment rate. The above can fully explain that the entrainment rate at 19 o'clock is greater than that at 07 o'clock. The cause of height weakening.

4.2.2 Different types of precipitation

According to the nature of precipitation, precipitation can be divided into stable precipitation and convective precipitation. Stable precipitation is continuous precipitation, and the cloud system is dominated by stratus clouds, and the atmospheric stratification is stable; while convective precipitation is episodic precipitation, and the cloud system is mainly convective clouds. Lord, the atmospheric stratification is unstable. Cloud distribution: Convective cloudless at 07:00, 2.55-3.35 km at 19:00; stable 0-4.55 km at 07:00, 1.15-3.05 km at 19:00, convective clouds are high and shallow, stable clouds are low and deep. Compare the relationship between precipitation with different properties and saturated water vapor pressure, saturated water vapor density and entrainment rate. The saturated water vapor pressure is higher in non-monsoon regions and convective precipitation, with a difference of 2-4 hPa; the saturated water vapor density is higher in stable precipitation, with a difference of 0.09-0.13 g/m3. The entrainment rate was less than 19 at 07:00, and the convection was less than stable below 700 and 300 m at 07:00 and 19:00, respectively, and the entrainment rate increased with height. On the contrary, it tended to be 1.0 × 10-6 m-1 at 3 km.

5 RELATIONSHIP WITH SUMMER MONSOON

5.1 Whether there is a Summer Monsoon

The entrainment rate has obvious diurnal variation in the non-monsoon area, monsoon swing area and monsoon impact area from the ground to 2.3, 1.7 and 1.5 km below, respectively, and is less than 19:00 at 07:00, the difference is the largest in the non-monsoon area, and the smallest in the monsoon swing area. There are no diurnal and regional differences above 3 km. At 07:00 and 19:00, it strengthens with altitude below 800m and 200m respectively, and weakens with altitude above. The entrainment rate is stronger in the non-monsoon area up to 5.0 × 10-6 m- 1 with a maximum height of 1.0 km; while in the monsoon swing area and monsoon affected area it is 4.0 × 10-6 m- 1 with a maximum height of 0.7 and 0.6 km. The entrainment rate from no monsoon to monsoon weakens, and the maximum height also decreases.

5.2 Duration of Summer Monsoon

The duration of the summer monsoon is divided into 0 pentad, 1-4 pentad, and 5 pentad and above. The non-monsoon-affected area and the monsoon swing area do not have a duration of more than 5 pentads, while the monsoon-affected area does not have a 0-pentad duration. There is no obvious difference in the duration of the entrainment rate between the non-monsoon-affected area and the monsoon-affected area. Only the monsoon swing area is below 700 m at 07:00, the pentad is strong, the middle and high level is 1-1.8 km, 1-4 pentad is strong, and at 19:00, it is below 200 m. 0 pentad is strong, middle and upper 1.7-2.1 km 1-4 pentad is strong, the longer the monsoon swing area lasts near the surface layer, the smaller the entrainment rate, and the opposite is true at 1-2 km. From strong to weak, it is the non-monsoon area, the monsoon swing area, and the monsoon-influenced area. The strongest entrainment height in the non-monsoon area and the monsoon swing area was as high as 2 km at 07:00, and as low as about 1 km at 19:00; The stratum entrainment rate increases with height to be greater than 19 hours, but the above decreases with height to be less than 19 hours.

5.3 Summer Monsoon Intensity

Three kinds of monsoon intensity index ZTCI (Zhang Tao Chen Index) (East Asian summer monsoon), dynamic normalized seasonality (DNS) and Asia-Pacific Oscillation (APO) were calculated by using the data of the National Center for Environmental Prediction (NCEP). ZTCI, DNS and APO are monsoon intensity indices defined by Zhang Qingyun et al.[18], Li Jianping[19] and Zhao Pingping[20] respectively. In terms of interdecadal changes: ZTCI was weaker in the 1960s and 1990s, stronger in the 1980s, and tended to normal after entering the 21st century; From the 1960s to the 1980s, the APO tended to weaken, and then to the 21st century, and then to the 21st century, and the trend of ZTCI and APO was opposite from the 1960s to the 1990s, but after the 1990s, they all tended to normal. The three monsoon intensity indices have poor correlations with precipitation and precipitation days, but APO has a good correlation with the total precipitation from May to September in the monsoon swing area, and the number of days with moderate rain and above precipitation, with correlation coefficients of 0.5 and 0.57, respectively, and The correlation coefficient with the boundary layer height of the monsoon-affected area reaches -0.74. Therefore, the APO index is selected as the monsoon intensity index in this paper to further discuss the relationship between the entrainment rate and monsoon intensity. The index size is divided into strong: greater than or equal to 0.5, normal: -0.5-0.5, weak: less than or equal to -0.5. Calculate the variation of entrainment rate with altitude from May to September under different monsoon intensities of APO from 2006 to 2016: at 07:00 below 800 m, it increases with altitude, and above 800 m, it weakens with altitude. The correlation between monsoon intensity and entrainment rate is not obvious; at 19:00 Below 300m, it strengthens with height, and above 300m, it weakens with height. The stronger the monsoon, the smaller the entrainment rate.

6 CONCLUSION AND DISCUSSION

By analyzing the entrainment rate at different heights in the monsoon transition zone in the eastern northwest, it is shown that the entrainment rate has a certain relationship with height, monsoon precipitation and summer monsoon. ① The entrainment rate is directly proportional to air temperature and saturated water vapor pressure, but inversely proportional to relative humidity. The relative humidity threshold of clouds is 65%. The higher the relative humidity threshold, the lower the cloud heights of different magnitudes of precipitation, and the cloud heights increase with the increase of rainfall. ② There are obvious early-night changes and regional differences in the entrainment rate, from the surface to 3 km 07 o'clock is obviously less than 19 o'clock, the near-surface layer below 500 m increases with height, and above it weakens with height, from small to large is the monsoon affected area, monsoon swing area and non-monsoon area, there is no regional difference above 3 km. The entrainment rate is closely related to the rain intensity: the entrainment rate of the near-surface layer decreases with the increase of the rain intensity, but the entrainment rate increases with the increase of the rain intensity from 400–800 m to 2–3 km; the near-surface layer's stable precipitation entrainment The volume is strong, and the convective precipitation above 700 m is strongly entrained. ③ The entrainment rate decreases from no monsoon to monsoon, and the maximum height of the strongest entrainment also decreases. There is no obvious difference in the duration of the entrainment rate between the non-monsoon area and the monsoon-affected area. Only in the monsoon swing area, the longer the duration near the surface layer, the smaller the entrainment rate, and the opposite is true at 1-2 km high. (4) The application of the APO monsoon intensity index shows that: at 07:00, it intensifies with height below 800 m, and weakens with height above, and the correlation between monsoon intensity and entrainment rate is not obvious; The smaller the strong entrainment rate. ⑤ Since the height of the boundary layer during the monsoon period is 2 600 m, 1 800 m and 1 500 m from the non-monsoon-affected area, the monsoon swing area to the monsoon-affected area, respectively, the above analysis shows that the entrainment rate decreases with the decrease of the boundary layer height, mainly concentrated in the 3km or less.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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