Climatic Variations in the Boundary Layer Height of Arid and Semiarid Areas in East Asia and North Africa

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Abstract

Based on the ERA-20C, climatic variations of the boundary layer height (BLH) over arid and semiarid areas in East Asia and North Africa that span 1900–2010 were analyzed. In East Asia, the BLH exhibited a descending trend from arid region centers to the periphery. Over the past 111 years, the BLH has had a rising trend of 14.0 m decade\(^{-1}\) in the representative region (EA1) of the eastern areas with the 111-year average of 725 m and a decreasing trend of \(-1.6\) m decade\(^{-1}\) in the representative region (EA2) of the western areas with the 111-year average of 792 m. From the mid-1960s to 1970s, EA1’s BLH had a sharp rise that caused the average to increase by 93 m after the 1980s. In North Africa, the BLH exhibited a high spatial distribution in the western and southern areas and a relatively low spatial distribution in the eastern and northern areas. Over the past 111 years, the BLH has had a rising trend of 9.7 m decade\(^{-1}\) in the representative region (NA1) of the southwestern region with the 111-year average of 915 m and a decreasing trend of \(-6.3\) m decade\(^{-1}\) in the representative region (NA2) of other regions with the 111-year average of 882 m. In the 1940s and the 1970s, NA1’s BLH had two obvious increases that caused the average to increase by 51 m and 22 m, respectively, while NA2’s BLH had two obvious declines that caused the average to decrease by 48 m and 7 m, respectively. On the spatial distribution, the BLH, sensible heat flux, latent heat flux, and volumetric soil water had a good corresponding relationship. On the temporal change, the BLH in East Asia had a stronger correlation with thermodynamic factors, whereas the BLH in North Africa had a stronger correlation with dynamic factors. Besides, the upper-level stratification also has some influence on the BLH’s change.

Keywords arid and semiarid areas; boundary layer height; climatic variations; heat flux; volumetric soil water; dynamic factor

1. Introduction

The atmospheric boundary layer (ABL) is a layer that is greatly influenced by the earth’s surface friction, thermal process and evaporation and is the nearest troposphere to the earth’s surface. It determines the exchange of heat, moisture, and momentum between the earth’s surface and the free atmosphere (Schmid and Niyogi 2012; Compton et al. 2013; Couvreux et al. 2009) and plays a role in the modulation of the atmosphere at weather and climatic time scales. Thus, it has an important role in extreme weather and climatic events. The ABL height, in general, is defined as the height at which insignificant turbulent transfers of heat, mass, and momentum between the earth’s surface and atmosphere occur when they are averaged over a period of the order of an hour (Arya et al. 1981); it ranges from less than 100 m to several kilometers (Molod et al. 2015). The boundary
layer height (BLH), a very important physical parameter of the ABL, characterizes the ABL in a fairly integrated manner and is closely related to the fundamental variables such as surface heat fluxes, cloud cover and water, etc (von Engeln and Teixeira 2013). It is determined by the surface heat flux and meteorological evapotranspiration (Stull 1988) and has a strong effect on the development and evolutionary process of the clouds and convection (Gamo 1996), thus revealing the uniqueness of its atmospheric boundary. Then, what kind of variation characteristics does the BLH of arid and semiarid areas show? The European Centre for Medium-Range Weather Forecast (ECMWF) released a new set of reanalysis data in 2015, called the ERA-20C, which spanned 1900–2010 with a spatial resolution of 0.125° × 0.125° and a temporal resolution of once every 3 h. This provides the data foundation for research on the BLH's change at larger scopes and longer time scales. This article analyzes the climatic variations of the BLH of arid and semiarid areas in East Asia and North Africa, especially at the inter-decadal scale, using the ERA-20C data and compares similarities and differences of the temporal and spatial variation in the BLH over the two regions. Based on this premise, we primarily studied the thermodynamic and dynamic factors' influence on the BLH's change in consideration of the climatic conditions over arid and semiarid areas. Previous studies showed that in arid areas, the water vapor has unexpected characteristics from existing knowledge (Mitsuta et al. 1995), and the variations of specific humidity do not obey Monin-Obukhov similarity (Tamagawa 1996). Thus, we also include some variables related to humidity, such as volumetric soil water. Through this study, we hope to make a preliminary analysis of the BLH characteristics over arid and semiarid areas.

2. Data and study areas

The ERA-20C, a set of reanalysis data from the ECMWF, was released in 2015 and contains 111 years of data; thus, it is possible to analyze the BLH climatic characteristics of longer time scales. The ECMWF also has another set of reanalysis data called the ERA-Interim. Although the ERA-Interim has assimilated a large amount of atmospheric satellite data, its time scale is only 37 years. We chose the ERA-20C as the primary data for our study. To verify the quality of the ERA-20C data, we compared the BLH of the ERA-20C and ERA-Interim. The result is shown in Figs. 1 and 2. On the spatial distribution, the BLH of the East Asian arid and semiarid areas indicated by ERA-20C is higher overall than that indicated
by ERA-Interim, and the BLH of the North African arid and semiarid areas indicated by the ERA-20C is almost similar to that indicated by ERA-Interim overall. However, the BLH’s basic change trend over time, indicated by the two sets of data, is consistent in both regions. In general, it can be concluded that ERA-20C is able to reasonably characterize the variation characteristics of the BLH.

The data primarily used in this study were monthly BLHs, sensible heat fluxes, latent heat fluxes, and four layers of volumetric soil water from ERA-20C. ERA-20C relies on a recent version of the ECMWF’s Integrated Forecast System (IFS) (Poli P et al. 2016). In the IFS (ECMWF 2014), to get a continuous field, the BLH’s parametrization of the mixed layer uses a BLH from an entraining parcel model, and a bulk Richardson method is used as a diagnostic, independent of the turbulence parametrization in neutral and stable situations. This method follows the conclusions of a recent study by Seidel et al. (2012). The volumetric soil water includes four layers, and the depths of the soil layers (Balsamo et al. 2009) are in an approximate geometric relation (7 cm for the top layer, then 21, 72, and 189 cm, respectively), as shown in Table 1. To explain some conditions that are not reasonable using only the thermodynamic factors, we also added some dynamic factors, choosing the monthly boundary layer dissipation, surface roughness, 10 m wind speed, 10 m U wind component (the meridional wind), 10 m V wind component (the zonal wind), 100 m U wind component, and 100 m V wind component of ERA-

Fig. 1. The spatial comparison between East Asia and North Africa. 1a is the East Asia BLH shown by ERA-20C, 1b is the East Asia BLH shown by ERA-Interim, 1c is the North Africa BLH shown by ERA-20C, and 1d is the North Africa BLH shown by ERA-Interim. (Note: the 200 mm annual precipitation line is the arid dividing line, and the 450 mm annual precipitation line is the semiarid dividing line.)

Fig. 2. Time comparison between East Asia and North Africa. 2a is East Asia’s BLH, and 2b is North Africa’s BLH. (Note: the black line is shown by ERA-20C, and the gray line is shown by ERA-Interim.)
The arid region of East Asia had an area of 3.90 × 10^6 km^2 and a BLH of 700–1100 m, and the semiarid region of East Asia had an area of 5.36 × 10^6 km^2 and a BLH of 500–800 m. There were three main high-value centers of BLH that were distributed at the junction of Gansu, Xinjiang, Inner Mongolia and Mongolia, northwest of the Taklimakan Desert and the Qaidam Basin. It is worth noting that the Tibet Plateau showed an obvious high-value center of BLH, which is consistent with the observations of previous research (Chen et al. 2013; Chen et al. 2016), thus proving the reliability of the ERA-20C data. Because our object is mainly for arid and semiarid areas, there is no particular analysis for the Tibet Plateau. The overall distribution expressed a descending trend from the center arid region to the periphery. The decline of the west area’s BLH was mainly affected by the Tianshan Mountains, and because of the relatively higher vegetation coverage and a more humid climate, the BLH there also presented a lower phenomenon. The decline of the north area’s BLH mainly occurred in the Altai Mountains, and the degressive gradient of Mongolia was significantly large because northern Mongolia has more rivers and lakes. The degressive gradient of the east area’s BLH was distributed more uniformly, with four periods of decline. The first decline was in the Badain Jaran Desert, the second one was in the Hetao Plain along the Yellow River basin, the third one was in the north of the North China Plain, and the fourth one was in the Northeast China Plain.

As shown in Fig. 3, good consistency exists between the BLH and the sensible heat flux, latent heat flux, and volumetric soil water (all four layers). The high-value center of the sensible heat flux is located at the junction of Xinjiang and Mongolia and the sensible heat flux decreases from the central arid region to the periphery. The low-value center of the latent heat flux and volumetric soil water (all four layers) is located in the area from the Taklimakan desert to the Badain Jaran Desert, increasing from the central arid region to the periphery. By comparing these variables’ distribution with the arid and semiarid boundary, it could be observed that there was good consistency, especially for the distribution profile of the arid boundary, which was strongly consistent with high values of the BLH and sensible heat flux and low values of the latent heat flux and volumetric soil water (all four layers).

The arid region in North Africa had an area of 1.25 × 10^7 km^2, with the western area’s BLH ranging between 800 and 1200 m and the eastern area’s BLH ranging between 500 and 800 m. The semiarid region in North Africa had an area of 4.63 × 10^6 km^2, with the southern semiarid area’s BLH ranging between 800 and 1200 m. There were three main high-value centers of BLH, which were located in the Atlas Mountains, the central Sahara Desert and the Bill Martha Desert. The overall distribution showed a high BLH in the western area, a low BLH in the eastern area, a high BLH in the southern area, and a low BLH in the northern area. In arid regions, larger BLH gradients were mainly located at the edge of the high BLH, and the BLH was lower in the east, mainly at the Nile River and its surrounding areas. The degressive gradient of the northern semiarid region was probably influenced by the Mediterranean Sea, and the degressive gradient of the southern semiarid area was probably influenced by some rivers and lakes, such as the Senegal River, Niger River, Lake Chad, Chari River, and White Nile.

### Table 1. The distribution of the volumetric soil water layers in the vertical direction.

| Level | Top (m) | Bottom (m) | Thickness (m) |
|-------|---------|------------|---------------|
| 1     | 0.00    | 0.07       | 0.07          |
| 2     | 0.07    | 0.28       | 0.21          |
| 3     | 0.28    | 1.00       | 0.72          |
| 4     | 1.00    | 2.89       | 1.89          |
River, from west to east.

As shown in Fig. 4, good consistency also exists in the BLH and the sensible heat flux, latent heat flux and volumetric soil water (all four layers), but it is less than in North Africa. The distribution of the sensible heat flux and the BLH corresponded well. In the middle of the arid region, the distribution showed some scattered BLH’s high-value centers, where the sensible heat flux correspondingly showed a high value. Moreover, the BLH and the sensible heat flux were both high in the southern semiarid region. The latent heat flux and volumetric soil water (all four
Fig. 4. Same as Fig. 3, except for North Africa.
layers) showed consistently low values in the middle of the arid region, which increased in the north and south and showed relatively higher values in the southern semiarid region and the nearby region. The distribution of the high sensible heat flux, low latent heat flux and volumetric soil water (all four layers) at the mid-western arid region, and the high sensible heat flux, latent heat flux, and volumetric soil water (all four layers) in the southern semiarid region made the BLH’s high-value center to appear at the mid-western arid region, and not at the southern semiarid region. By comparing the distribution of these variables with the arid and semiarid boundary, it could be observed that the distribution profile of the arid and semiarid boundary was consistent with the BLH, sensible heat flux, latent heat flux, and volumetric soil water (all four layers).

By conducting a contrast analysis of the BLH, sensible heat flux, latent heat flux and volumetric soil water of the arid, and semiarid areas in East Asia and North Africa, we found that there was a good corresponding relationship between the BLH, sensible heat flux, latent heat flux, volumetric soil water and the drought degree; that is, the drier the region is, the lower the volumetric soil water and the latent heat flux are and the higher the sensible heat flux and BLH are. However, the sensible heat flux reflected some exceptions in the corresponding relationship. In arid and semiarid areas in East Asia and the typically extreme arid areas, the Taklimakan Desert’s BLH was not the most obvious high-value center. By contrasting the distribution of the sensible heat flux, latent heat flux, and volumetric soil water, we found that although the latent heat flux and volumetric soil water of the Taklimakan Desert were obviously low, the sensible heat flux in the desert was observed to be abnormally low. In North Africa, which is a typical extreme arid area, the west Sahara Desert’s sensible heat flux was lower than the southern semiarid regions. This indicates that albeit a drier the region tends to have a higher sensible heat flux, this increase is limited in the case of extreme drought, thus affecting the development of the boundary layer. The cause of this phenomenon is worth exploring.

By combining Figs. 3 and 4 and Table 2 to compare the BLH, sensible heat flux, latent heat flux and volumetric soil water of East Asia and North Africa, we found that the BLH of North Africa was, obviously higher than that of East Asia. The difference is that the sensible heat flux of North Africa is higher than that of East Asia, and the latent heat flux and volumetric soil water of North Africa are less than those of East Asia. The BLH of EA2 is higher than that of EA1, while the sensible heat flux of the two regions is similar, but the differences of the two regions in the latent heat flux and volumetric soil water are obvious. Similarly, the BLH of NA2 is higher than that of NA1, while the sensible heat flux of the two regions is similar, but the differences of the two regions in the latent heat flux and volumetric soil water are obvious. This explains that the spatial differences of BLH in East Asia and North Africa mainly lies in the latent heat flux and volumetric soil water.

### 3.2 Spatial distribution of change trend

The BLH’s climatic trend rate of arid and semiarid areas in East Asia presented a distribution that the value the western area was negative, with a value of $-3–0$ m decade$^{-1}$, and the value the eastern area was positive, with a value of $0–10$ m decade$^{-1}$, as shown in Fig. 5. This indicated that in the past 111 years, the BLH presented a decreasing trend in the western area and a rising trend in the eastern area. In the eastern area, the high-value center of the BLH’s climatic trend rate extended from the North China Plain northeastward to the southern Great Khingan, and then northwestward to central Mongolia, thus forming a V shape. The distribution of the V shape was largely similar to the distribution of the 200, 450 mm annual precipitation lines and located between the two lines, thus showing that in the east of the arid and semiarid boundary and the semiarid areas, the BLH increased more quickly.

As shown in Fig. 5, there was good consistency among the climatic trend rate of the BLH, sensible heat flux, latent heat flux, volumetric soil water. The

|      | BLH (m) | SH (W m$^{-2}$) | LH (W m$^{-2}$) | VSW1 (m$^3$ m$^{-2}$) | VSW2 (m$^3$ m$^{-2}$) | VSW3 (m$^3$ m$^{-2}$) | VSW4 (m$^3$ m$^{-2}$) |
|------|---------|----------------|----------------|----------------------|----------------------|----------------------|----------------------|
| EA1  | 725     | 32             | 26             | 0.2127               | 0.2074               | 0.1932               | 0.1956               |
| EA2  | 792     | 31             | 13             | 0.0867               | 0.1124               | 0.1046               | 0.1012               |
| NA1  | 915     | 44             | 5              | 0.0342               | 0.0379               | 0.0240               | 0.0192               |
| NA2  | 882     | 44             | 2              | 0.0018               | 0.0039               | 0.0005               | 0.0000               |

Table 2. The average of the BLH, sensible heat flux (SH), latent heat flux (LH) and volumetric soil water of layers 1–4 (VSW1, VSW2, VSW3, and VSW4).
sensible heat flux’s climatic trend rate in East Asia presented a distribution that showed that the western area was negative, and the eastern area was positive, thus indicating that in the past 111 years, the sensible heat flux presented a decreasing trend in the western area and a rising trend in the eastern area. The high-value center of the sensible heat flux climatic trend rate was the same, with the BLH’s forming a V shape. The latent heat flux’s and volumetric soil water’s climatic trend rates in East Asia presented a distribution in which the western area was positive, and the eastern area was negative, thus indicating that in the past 111 years, the latent heat flux and volumetric soil water presented a rising trend in the western area.
area and a decreasing trend in the eastern area. The low-value center of the sensible heat flux climatic trend rate also formed a V shape at the same place at that of the sensible heat flux and the BLH.

The BLH’s climatic trend rate of arid and semi-arid areas in North Africa presented a distribution in which

Fig. 6. Same as Fig. 5, except for North Africa.
the southwestern region was positive, with a value of 0–10 m decade\(^{-1}\), and other regions were negative, with a value of −5–0 m decade\(^{-1}\), as shown in Fig. 6. This indicated that in the past 111 years, the BLH presented a rising trend in the southwestern region, and a decreasing trend in the other regions. To the west of 5°E, the climatic trend rate was mainly positive around the southern arid and semiarid boundaries. To the east of 5°E, the values at the arid boundary were mainly negative, whereas they were around zero at the semiarid boundary.

As shown in Fig. 6, there was some consistency among the climatic trend rate of the BLH, sensible heat flux, latent heat flux, volumetric soil water, but the consistency was less than in North Africa. In the southwestern region, the sensible heat flux, latent heat flux, and volumetric soil water showed a decreasing trend, while the BLH showed a rising trend, thus indicating that in the change of BLH, the latent heat flux and volumetric soil water contributed more than the sensible heat flux. In the other regions, the sensible heat flux, latent heat flux, and volumetric soil water showed a rising trend, while the BLH showed a decreasing trend, thus also indicating that in the change of BLH, the latent heat flux and volumetric soil water contributed more than the sensible heat flux.

By comparing the change trend distribution on space, it was found that the BLH’s change in East Asia was dominated by the sensible heat flux, latent heat flux, and volumetric soil water, while the BLH’s change in North Africa was mainly dominated by the latent heat flux and volumetric soil water.

### 3.3 Temporal change characteristics

For convenience, we selected four representative areas as follows: EA1, which represented the BLH’s positive change areas in East Asia; EA2, which represented the BLH’s negative change areas in East Asia; NA1, which represented the BLH’s positive change areas in North Africa; and NA2, which represented the BLH’s negative change areas in North Africa. Figs. 5 and 6 show the analysis of the change of arid and semiarid areas in East Asia and North Africa in detail.

In the EA1 region of East Asia, the BLH average was 725 m, with a maximum of 892 m, a minimum of 615 m, and a climatic trend rate of 14.0 m decade\(^{-1}\), which passed the 99% significance test. The average volumetric soil water of layer 1 was 0.21 m\(^3\) m\(^{-3}\), with a maximum of 0.26 m\(^3\) m\(^{-3}\), a minimum of 0.15 m\(^3\) m\(^{-3}\), and a climatic trend rate of −0.005 m\(^3\) m\(^{-3}\) decade\(^{-1}\), which passed the 99% significance test. The average volumetric soil water of layer 2 was 0.21 m\(^3\) m\(^{-3}\), with a maximum of 0.26 m\(^3\) m\(^{-3}\), a minimum of 0.15 m\(^3\) m\(^{-3}\), and a climatic trend rate of −0.005 m\(^3\) m\(^{-3}\) decade\(^{-1}\), which passed the 99% significance test. The average volumetric soil water of layer 3 was 0.19 m\(^3\) m\(^{-3}\), with a maximum of 0.25 m\(^3\) m\(^{-3}\), a minimum of 0.15 m\(^3\) m\(^{-3}\), and a climatic trend rate of −0.005 m\(^3\) m\(^{-3}\) decade\(^{-1}\), which did not pass the 99% significance test.

As shown in Figs. 7a–g, in the EA1 region, the BLH presented a significant upward trend, the sensible heat flux presented a significant increasing trend, the latent heat flux presented a significant decreasing trend, the volumetric soil water of layers 1–3 presented a significant decreasing trend, and the volumetric soil water of layer 4 presented an increasing trend. During 1900–1920, the change of the BLH was relatively stable; during 1920–1960, the BLH presented a slowly increasing trend. From the mid-1960s to the early 1970s, there was a sharp BLH rise; the BLH then dropped in the mid-1970s to finally follow a trend of inter-annual oscillation with a greater height than that in the 1960s. During this time, the BLH average was 684 m before the 1960s, and 777 m after the 1980s, and the difference between the two values was 93 m. Correspondingly, during 1900–1920, the change of the sensible heat flux was relatively stable. During 1920–1960, the sensible heat flux presented a slowly increasing trend, and from the 1960s to the 1970s, there was a sharp rise. The sensible heat flux dropped in the mid-1970s, finally showing a trend of inter-annual oscillation with higher values than those in the 1960s. The average sensible heat flux was 29 W m\(^{-2}\) before the 1960s and 35 W m\(^{-2}\) after the 1980s. During 1900–1920, the change in the latent heat flux was relatively stable. During 1920–1960, the latent heat flux presented a slowly decreasing trend, whereas from the 1960s to the 1970s, there was a sharp decrease. The latent heat flux increased in the mid-1970s, finally showing a trend of inter-annual oscillation with lower values than in the 1960s. The average latent heat flux was 29 W m\(^{-2}\) before the 1960s and 23
W m$^{-2}$ after the 1980s. Similarly, during 1900–1920, the change in the volumetric soil water was relatively stable. During 1920–1960, the volumetric soil water exhibited a slowly decreasing trend, and from the 1960s to the 1970s, there was a sharp decrease. The volumetric soil water increased in the mid-1970s, finally showing a trend of inter-annual oscillation with lower values than those in the 1960s. The amplitude of the change decreased with the increase of soil depth. From the analysis, it is clear that the BLH of EA1 appears to have a positive correlation with the sensible heat fluxes and negative correlation with the latent heat flux and volumetric soil water.

In the EA2 region of East Asia, the BLH average was 792 m, the maximum was 887 m, the minimum was 714 m, and the climatic trend rate was $-1.6$ m decade$^{-1}$, which did not pass the significance test. The region had a sensible average heat flux of 31 W m$^{-2}$, a maximum of 36 W m$^{-2}$, a minimum of 28 W m$^{-2}$, and a climatic trend rate of $-0.04$ W m$^{-2}$ decade$^{-1}$, which did not pass the significance test. The region’s had a latent heat flux average of 13 W m$^{-2}$, with a maximum of 17 W m$^{-2}$, a minimum of 9 W m$^{-2}$, and a climatic trend rate of 0.15 W m$^{-2}$ decade$^{-1}$, which passed the 99% significance test. It had an average volumetric soil water of layer 1 of 0.09 m$^3$ m$^{-3}$, with a maximum of 0.12 m$^3$ m$^{-3}$, a minimum of 0.05 m$^3$ m$^{-3}$, and a climatic trend rate of 0.0004 m$^3$ m$^{-3}$ decade$^{-1}$, which did not pass the significance test. It had an average volumetric soil water of layer 2 of 0.11 m$^3$ m$^{-3}$, a maximum of 0.14 m$^3$ m$^{-3}$, a minimum of 0.08 m$^3$ m$^{-3}$, and a climatic trend rate of
0.0006 m$^3$ m$^{-3}$ decade$^{-1}$, which did not pass the significance test. It has an average volumetric soil water of layer 3 of 0.10 m$^3$ m$^{-3}$, a maximum of 0.13 m$^3$ m$^{-3}$, a minimum of 0.07 m$^3$ m$^{-3}$, and a climatic trend rate of $-0.0007$ m$^3$ m$^{-3}$ decade$^{-1}$, which did not pass the significance test. It had an average volumetric soil water of layer 4 of 0.10 m$^3$ m$^{-3}$, a maximum of 0.13 m$^3$ m$^{-3}$, a minimum of 0.09 m$^3$ m$^{-3}$, and a climatic trend rate of $-0.002$ m$^3$ m$^{-3}$ decade$^{-1}$, which passed the 99% significance test.

As shown in Figs. 7h–n, in the EA2 region, the BLH presented a significant downward trend, the sensible heat flux presented a significant decreasing trend, the latent heat flux presented a significant increasing trend, the volumetric soil water of layers 1–2 presented a significant increasing trend, and the volumetric soil water of layers 3–4 presented a decreasing trend. The change in the EA2 region was relatively stable, and the overall trend is not obvious, as it did not pass the significance test. During 1900–1940, the BLH presented an upward trend of fluctuations. During 1940–2010, the BLH presented a slow downward trend. Correspondingly, during 1900–1940, the sensible heat flux presented an increasing trend of fluctuations; during 1940–2010, the sensible heat flux presented a slowly decreasing trend. During 1900–1940, the latent heat flux presented the decreasing trend of fluctuations; during 1940–2010, the latent heat flux presented a slowly increasing trend. During 1900–1940, the volumetric soil water of layers 1–3 presented a decreasing trend of fluctuations. During 1940–2010, the volumetric soil water of layers 1–3 presented a slowly increasing trend. The volumetric soil water of layer 4 presented a decreasing trend of fluctuations in 1900–1960 and a slowly increasing trend in 1960–2010. From the analysis, it is clear that the BLH of EA2 appears to have a positive correlation with the sensible heat fluxes and a negative correlation with the latent heat flux and volumetric soil water.

In the NA1 region of North Africa, the BLH average was 915 m, the maximum was 1,004 m, the minimum was 807 m, and the climatic trend rate was 9.7 m decade$^{-1}$, which passed the 99% significance test. The region had a sensible heat flux average of 44 W m$^{-2}$, a maximum of 46 W m$^{-2}$, a minimum of 40 W m$^{-2}$, and a climatic trend rate of $-0.05$ W m$^{-2}$ decade$^{-1}$, which did not pass the significance test. Its latent heat flux average was 5 W m$^{-2}$, with a maximum of 10 W m$^{-2}$, a minimum of 2 W m$^{-2}$, and a climatic trend rate of 0.05 W m$^{-2}$ decade$^{-1}$, which did not pass the significance test. The region’s average volumetric soil water in layer 1 was 0.03 m$^3$ m$^{-3}$, with a maximum of 0.04 m$^3$ m$^{-3}$, a minimum of 0.026 m$^3$ m$^{-3}$, and a climatic trend rate of 0.00004 m$^3$ m$^{-3}$ decade$^{-1}$, which did not pass the significance test. It had an average volumetric soil water of layer 2 of 0.04 m$^3$ m$^{-3}$, a maximum of 0.08 m$^3$ m$^{-3}$, a minimum of 0.02 m$^3$ m$^{-3}$, and a climatic trend rate of 0.0005 m$^3$ m$^{-3}$ decade$^{-1}$, which passed the 95% significance test. Its average volumetric soil water of layer 3 was 0.02 m$^3$ m$^{-3}$, with a maximum of 0.04 m$^3$ m$^{-3}$, a minimum of 0.018 m$^3$ m$^{-3}$, and a climatic trend rate of 0.0003 m$^3$ m$^{-3}$ decade$^{-1}$, which passed the 95% significance test. Its latent heat flux average was 5 W m$^{-2}$, a maximum of 10 W m$^{-2}$, a minimum of 4 W m$^{-2}$, and a climatic trend rate of 0.2 W m$^{-2}$ decade$^{-1}$, which passed the 99% significance test. It had a latent heat flux average of 2 W m$^{-2}$, a maximum of 4 W m$^{-2}$,
a minimum of 1 W m$^{-2}$, and a climatic trend rate of 0.07 W m$^{-2}$ decade$^{-1}$, which passed the 99% significance test. The average volumetric soil water of its layer 1 was 0.002 m$^3$ m$^{-3}$, the maximum was 0.04 m$^3$ m$^{-3}$, the minimum was 0.0001 m$^3$ m$^{-3}$, and the climatic trend rate was 0.0001 m$^3$ m$^{-3}$ decade$^{-1}$, which passed the 99% significance test. The average volumetric soil water of its layer 2 was 0.004 m$^3$ m$^{-3}$, the maximum was 0.04 m$^3$ m$^{-3}$, the minimum was 0.00 m$^3$ m$^{-3}$, and the climatic trend rate was 0.0008 m$^3$ m$^{-3}$ decade$^{-1}$, which passed the 99% significance test. The average volumetric soil water of its layer 3 was 0.0005 m$^3$ m$^{-3}$, the maximum was 0.004 m$^3$ m$^{-3}$, the minimum was 0.00 m$^3$ m$^{-3}$, and the climatic trend rate was 0.0001 m$^3$ m$^{-3}$ decade$^{-1}$, which passed the 99% significance test. The volumetric soil water value of its layer 4 continued to be 0.

As shown in Figs. 8h–n, in the NA2 region, the BLH presented a significant downward trend, the sensible heat flux presented a significant increasing trend, the latent heat flux presented a significant increasing trend, and the volumetric soil water of layers 1–3 presented a significant increasing trend, and the volumetric soil water of layer 4 stayed at 0. The BLH had the following two declines: one was in 1940 with a decreasing value of 48m, and the other was in 1970 with a decreasing value of 7m. The BLH average was 914 m before 1940, 866 m during 1940–1970, and 859 m after 1970. The sensible heat flux showed a stable change before 1930 and after 1960 and a slowly increasing trend during 1930–1960. The latent heat flux presented a slowly increasing trend of fluctuations, with smaller fluctuations before 1930 and larger fluctuations after 1930; and after 1970, the latent heat flux showed an obvious inter-annual oscillation. The volumetric soil water of layer 1 showed a similar change in the latent heat flux. The volumetric soil water of layers 2–3 was more in 1950–2000, and it showed obvious fluctuations. From the analysis, it is clear that the BLH of NA2 appears to have no clear trend, the latent heat flux presented a significant increasing trend, the volumetric soil water of layers 1–3 presented a significant increasing trend, and the volumetric soil water of layer 4 stayed at 0. The BLH had the following two declines: one was in 1940 with a decreasing value of 48m, and the other was in 1970 with a decreasing value of 7m. The BLH average was 914 m before 1940, 866 m during 1940–1970, and 859 m after 1970. The sensible heat flux showed a stable change before 1930 and after 1960 and a slowly increasing trend during 1930–1960. The latent heat flux presented a slowly increasing trend of fluctuations, with smaller fluctuations before 1930 and larger fluctuations after 1930; and after 1970, the latent heat flux showed an obvious inter-annual oscillation. The volumetric soil water of layer 1 showed a similar change in the latent heat flux. The volumetric soil water of layers 2–3 was more in 1950–2000, and it showed obvious fluctuations. From the analysis, it is clear that the BLH of NA2 appears to have no clear
relation with the sensible heat flux, latent heat flux, and volumetric soil water.

Considering that the thermodynamic factors in North Africa could not explain the BLH’s change well, we added some dynamic factors, including the boundary layer dissipation, surface roughness, 10 m wind speed, 10 m U wind component, 10 m V wind component, 100 m U wind component, 100 m V wind component, wind shear of the U component, and wind shear of the V component, as shown in Fig. 9; here, we only show the graph of EA1, and those of EA2, NA1, and NA2 are not shown due to limited space. Boundary layer dissipation is the amount of kinetic energy dissipation in the boundary layer per unit time per unit area, just like sensible heat flux, and its unit is W m$^{-2}$. In the EA1 region, it can be observed that among these dynamic factors, the boundary layer dissipation had good consistency with the BLH’s change, and the 10 m U wind component and the wind shear of the U component also had a good corresponding relationship with the BLH’s change. In the EA2 region, the boundary layer dissipation and surface roughness had good consistency with the BLH’s change, and the amount of the wind also had a good corresponding relationship with the BLH’s change. In the NA1 region, the boundary layer dissipation had good consistency with the BLH’s change, and the amount of the wind also had a good corresponding relationship with the BLH’s change. In the NA2 region, the quantities of the wind had a good corresponding relationship with the BLH’s change.

Besides these land-surface factors, the upper troposphere stability, which may have some influence on the entrainment at the boundary layer top, may be another reason for changes in BLH. Then, we added the same analysis of the vertical gradient of temperature near the boundary layer top, as shown in Fig. 9j. By comparing the change of the BLH and the vertical gradient of temperature near the boundary layer top, it can be found that there was a negative relationship between the BLH and the vertical gradient of temperature near the boundary layer top.
Table 3. The determination coefficients of the BLH and climate trend rates of the BLH, sensible heat flux (SH), latent heat flux (LH), volumetric soil water of layers 1–4 (VSW1, VSW2, VSW3, and VSW4), surface roughness (Rou), boundary layer dissipation (BLS), 10 m wind speed (w), 10 m U wind component (10U), 10 m V wind component (10V), 100 m U wind component (100U), 100 m V wind component (100V), the wind shear of the U component (uQB), and the wind shear of the V component (vQB). (Note: ** means 99 % significance test and * means 95 % significance test.)

| R      | EA1   | EA2   | NA1   | NA2   |
|--------|-------|-------|-------|-------|
| SH     | 0.9025** | 0.7056** | 0.0625** | 0.2401** |
| LH     | 0.8836** | 0.4761** | 0.1156** | 0.1936** |
| VSW1   | 0.8863** | 0.4225** | 0.1225** | 0.1156** |
| VSW2   | 0.8863** | 0.3249** | 0.0004 | 0.0784** |
| VSW3   | 0.6889** | 0.1225** | 0.0169 | 0.0729** |
| VSW4   | 0.0049 | 0.0100 | 0.1225** | 0.0000 |
| Rou    | 0.9096** | 0.4127** | 0.2942** | 0.0019 |
| BLS    | 0.5978** | 0.0908** | 0.2570** | 0.0055 |
| W      | 0.4622** | 0.1438** | 0.0056 | 0.4448** |
| 10U    | 0.5444** | 0.0803** | 0.5210** | 0.5340** |
| 10V    | 0.0087 | 0.4475** | 0.1749** | 0.1328** |
| 100U   | 0.5454** | 0.1188** | 0.4803** | 0.5238** |
| 100V   | 0.0079 | 0.3911** | 0.2186** | 0.0964** |
| uQB    | 0.5270** | 0.1795** | 0.3810** | 0.4860** |
| vQB    | 0.0065 | 0.1554** | 0.2950** | 0.0308 |
| VGT    | 0.4458** | 0.3624** | 0.4121** | 0.5854** |

indicates that the more stable the boundary layer top is, the lower the BLH is; conversely, the less stable the boundary layer top is, the higher the BLH is.

To further clarify the relationship between the BLH and the quantities, determination coefficients were calculated, as shown in Table 3. In the EA1 region, the BLH had a strong correlation with the thermodynamic factors, and the determination coefficients with the sensible heat flux and the latent sensible flux reached 0.9025 and 0.8836, respectively. The BLH also had a good correlation with the dynamic factors, and the determination coefficient with the surface roughness was 0.4127. The determination coefficients with the 10 m and the 100 m V wind components were 0.4475 and 0.3911, respectively. Besides, the BLH had a good correlation with the vertical gradient of temperature near the boundary layer top, and the determination coefficient was 0.3624. In the NA1 region, the relationship between the BLH and the dynamic factors was more apparent, and the determination coefficients with the surface roughness and the boundary layer dissipation were 0.2942 and 0.2570, respectively. The determination coefficients with the 10 m U wind component, the 100 m U wind component, and the wind shear of the U component were 0.5210, 0.4803, and 0.3810, respectively. Besides, the BLH had a good correlation with the vertical gradient of temperature near the boundary layer top, and the determination coefficient was 0.4121. In the NA2 region, the relationship between the BLH and the dynamic factors was more apparent, and the determination coefficients with the 10 m U wind component, the 100 m U wind component, and the wind shear of the U component were 0.5340, 0.5238, and 0.4860, respectively. Additionally, the BLH also had some correlation with the sensible heat flux, which had a determination coefficient of 0.2401. Besides, the BLH had a good correlation with the vertical gradient of temperature near the boundary layer top, and the determination coefficient was 0.5854.

4. Conclusions

By analyzing the climatic variation characteristics of the BLH and its relationship with the change in thermodynamic and dynamic factors over arid and semiarid areas in East Asia and North Africa, spanning 1900–2010, some conclusions have been drawn as follows:

In arid and semiarid areas over East Asia, the BLH exhibited a descending trend from the central arid region to the periphery. In the past 111 years, the BLH of the western areas had a decreasing trend, and the east had a rising trend. The change of the eastern representative region over time is as follows: in 1900–1920, the BLH showed a relatively stable change; during 1920–1960, the BLH presented a slowly increasing trend, and from the mid-1960s to the 1970s, there was a sharp rise in the BLH. The BLH dropped in the mid-1970s to finally exhibit a descending trend from the central arid region to the periphery. In the past 111 years, the BLH of the western areas had a decreasing trend, and the east had a rising trend. The change of the eastern representative region over time is as follows:
the overall change was relatively stable and did not pass the significance test. The BLH presented an upward trend of fluctuations during 1900–1940, and a slowly downward trend during 1940–2010. In arid and semiarid areas in North Africa, the BLH exhibited a high spatial distribution in the western areas, a low distribution in the eastern areas, a high distribution in the southern areas, and a low distribution in the northern areas. In the past 111 years, the BLH of the southwestern areas had a rising trend, while other regions had a decreasing trend. The BLH change in the southwestern representative region over time is as follows: two obvious rises occurred; one was in 1940, and the other was in 1970. The change of the others representative regions over time is as follows: the BLH had two obvious declines; one was in 1940, and the other was in 1970.

The reason that the BLH of North Africa is higher than that of East Asia mainly is the fact that the sensible heat flux of North Africa is greater than that of East Asia, and the latent heat flux and volumetric soil water of North Africa are less than those of East Asia. The eastern and western sensible heat fluxes of East Asia are almost equivalent; thus, the reason that the BLH of the west is higher than that of the east is mainly due to the latent heat flux and volumetric soil water of the west being less than that of the east. The southwest and other regions’ sensible heat fluxes in North Africa are almost equivalent; thus, the reason that the BLH of the southwest is higher is the latent heat flux and volumetric soil water of the southwest being less.

A good corresponding relationship exists between the BLH, arid and semiarid boundaries, sensible heat flux, latent heat flux, and volumetric soil water; that is, the drier the region is, the lower the volumetric soil water is; the lower the latent heat flux is, the higher the sensible heat flux and the BLH are. In East Asia, the BLH had a strong correlation with the thermodynamic factors and a good correlation with the dynamic factors. In the east of East Asia, the change in the BLH was more related to the sensible heat flux, latent heat flux, boundary layer dissipation, 10 m U wind component, 100 m U wind component, and the wind shear of the U component. In the west of East Asia, the change in the BLH was more related to the sensible heat flux, latent heat flux, surface roughness, 10 m V wind component, and the 100 m V wind component. In North Africa, the relationship between the BLH and the dynamic factors was more apparent. In the southwest of North Africa, the change in the BLH was more related to the surface roughness, boundary layer dissipation, 10 m U wind component, 100 m U wind component, and the wind shear of the U component. In the other regions of North Africa, the change in the BLH was more related to the 10 m U wind component, 100 m U wind component, the wind shear of the U component, and the sensible heat flux. In addition, the BLH had a good correlation with the stability of the boundary layer top, which indicates that upper-level stratification also has some influence on the BLH’s change.

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