A Dynamic Study of Ekman Characteristics by Using 1998 SCSMEX and TIPEX Boundary Layer Data

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ABSTRACT

A dynamic study on Ekman characteristics by using 1998 SCSMEX and TIPEX boundary layer data is made. The results are as follows: (1) Similar dynamical Ekman characteristics are observed in the Tibetan Plateau and in the South China Sea and its surrounding area. (2) The thickness of the boundary layer is about 2250 m over the Tibetan Plateau, and considering its variation, the thickness could be up to 2250–2750 m. In the tropical southwest Pacific, the thickness of the boundary layer is about 2000 m, and the variation is smaller; a smaller thickness of the boundary layer is in the plain area of the Bohai Sea. (3) Because of the difference in elevation between the Tibetan Plateau and the tropical ocean area, the influence of the boundary layer on the atmosphere is quite different although the two areas have almost the same thickness for the boundary layer, the height where the friction forcing occurs is quite different. (4) The vertical structure of turbulence friction is quite different in the Plateau and in the tropical ocean area. Calculations by 1998 SCSMEX and TIPEX boundary layer data indicate that even in the lowest levels, eddy viscosity in the Tibetan Plateauan can be 2.3 times than in the tropical ocean area.

Key words: Ekman characteristics, 1998 TIPEX, SCSMEX observations, comparison of the boundary layer of the Tibetan Plateau with the tropical ocean area

1. Introduction

In the early 20th century, Taylor (1916) pointed out that the wind varying with height coincides with the dynamics, which is a distribution of Ekman spirals drawn by the frictional force. This atmosphere layer is called the upper frictional layer or Ekman layer when this dynamical characteristic is satisfied. In fact, much more natural events, including the atmosphere cycle, biosphere cycle, and water cycle, take place at this frictional layer of the atmosphere. In recent years, more attention has been paid to Ekman spiral characteristics and their impact on environmental atmosphere e.g., (by Nicholls, 1985 and Panchev, 1987). Saffman (1962) and Smith (1965) pointed out that the transportation of pollutants in the atmosphere is related to the variation of wind direction and speed with height. This is an indication that the dispersion of material could be found from a point source in the ground layer and consequently formed into an Ekman spiral wind field. Saffman (1962) concluded that the dispersion due to shear would eventually be in a horizontal turbulent diffusion. Taylor (1982) pointed out that in special conditions, the wind varying with height corresponds to a hypothetical Ekman spiral, where cloud buildup is stretched into a particular direction, and is drawn into a modified Ekman boundary layer. The studies from Xu et al. (2002) indicated that over the Tibetan Plateau, cumulus clusters develop very frequently. Under the influence of the disturbance boundary layer over the Tibetan Plateau, convective clusters usually move out from the Tibetan Plateau in a particular trajectory. This then gives an important impact on the flooding of the Yangtze River in 1998. However the frequent development of convection systems is related also with water vapor transportation and disturbance activities in the monsoon water vapor region of influence.

Turbulence exchange in the planet boundary layer can be described theoretically by a friction coefficient $k(z)$. In the 1950s, under the assumption of momentum conservation, Yang (1957) gave his study on the expression of $k(z)$ under the assumption of momentum theory:

$$k(z) = (a - bz)^2,$$

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By using the expression of $k(z)$ above and data from Beijing to represent the plain cities and Dalian for a seaport station, Yang (1957) and Yang and Tseng (1958) also revealed the different distributions of $k(z)$ between the continent friction winds and sea friction winds. They showed that the friction wind can be characterized by a typical Ekman spiral in the plane area. Figure 1 shows a wind profile describing an Eckman spiral in Beijing of the North Plain area of China. From Fig. 1, it is indicated that there is a typical Ekman spiral in the lower levels of 100–200 m, and the angle between the surface and gradient winds is 45°. The thickness of the frictional layer described by the height of the gradient-wind is 1500–1600 m.

Zhao (1956) pointed out that it is very difficult to measure the turbulence exchange coefficient k directly. Its variation is significant even in the same location. The daily variation of k is from 20 $\mathrm{m^2\ s^{-1}}$ to 90 $\mathrm{m^2\ s^{-1}}$; the vertical variation of k could be 4 $\mathrm{m^2\ s^{-1}}$ to 223 $\mathrm{m^2\ s^{-1}}$ in Beijing. It is very significant to perform an observational study on the turbulence exchange coefficient k for the continent and sea area over a large area of China.

The Tibetan Plateau is located in western China. It is more than 2000 km long from east to west and 1000 km long from north to south. It covers about one sixth of East Asia. The mean sea level elevation is about 4000 m, which is about one third of the troposphere. The topography of the Tibetan Plateau is very sophisticated with the Kunlun Mountain range, Gangdisê Mountain, and Himalaya Mountains as the main body of the Plateau. Between these mountains, there are not only relative plains and widespread North Tibet grasslands, but also the Yangtze River, as well as lakes and basins. The physical features of various land surfaces are very complex.

We know that both the equatorial Pacific and the Tibetan Plateau are the largest forcing source in the world's monsoon areas. They have important effects on the general circulation and weather systems. Research on the planetary boundary layer (PBL) characteristics of the Tibetan Plateau and South Pacific has always been important and interesting, according to Song (1984). However, because of lack of data, it is very difficult to carry out research in this area. Very little work has been done on the Tibetan boundary layer with real data. Considering the needs of numerical models and research work, data is especially needed for work on the influence of the turbulent parameterization in the boundary layer over the Tibetan Plateau and the ocean area on global general circulation, dynamic and thermodynamic processes. It is very important to obtain reasonable characteristics of the boundary layer in the Tibetan Plateau and the equatorial Pacific Ocean (Wang and Yang, 1999; Luo and Yanai, 1984; Zhao and Miao, 1992).

The Tibetan Plateau Scientific Experiment (TIPEX) and South China Sea Monsoon Experiment (SCSMEX) were both held in 1998. In this paper, a study on height characteristics of the PBL by using 1998 SCSMEX and TIPEX field-observed data is made. By the same method, a parallel contrast analysis of PBL characteristics of the Tibetan Plateau at Damxung station with data over the equatorial Pacific area at Singapore Island is discussed. This study seeks to give a better understanding of boundary height and Ekman spiral characteristics in the Plateau and the ocean, where cumulus convective systems actively develop. Furthermore, as a sensitive area, there is quite a variation in land surface and elevation.

2. Observed characteristics of winds in the boundary layer over the Plateau and equatorial Pacific Ocean

The higher resolution sounding data of the 1998 TIPEX at Damxung are used in this study. The wind profile for the frictional layer over the Tibetan Plateau is analyzed. Damxung is located in the east of the mid Plateau, orientated in the NE–SW river valley area. The observed station is selected a pasturing area, 4 km to the west of Damxung city, which is just the center of the valley. The station is located 30°02'N, 91°06'E, with 4200 m elevation and in a valley 20 km wide with plain topography and sandy soil (Fig. 2). The most of the vegetation over the station is occupied by ruderal and a piece of winter grassplot is to the south of the station, where the vegetation is thicker.

Also in this study, the observations of the wind profile over Singapore Island from the 1998 SCSMEX are used. The soundings are from 3000 m and above. Singapore Island is located in the tropical ocean near the equator at 01°23'N, 103°43'E. The island is deep

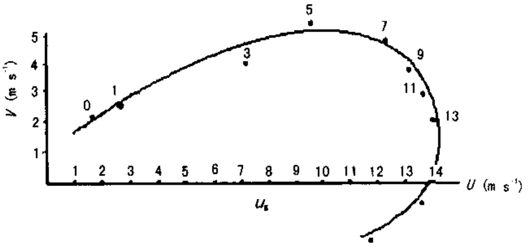

Fig. 1. Wind profile for the situation of big winds in Beijing (by Yang, 1957). The symbol crosses in the figure are the end of wind vectors. The numbers in the figure correspond to the height (m) for the particular wind vector.

in the ocean area, where it is one of the areas that convective activities are observed more frequently. It was also a key station to monitor the characteristics of convective activities during SCSMEX. So, the Damxung and Singapore stations selected in this study are significant representatives of the Tibetan Plateau and the ocean area respectively.

In this paper, data samples are chosen on the principle that wind speed increases gradually with height and wind direction turns right with height. New and representative data are selected, which are complete field observations for the special scientific experiments over the Tibetan Plateau area—the best data internationally up to now.

There are 79 samples for Damxung during 1–29 June 1998. Because the purpose of this paper is to show the dynamics effect of the wind profile, in these chosen data, the influence of irregular factors caused by weather systems needs to be removed. Also, wind records with sudden changes in speed or direction cannot be representative. From the point of view of the dynamics of winds in the atmosphere, the wind speed increases gradually with height in the frictional layer, and it will become consistent with the geo-gradient wind under a friction-free force. Because of the friction force, a slight wind will be found in the lower layer, up to a reasonable height, where the friction is much smaller. Then wind direction is the same as the gradient wind, and this height would be the height for the top of the friction layer. That is why the principle that wind speed increases gradually with height, and wind direction tends towards maximum wind at a particular height, is the standard for our data selection.

So, the principle for data selection is to choose those records in which wind speed increases gradually with height, as mentioned above. Those are data that the levities of the winds, in which the influence of irregular factors caused by weather systems, are removed. This principle is agreed with in the studies by Yang (1957) and Yang and Tseng (1958). In this way, 26 of the 79 records as data samples in the frictional layer of Damxung and 58 of 89 for Singapore are used to analyze wind in the frictional layer over the South Pacific Ocean. The influence of irregular factors caused by weather systems has been removed. Diagnosis of the basic characteristics of turbulence exchange on both the Plateau and the ocean are made. In this way, the defined frictional layer elevation for the Plateau and Ocean area can be meaningful also. First, each individual observed winds on various levels are decomposed into the east-west component u and north-south component v, where u must include the orientation of maximum wind (consider it as the gradient wind for the particular case) to the coordinate x:

$$\begin{pmatrix} u \\ v \end{pmatrix} = -V \begin{pmatrix} \sin\theta \\ \cos\theta \end{pmatrix}$$

where V denotes re-oriented wind speed, and θ is the angle of re-oriented wind direction with gradient wind (maximum wind) for each particular case. Figure 3 gives the integrated distribution of components u and v for the frictional layer in Damxung by those 26 samples. Each point in Fig. 3 represents the end point of the integrated average vector. From Fig. 3, we can see that the model of the wind profile in the Damxung boundary layer is the same as the classical Ekman spiral. Component v is close to zero at 2200 m height. It has a slight variation with an oscillation between 0.3 and 0.3 m s^{-1} . The results mentioned above indicate that the altitude of the frictional layer is among points 22–33, which is from 1850 m–2750 m, and the first height for v close to zero occurs at 1850 m (point 22, v=0.09 m s^{-1} , u=4.03 m s^{-1}). The maximum u value is located 2750 m height at point 31 (v= −0.77 m s^{-1} , u=6.50 m s^{-1}). From points 22–31, the particular oscillation of u and v is seen. The first maximum of u is found at 2250 m (point 26), where u is 5.67 m s^{-1} and v is −0.29 m s^{-1} . Only a little decrease in u above this height can be seen. Although at the height of 2750 m, u approaches 6.5 m s^{-1} , but v is too far from zero, approaching −0.77 m s^{-1} , so, considering the oscillation characteristics of the Ekman spiral at the height of the gradient wind, the first maximum u value is at 2250 m and v is a smaller one. This height would be considered as the height of the gradient wind for Damxung. The characteristic oscillation height for the boundary layer varies from 1850 to 2750 m.

The vertical variation of frictional layer wind at Damxung is rather similar to the classic Ekman spiral (Holmbore, 1947; Hulton, 1972). The value of the v component is close to zero around the 2000 m level, which is consistent with Ye and Gao (1979).

Figure 4 gives the distribution of wind vectors for the Singapore Island in June 1998. From Fig. 4 we can see that in Singapore case, a typical model of the tropical ocean boundary layer is described. The angle of the winds at the sea surface with gradient wind is larger than 45 degrees. This indicates that the disturbances are very strong in the lower layer of the tropical ocean atmosphere. The period of June 1998 is just the time for the break out of the surges of the South China Sea Monsoon, where very intense convective activities occur in the South China Sea area. Singapore is located just south of the channel for monsoon water vapor transportation. Wind speed increases rapidly with height. The maximum wind speed is 10.06 m s^{-1}

Fig. 2. The base of Damxung station for boundary layer observation.

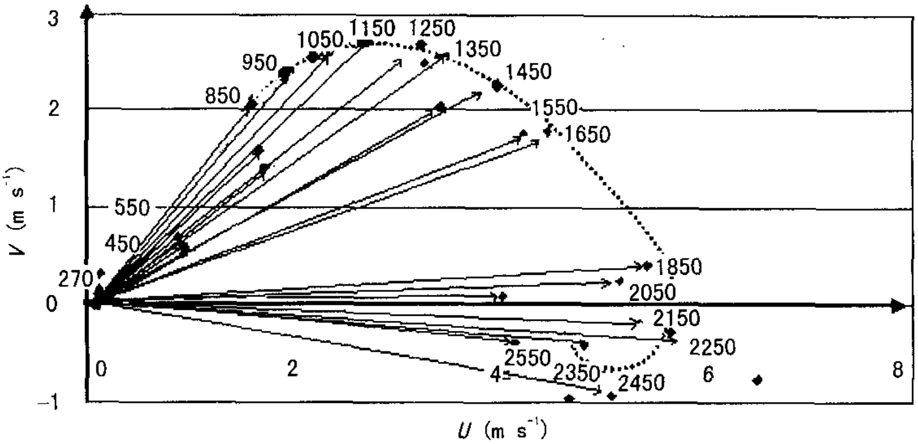

Fig. 3. An Ekman spiral in the boundary layer at Damxung, Tibetan Plateau (June 1998). Arrows are wind vectors. The numbers in the figure correspond to the height (m) for the particular wind vector.

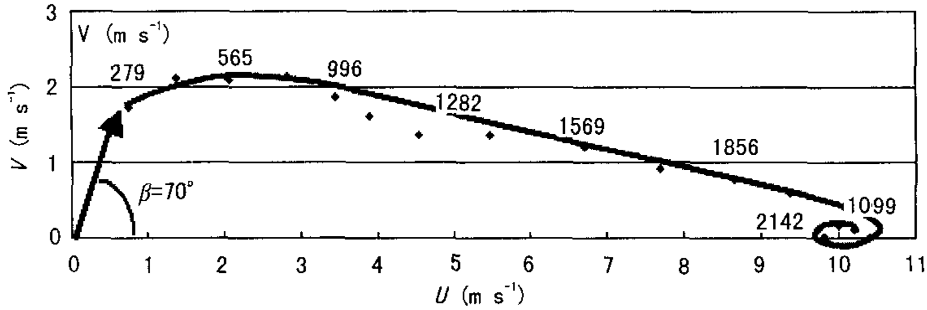

Fig. 4. An Ekman spiral for Singapore.

which occurs at a height of about 2000 m. The value of u approaches a maximum, the value v tends to zero. So therefore, the height of the gradient wind will reach up to 2000 m. The frictional layer is also deep. A diagram of the ocean Ekman spiral is shown in Fig. 5. This is a 3-dimensonal diagram for the wind distribution of the sea boundary layer. In order to show the right-turning of the wind direction as the height varies, we define the downward-coordinate of height as the positive one. From Fig. 5, a south-western wind is observed in the lower atmosphere to the south of the South China Sea, and a strong equatorial west wind occupies the upper levels at about 2000 m. The results of the composite wind distribution as varying with height obtained by filtering out the non-frictional effect samples, indicate that the cross-equatorial westerly current at the lower-level and westerly wind at the upper-level is very remarkable.

3. Turbulence characteristics over the Tibetan Plateau and the Tropical Ocean

As we know, serious rainstorms and flooding occurred along the Yangtze River in 1998. The study from Xu et al. (2002) shows that the "Large Triangle affecting region", with a peak in the Tibetan Plateau and valley in the Indian Ocean and South China Sea, is a key area that affects the monsoon water vapor transformation. The last ten-day period in July 1998 is a key period for this particular flood event. By examining the figure of the mean temperature for the cloud top TBB for 7 days (8 times a day) during 23 June 29 June, we can see the existence of a very strong convection activity area, where the top of the clouds is higher. It occurred in the area of the South China Sea, the southwest Pacific, the Indian Ocean, and the Plateau. In order to analyze the relationship of characteristics for turbulence exchanges between the underlying surface of the continent and the ocean, the observations from Damxung of TIPEX and Singapore of SCSMEX are selected. These two stations are located in the experiment area to give the special boundary observations. They are also representative stations with simultaneous records for monitoring the 1998 Yangtze River flooding rainstorms. The analysis of boundary characteristics in Damxung and Singapore indicates that in the Tibetan Plateau and the South China Sea, the wind distribution can be characterized by the Ekman spiral. This is perhaps one of the important reasons why the area is a key area, where convective activity, turbulence activity, and water vapor transportation occurs frequently. The comparison of turbulence activities in this key area of convection activity and monsoon water vapor transportation over the Tibetan Plateau and the tropical ocean is helpful for a better understanding of this.

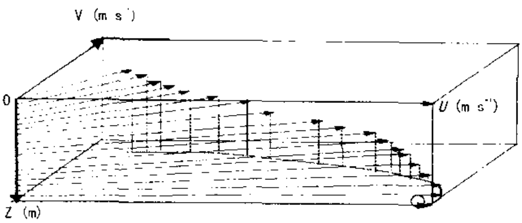

Fig. 5. A 3-dimensinal diagram for an Ekman spiral of the tropical ocean boundary layer. The x-coordinate is the u wind component, the y-coordinate is the v wind component (inside is positive), and z-coordinate is the height (downward is positive).

In comparing Fig. 3 and Fig. 4, we find the following:

(1) The thickness of the frictional layer over the Tibetan Plateau and the Singapore Island in the south of the South China Sea is 2250 m and 2000 m respectively. In fact, a deep thickness of the boundary layer in both the Plateau and the South China Sea is observed. It is a little deeper in the Plateau than in the sea area.

(2) A thickness variation of the boundary layer can be seen over Plateau rather than over the Pacific Ocean area.

(3) Considering that the altitude of Damxung is 4200 m, the elevation for the boundary layer will be 4000–7000 m giving a pressure of 300 600 hPa in the Plateau, but the elevation in Singapore is only 12 m giving a pressure over the height of the boundary layer of 850–700 hPa, where the low-level cross-equatorial current just passes over. Although the same thickness occurs for the upper frictional layer in both areas, the height where the friction occurs is quite different (especially in the vertical direction).

(4) The angle β between the low-level wind direction and the upper-level gradient wind is close to 70° over the tropical ocean, but 50° over the Tibetan Plateau. These values are both bigger than the 45° value in the theory of Ekman spirals. As we know, the main characteristics of turbulence can be described by the eddy viscosity. The expression of eddy viscosity due to the frictional force and its angle (β) is as follows (by Yang, 1957; Holmbore, 1947). When $Z=0$.

$$\bar{\tau} = \sqrt{2}u_g f \sin\bar{\beta} e^{i\left(\bar{\beta}+\frac{5}{4}\pi\right)}$$

where u_g is the gradient wind, f is the Coriolis parameter averaged over the area, and $\bar{\beta}$ is an angle between the average wind for multi-levels in the friction layer with wind at the elevation of the gradient wind. If we consider the low-level $\bar{\beta}$ only, then being closer to the lower levels gives a bigger $\bar{\beta}$ and eddy viscosity, which can be obtained in the ocean area rather than in the Tibetan Plateau area. This may be related to the surges and very strong sea-air turbulence exchanges.

Yang and Tseng (1958) discussed the wind frictional characteristics over the ocean and continent by using Dalian data (Fig. 6). It is indicated that from the point of view of the influence of surface roughness upon the turbulent exchange coefficient k, it will be bigger in the sea area than in the continent. Perhaps the reason is because large waves and roughness occur frequently in the sea area. This means that a frequent event could be that the large eddy viscosity is usually seen in the sea area.

From Fig. 6, we can see that the height of the frictional layer is 1650 m in the Bohai Sea, and its maximum wind speed is 10.5 m s^{-1}, which coincides with the results in this study.

(5) Importantly, it is seen that the angle between the wind vector and gradient wind in the upper levels is decreasing rapidly with height in the sea area (Fig. 4). However, over the Tibetan Plateau (Fig. 3), it keeps a bigger angle even up to the high levels. This is quite a difference in the vertical structure of friction over the Tibet Plateau compared to the sea area. This is one of the indications that the disturbance is stronger over the Tibetan Plateau. It is indicated that low-level eddy viscosity is stronger in the ocean area, but it decreases rapidly with height. It is also seen that the height of zero curvature for the Ekman spiral is 565 m over the sea area, but 1350 m for the Tibetan Plateau. The height of zero curvature represents the height where the eddy viscosity decreases with height. So this means the influence of turbulence in the vertical direction is much stronger in the Tibetan Plateau than in the sea area; the other of saying this is that only in the low levels, the eddy viscosity, due to the surging and roughness over the sea, is stronger there than in the Plateau. Basically, the effect of turbulence over the Tibetan Plateau, especially in the upper layer, is very important. (6) For the influence of eddy viscosity, the parameter of latitude needs to be considered. Suppose the average latitude is 30°N and 10°N respectively for the Plateau and the tropical ocean, areas where the convective systems are more active, and the angle β is 50° and 70° in the Plateau area and the tropical sea area respectively. The results calculated by using TIPEX and CSCMEX data, giving an eddy viscosity τ of 4.94×10^{-2} and 2.18×10^{-2} m s^{-2} for the Tibetan Plateau and for the low levels of the tropical ocean area respectively. This means that eddy viscosity can be 2.3 times in the Tibetan Plateau than in the tropical ocean area.

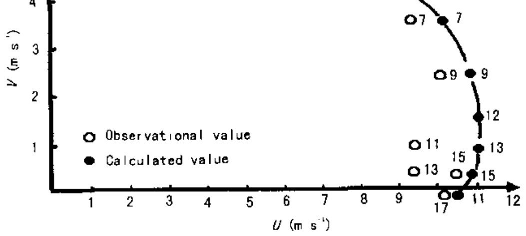

Fig. 6. Wind distribution under the condition of a sea breeze at Dalian (by Yang and Tseng, 1958).

4. Conclusion and discussion

The primary results in this study are as follows:

(1) Similar dynamical Ekman characteristics can be observed in the Plateau, and in the South China Sea and its surrounding area.

The analysis of field observations by using data from Damxung of 1998 TIPEX and from Singapore of SCSMEX shows that dynamic pump characteristics of Ekman spirals are observed at the boundary layer in the Tibetan Plateau and the tropical ocean area (Hulton, 1972). The similar physical mechanism of convective mixing and characteristics of the turbulence boundary layer can be seen clearly. This may be an important reason why the Plateau and Ocean area is a key area where convection systems develop frequently, and where the water vapor transformation and turbulence are very active. So this means there are similar dynamical influences in the Tibetan Plateau and in the tropical ocean area.

(2) The thickness of the friction layer is quite different in the Tibetan Plateau, tropical ocean, and plain area

The thickness of the friction layer is 2250 m, 2000 m and 1600 m in the Tibetan Plateau, the South west Pacific, and Bohai Sea area (Dalian, Fig. 6) respectively. This indicates that the thickness of the frictional layer, greatest in the Tibetan Plateau, including its variation could be up to 2250–2750 m. In the tropical Southwest Pacific, the thickness is about 1600–2000 m, and its variation is smaller. The thickness of the frictional layer in the sea area is higher than in the plain area. It should also be different in the particular oceans and different seasons. The discussion in this paper is for the period during the active monsoon season, when the thickness of the frictional layer is little higher. According to previous studies, the thickness of the frictional layer is 1400 m in the North plain of China (Beijing), and 900–1000 m in the Yellow plain (Zhang et al., 2000). These results will be useful as references for numerical simulations and theoretical studies of the East Asian monsoon and Tibetan Plateau dynamics.

(3) Because of the difference in elevation between the Tibetan Plateau and the tropical ocean area, the influence of the friction boundary layer on the atmosphere is quite different.

Considering that the altitude of Damxung in the Tibetan Plateau, is 4200 m, the elevation of the boundary layer will be up to the troposphere at 4000–7000 m with a pressure of 300–600 hPa, but the elevation of Singapore is only 12 m and the pressure at the height of the boundary layer is 850–700 hPa where the low-level cross-equatorial current passes through. Although the upper frictional layer has the same thickness in both areas, the height where the friction forcing occurs is quite different.

(4) The vertical structure of the turbulence friction is quite different in the Plateau than in the tropical ocean area.

The comparison in this study shows that above 565 m, the angle between the wind vector and the gradient wind in the tropical ocean area decreases rapidly with height. On the other hand, in the Plateau (4200 m), up to the height of 5000–6000 m, a large angle is maintained. This is the important difference in disturbance characteristics in the vertical structure between the Tibetan Plateau and the tropical ocean area. It is also one of the important reasons why the influence of the disturbance is stronger in the Tibetan Plateau area.

Considering the latitude parameter, the average latitude is 30°N and 10°N and the angle β is 50° and 70°, in the Tibetan Plateau and the tropical sea area respectively. The results calculated by using TIPEX and SCS data, the eddy viscosity τ is 4.94×10^{-2} and 2.18×10^{-2} m s^{-2} in the two lower layer areas respectively. This means that even in the lowest levels, the eddy viscosity can be 2.3 times greater in the Tibetan Plateau than in the tropic ocean area.

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’98 南海季风(SCSMEX) 和高原科学试验(TIPEX) 边界层

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摘　要

P425　A

使用1998年南海季风（SCSMEX）试验和青藏高原科学试验（TIPEX）的边界层资料对Ekman特征进行了动力学研究。得到如下结果：(1) 在青藏高原和南海及其周围区域有类似的Ekman动力学特征。(2) 比较研究表明，边界层厚度在青藏高原约为2250 m且考虑到它的摆动特性，其厚度可在2250–2750 m之间。在热带西南太平洋边界层厚度约为2000 m，其厚度摆动较小，在平原地区边界层厚度较低。(3)由于高原和热带海域海拔高度的不同，尽管在高原和热带海区有着几乎同样的边界层厚度，但边界层对大气的影响是相当不同的。考虑到海拔高度的影响，在这两个地区摩擦力作用的空间部位的高度有相当大的差别。(4) 这两个区域的湍流摩擦的垂直结构差异较大。使用’98 SCSMEX和TIPEX边界层资料计算结果表明，即使在低层,平均湍流粘性力在高原上是热带海域的2.3倍。

关键词: Ekman 特征, ’98高原科学试验、南海季风试验、边界层特征对比