Interannual and seasonal variations of sand-dust events in Tarim Basin, China

Lili Jin (269296387@qq.com)
Yunnan University https://orcid.org/0000-0003-2256-001X
Qing He
Zhenjie Li
Mingzai Deng
Alim Abbas

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Abstract

Dust events frequently occur in Tarim Basin (TB), China. However, research is scarce on the variation characteristics of sand–dust, floating dust, sand blowing, and sandstorms in the mountains, oases, and deserts in TB. Therefore, we conducted in–depth studies on the distributions and variations of dust events in TB. The results indicate that dust events tend to increase from south to north. The yearly sand–dust event occurrence rate trend is deserts > oases > mountainous regions. In spring, sand–dust, floating dust, sand blowing, and sandstorm days account for 35.9 %, 36.0 %, 38.5 %, and 47.1 % of the whole year, while in summer they account for 33.6 %, 33.5 %, 43.8 %, and 60.3 % of the whole year. From 1961 to 2015, most stations (annual average > 30 stations) showed a downward linear trend in sand dust, floating dust, sand blowing, and sandstorms in TB. All types of sand–dust events in mountains and oases decreased substantially after 1975 to 1978. In spring and summer, the downward dust trends are the most obvious, which the largest annual average downward linear trend rates of floating dust, sand blowing, and sandstorms are -0.33 d/yr (QM station), -0.21 d/yr (TGLK station), and -11 d/yr (KP station), respectively, in spring, and -0.28 d/yr (QM station), -0.17 d/yr (TGLK station), and -0.14 d/yr (KP station), respectively, in summer. It is found that the decreasing and increasing trends of floating dust are the most obvious during sand–dust events. There is a significant positive correlation between wind speed and relative humidity in mountains, and a significant positive correlation between wind speed in oases.

1. Introduction

Central Asia, North America, and Australia have the high incidence of sand–dust weather in the world. Meanwhile, the northwest and north of China provide abundant sand sources for the occurrence of sand–dust weather, and they are among the most important regions with high incidences of sand-dust weather, in central Asia. Wind erosion desertification in China covers an area of 1.61×10^6 km^2, mainly distributed in arid and semi–arid areas in the west. Xinjiang contains deserts amounting to an area of 4.3×10^5 km^2 and the Gobi deserts have an area 3.26×10^5 km^2. There are 2.13×10^5 km^2 of deserts in Inner Mongolia and 1.88×10^5 km^2 of Gobi. Qinghai has 3.80×10^5 km^2 of deserts and 3.70×10^5 km^2 of Gobi (Tan, 2019; Han et al., 2012; Varga, 2020).

China's sand dust is mostly located north of the Yangtze River, more in the northwest than in the northeast, more in plains (or basins) than in mountains, and more in deserts and their edges than in any other region. The spatial distribution of sand dust in China is characterized by a large area, concentrated in high–frequency areas, and it has a close correlation with the degree of surface desertification (Chen, 2013). Sandstorm–prone areas in China are divided into seven sub–regions (northern Xinjiang, southern Xinjiang, Hexi, Qaidam Basin, Hetao, northeast China, and Qinghai–Tibet). Sandstorms and floating dust occur most frequently in southern Xinjiang, and sand blowing occurs most frequently in Hexi (Wang et al., 2003).

Since the 1920s, studies on the spatial and temporal distributions, causes, structure, monitoring, and countermeasures of sand dust have been carried out abroad. Research on sand dust has mainly focused on sub–Saharan Africa (Westphal et al., 1988; Helgren et al., 1987), while studies of sandstorm processes in East Asia, West Asia, and the Middle East began in recent decades (Kurosaki and Mikami, 2003; Wang et al., 2008; Gharibzadeh et al., 2017; Khusfi et al., 2020; Rezazadeh et al., 2013; Jung et al., 2019; Kwon et al., 2002; Chen et al., 2004). The highest frequency of global dust events takes place in Sudan, where the occurrence of suspended dust and severe dust storm is a maximum (Rezazadeh et al., 2013). Sand–dust weather is a frequent, disastrous weather in northern China during spring and summer, the direct causes of which are frequent cold air and cyclonic activities (Ye et al., 2000; Yang et al., 2019; Zhang et al., 2019; Zhang et al., 2019). Large–scale climate warming, the consequent strengthening of the zonal characteristics of atmospheric circulation, and increased precipitation in the mid–latitude zone constitute the climatic background for the decreased frequency of sand–dust weather in northern China in the last half century (Tao, 2007). Wang et al. (2018) found that the occurrences of dust storms, blowing dust, and floating dust over northern China decreased by 76.7 %, 68.5 %, and 64.5 % since the beginning of the 21st century. The percentage of anthropogenic dust column burdens to the total mineral dust was 76.8 % during 2007 to 2014 in eastern China, but was less than 9.2 % in near–desert regions in northwestern China during the same period.

Over the past 50 years, the number of sandstorms in China has displayed a relatively obvious downward trend, while the number of strong sandstorms appears to have a relatively obvious upward trend (Lian, 2002). Wei et al. (2020) pointed out that by controlling the Kubuqi desert, the influence of sand-dust weather in the Beijing–Tianjin–Hebei Region area was effectively reduced. The sources of sandstorms in China are mainly concentrated in the deserts of southern Xinjiang and northern Xinjiang and their surrounding areas, Hexi Corridor of Gansu Province, dry deserts of Inner Mongolia, and Qaidam Basin of Qinghai Province (Qiu et al., 2001). Jia et al. (2019) pointed out that China's sand–dust emission sources are mainly the Taklimakan desert (TD) and Badain Jaran Desert. In the process of eastward transport, sand dust is lifted by high–altitude air streams which mixes with local man–made pollutants to turn into polluting sand dust; these, in turn, directly affect the eastern part of China. Dust weather, caused by interactions between wind and sand, is highly destructive and can result in serious consequences, such as poor air pollution, topsoil migration, reduced agricultural production, human and animal casualties, etc., making it a disastrous weather with a large scope of influence in China. Due to large–scale atmospheric circulation and weather systems, the influence of dust moves as the corresponding weather system moves, not only within the dust–source area, but for thousands to tens of thousands of kilometers, thereby affecting atmospheric environmental quality and ecological environments over exceedingly large areas. Indeed, such movement can dramatically increase the concentration of atmospheric particulate matter, causing different degrees of pollution along the route in which it travels (Lue et al., 2010; Liu et al., 2006; Zhao et al., 2008); such movement also influences meteorological elements. The appearance of sandstorms has obvious seasonal changes (Littmann,1991), which is related to the seasonal distribution of annual precipitation (Yu et al.,1993), vegetation cover, soil freezing, weather systems generating strong winds, and agricultural activities affecting the surface (Yu et al.,1993). For example, sandstorms in Mexico City have the highest frequency in March, where the rainfall has been less than 13 mm for the three consecutive, preceding months. Sandstorms frequently occur in Mexico City, although the lowest frequency of such storms occurs in September (Jauregui, 1989). The sandstorms in northwest India mainly occur from April to June, which is consistent with the frequency of sandstorms in Xinjiang, China.

The TD contains the highest amount of dust weather, and is a leading source of dust weather, in China. According to CALIPSO satellite data, the main TD aerosol subtype is dust (Meng et al., 2018). Dust events in the TD severely affect the air quality of most cities in northwest China, including eastern Xinjiang, Hexi Corridor, Guanzhong Basin, and northern regions of southwest China, leading to the mass concentrations of PM_{10} (i.e. particulate matter with diameters smaller than 10 microns) on dust days increasing by 1 to 173 % compared with non-dust days, while the mass concentration of $PM_{2.5}$ (i.e. particulate matter with diameters smaller than 2.5 microns) increasing by 21 to 172 % (Li et al., 2018). Therefore, it is necessary to understand the basic climatic characteristics of dust weather in the TD and surrounding areas. For example, Yang et al. (2015) analyzed observations of blowing dust events in the TD using 10 desert–edge meteorological stations and two inner–desert meteorological stations. Pi et al. (2017) showed atmospheric dust events in central Asia, including a discussion on what is driving their findings. Although scholars have studied the dust weather in the TD, thorough analysis on the seasonal variation of different types of sand–dust events of the underlying surface has not yet been performed in Tarim Basin (TB).

Therefore, the spatial and temporal variations of sand–dust, floating dust, sand blowing, and sandstorm are analyzed here using data obtained at 42 meteorological stations (4, 1, and 37, respectively, from mountain, desert and oasis stations) in the TB. The analysis of the TB is helpful for further our understanding of the distribution characteristics of dust events. The remainder of this paper is organized as follows. In Sect. 2, we describe the study area and data. In Sect. 3, we present the spatial and temporal variations of dust events of the TB, including sand-dust, floating dust, sand blowing, and sandstorm. Finally, we give our conclusions based on this analysis in Sect. 4.

2. Study Area And Data

TB, the largest inland basin in China, lies between the Tianshan and Kunlun Mountains. Its widest extent from north to south is 520 km, that from east to west is 1,400 km, and it covers an area of more than 400,000 km^2 (Fig. 1). TB has a warm temperate climate with an annual solar radiation budget of 575–627 kJ/cm^2, with about 3,000 annual sunshine hours in the north, and fewer than 3,000 hours in the south. All regions contain windy and dusty weather. The average annual temperature is 9–11 °C, and the south is slightly warmer than the north. In winter, the east is colder than the west. In winter, the average temperature in TB is lower than − 20 °C for only 1–2 days. The average temperature in July in TB is 25–27 °C. The accumulated temperature varies greatly from year to year. The frost–free period is 200–210 days in the north and 220 days in the south.

A dust event refers to a weather phenomenon in which sand particles and dust are suspended in the air due to wind, and move with the wind to make the air cloudy and reduce visibility. According to the horizontal visibility when dust weather occurs, dust weather is divided into five levels, namely floating dust, sand blowing, sand storm, strong sand storm, and extra–strong sand storm (GB/T 20480 − 2017). Floating dust means that there is no wind or the wind force is no more than level 3 (3.4–5.4 m/s), sand particles and dust floating in the air make the air cloudy, and the horizontal visibility is less than 10 km. Sand blowing means that the wind blows ground sand and dust to make the air quite cloudy, and the horizontal visibility is 1–10 km. A sandstorm refers to wind blowing ground sand and dust to make the air very cloudy, with horizontal visibility < 1 km; a strong sandstorm has a horizontal visibility < 500 m; and an especially strong sandstorm has a horizontal visibility < 50 m.

In this work, we define the occurrence of floating dust, sand blowing, or a sandstorm during a 24-hr period as 'dust weather'. Additionally, the occurrence of any two or three kinds of floating dust, sand blowing, and/or sandstorm is calculated according to a day of dust weather.

This study investigates trends in annual and seasons sand–dust, floating dust, sand dust and sandstorms days using the Mann–Kendall (M–K) (Kendall, 1934, 1938; Mann, 1945).

3. Results And Discussion

3.1 Spatial variations

Figure 2 shows the distribution characteristics of the annual average sand dust, floating dust, sand blowing, and sandstorm days in mountain, oasis and desert regions in TB. The dust event distribution in TB features more in the south and hinterlands, and less in the north (Fig. 2). In mountainous regions, the maximum occurrence of annual average sand–dust, floating dust, sand blowing, and sandstorm days are 48.7 d/yr (AHQ station), 42.7 d/yr (WQ station), 14 d/yr (AHQ station), and 8 d/yr (AHQ station), respectively; in oasis regions, they are 195.8 d/yr (HT station), 193.6 d/yr (HT station), 66 d/yr (PS station), and 38 d/yr (XT station), respectively; and in desert regions, they are 48.9 d/yr, 40.6 d/yr, 23 d/yr, and 6 d/yr, respectively. These results indicate that floating dust accounts for the highest ratio of dust events in TB, comprising 87.7 %, 98.9 %, and 83.3 % in mountain, oasis, and desert regions, while sandstorms account for the lowest occurrence of dust events in TB, accounting for 16.4 %, 19.4 %, and 12.3 %, respectively, in the three regions.

Figure 2(a) indicates that, interestingly, deserts (TZ station) do not contain the highest annual average amount of sand dust (48.9 d/yr); instead, the highest of 195.8 d/yr occurs in HT (oasis, south of TB), while the lowest of 11.1 d/yr occurs in TSKEG station (mountain, west of TB). There are 13 stations with annual average sand–dust exceeding 100 d/yr (YT, QM, MF, LP, HT, MY, CL, PS, SC, YJS, KP, BC, and KS station), all of which are oases. Figure 2(b) indicates that largest annual average floating dust occurrence rate is 193.6 d/yr in HT station (oasis), while the lowest is 6.0 d/yr in TSKEG station (mountain). There are 10 stations with annual average floating dust occurrence rates exceeding 100 d/yr (YT, QM, MF, LP, HT, MY, CL, PS, SC, and XT station), all of which are oases. Figure 2(c) indicates that the largest annual average sand blowing occurrence rate is 66.0 d/yr in PS station (oasis, south of TB), while the lowest is 0 d/yr in TEGT station (mountain, west of TB). Figure 2(d) indicates that largest annual average sandstorm occurrence rate is 38.0 d/yr in XT station (oasis, north of TB), while the lowest is 0 d/yr in TEGT station (mountain). These results accord with those of Yang et al. (2015), who reported that TZ station (desert) did not have the highest occurrence of sandstorms from 1961 to 2010 in the desert, whereas Xiaotang station (oasis) has the highest occurrence of sandstorms.

3.1.1 Seasonal spatial distribution of sand-dust

Figures 3 (a–d) show the spatial distributions of sand–dust days in spring, summer, autumn, and winter. The average maximum occurrence rates of sand-dust are 70.3 d/yr (HT station), 65.7 d/yr (HT station), 36.3 d/yr (HT station), and 23.5 d/yr (HT station), respectively, accounting for 35.9 %, 33. 6 %, 18.5 %, and 12.0 %, respectively, of the total annual average sand–dust days. The average minimum occurrence rates of sand–dust are 5.2 d/y (TSKEG station), 2.5

d/y (TSKEG station), 1.9 d/y (YQ station, oasis, north of TB), and 0.4 d/y (TEGT station), respectively, in spring, summer, autumn and winter, accounting for 47.0 %, 22.2 %, 8.8 %, and 2.4 %, respectively, of the total annual average sand–dust days. Spring and summer are the seasons with the highest rates of sand–dust in TB, accounting for 69.5 to 77.0 % of the annual sand–dust days; meanwhile, the sand–dust days in autumn and winter account for 23.0 to 30.5 % of the total amount of annual sand–dust days.

3.1.2 Seasonal spatial distribution of floating dust

Figures 4 (a–d) show the spatial distributions of floating–dust days in spring, summer, autumn, and winter. The average maximum occurrences of floating–dust days are 69.6 d/yr, 64.9 d/yr, 35.9 d/yr, and 23.2 d/yr, respectively, all at HT, in spring, summer, autumn, and winter, accounting for 36.0 %, 33.5 %, 18.5 %, and 12.0 %, respectively, of the total annual average number of floating–dust days. The average minimum occurrences of floating–dust days are 2.3 d/yr (TSKEG station), 0.5 d/yr (YQ station), 0.7 d/yr (YQ station), and 0.1 d/yr (TSKEG station), respectively, in spring, summer, autumn, and winter, accounting for 37.8 %, 5.9 %, 8.2 %, and 0.9 %, respectively, of the total annual average number of floating–dust days. Spring and summer are the seasons with highest amounts of floating dust in TB, accounting for 69.5 to 77.8 % of the total annual floating–dust days; meanwhile, the number of floating–dust days in autumn and winter account for 22.2 to 30.5 % of the total annual floating dust days.

3.1.3 Seasonal spatial distribution of sand blowing

Figures 5(a–d) show the spatial distributions of sand–blowing days in spring, summer, autumn, and winter. The average maximum occurrence rates of sand–blowing days are 25.4 d/yr (PS station, oasis, south of TB), 28.9 d/yr (TZ station, hinterland of TB), 10.3 d/yr (PS station), and 4.1 d/yr (MF station, oasis, south of TB), respectively, in spring, summer, autumn, and winter, accounting for 38.4 %, 45.9 %, and 15.6 %, and 8.3 %, respectively, of the total annual average number of sand–blowing days. The average minimum occurrence rates of sand–blowing days are 0.3 d, 0.1 d, 0.02 d, and 0.04 d, respectively, all in TEGT station, in spring, summer, autumn, and winter, accounting for 56 %, 32 %, 4 %, and 8 %, respectively, of the total annual average number of sand–blowing days. Spring and summer are the seasons with the highest amounts of sand blowing in TB, accounting for 79.0 to 87.0 % of the total annual number of sand–blowing days; meanwhile, the number of sand–blowing days in autumn and winter account for 13.0 to 21.0 % of the total annual number of sand–blowing days.

3.1.4 Seasonal spatial distribution of sandstorms

Figures 6(a–d) shows the spatial distributions of sandstorm days in spring, summer, autumn, and winter. The average maximum occurrence rates of sandstorm days are 17.9 d/yr (XT station), 22.9 d/yr (XT station), 4.4 d/yr (XT station), and 1.3 d/yr (MF station), respectively, in spring, summer, autumn, and winter, accounting for 39.2 %, 50.1 %, 50 %, and 50 %, respectively, of the total annual average number of sandstorm days. The average minimum occurrence rates of sandstorm days are 0 d/y, 0 d/y, 0.02 d/y, and 0.02 d/y, respectively, all at TEGT station, in spring, summer, autumn, and winter, accounting for 0 %, 0 %, 50 %, and 50 %, respectively, of the total annual average number of sandstorms days. Spring and summer are the seasons with the highest amounts of sandstorms in TB, accounting for 0 to 87.7 % of the total annual number of sandstorm days; meanwhile, the number of sandstorm days in autumn and winter account for 12.3 to 100 % of the total annual number of sandstorm days.

3.2 Trend variations

Figure 7 shows that 38 stations, 40 stations, 32 stations and 36 stations present a downward trend, and only 1 station, 2 stations, 4 stations and 1 station present an upward trend, of sand–dust days, floating dust days, sand blowing days and sandstorm days in all seasons. Among the stations that negative trend have 38, 37, 23 and 33 stations passed 99% confidence level, of sand–dust days, floating dust days, sand blowing days and sandstorm days in all seasons. Positive trend have 2, 1, 3 and 0 stations passed 99% confidence level, of sand-dust days, floating dust days, sand blowing days and sandstorm days in all seasons.

The largest annual average downward linear trend rates are − 2.83 d/yr (QM station, oasis, southwest of TB), -2.80 d/yr (QM station), -1.50 d/yr (TGLK station, oasis, northeast of TB), and − 0.87 d/yf (KP station, oasis, west of TB), respectively, for sand-dust, floating dust, sand blowing, and sandstorms in TB. Previous studies noted that the frequencies of sandstorms, sand blowing and floating dust decreased by as much as 76.7%, 68.5%, and 64.5%, respectively, near the source regions around the TD, Gobi Desert, and Badain Jaran Desert (Wang et al., 2018). However, the largest annual average upward trends found here are 4.0 d/yr, 5.1 d/yr, 1.6 d/yr, and 0.2 d/yr, respectively, all at TZ station, for sand dust, floating dust, sand blowing, and sandstorms in TB.

3.2.1 Seasonal trend variations of sand dust

Figure 8 shows that 36 stations, 36 stations, 34 stations and 0 station present a downward trend, and only 1 station, 1 station, 1 station and 0 station present an upward trend, of spring, summer, autumn and winter in sand–dust days. Among the stations that negative trend have 30, 32, 21 and 0 stations passed 99% confidence level, of spring, summer, autumn and winter in sand–dust days. Positive trend all have 0 station passed 99% confidence level, of spring, summer, autumn and winter in sand–dust days.

The largest annual average downward linear trend rates of sand–dust are − 0.33 d/yr (QM station), -0.27d/yr (QM station), and − 0.19 d/yr (QM station), respectively, in spring, summer, and autumn in TB. However, the largest annual average upward trends of sand–dust are 0 d/yr, 0.02 d/yr (LT station, oasis, north of TB), 0.03 d/yr (LT station), respectively, in spring, summer, and autumn in TB.

3.2.2 Seasonal trend variations of floating dust

Figure 9 shows that 34 stations, 33 stations, 29 stations and 32 stations present a downward trend, and only 3 stations, 2 stations, 1 station and 1 station present an upward trend, of spring, summer, autumn and winter in floating dust days. Among the stations that negative trend have 25, 29, 23 and 22 stations passed 99% confidence level, of spring, summer, autumn and winter in floating dust days. Positive trend have 1, 0, 3 and 0 stations passed 99% confidence level, of spring, summer, autumn and winter in floating dust days.

The largest annual average downward linear trend rates of floating dust are − 0.33 d/yr (QM station), -0.28 d/yr (QM station), -0.19 d/yr (QM station), and − 0.18 d/yr (HT station), respectively, in spring, summer, autumn, and winter in TB. However, the largest annual average upward trends of floating dust are 0.67 d/yr, 0.36 d/yr, 0.33 d/yr, and 0.17 d/yr, respectively, all at TZ station, in spring, summer, autumn, and winter in TB.

3.2.3 Seasonal trend variations of sand blowing

Figure 10 shows that 24 stations, 26 stations, 19 stations and 9 stations present a downward trend, and only 5 stations, 4 stations, 2 stations and 0 station present an upward trend, of spring, summer, autumn and winter in sand blowing days. Among the stations that negative trend have 14, 16, 16 and 4 stations passed 99% confidence level, of spring, summer, autumn and winter in sand blowing days. Positive trend have 2, 1, 1 and 0 stations passed 99% confidence level, of spring, summer, autumn and winter in sand blowing days.

The largest annual average downward linear trend rates of sand blowing are − 0.21 d/yr (TGLK station), -0.17 d/yr (TGLK station), -0.07 d/yr (TGLK station), and − 0.04 d/yr (PS station, oasis, southwest of TB), respectively, in spring, summer, autumn, and winter in TB. However, the largest annual average upward trends of sand blowing are 0.39 d/yr (TZ station), 0.77 d/yr (TZ station), 0.05 d/yr (TZ station), and 1.10 d/yr (WS station, oasis, west of TB), respectively, in spring, summer, autumn, and winter in TB.

3.2.4 Seasonal trend variations of sandstorms

Figure 11 shows that 30 stations, 17 stations, 4 stations and 1 stations present a downward trend, and all 0 station present an upward trend, of spring, summer, autumn and winter in sandstorms days. Among the stations that negative trend have 29, 22, 4 and 1 stations passed 99% confidence level, of spring, summer, autumn and winter in sandstorms days.

The largest annual average downward linear trend rates of sandstorms are − 0.11 d/yr (KP station, oasis, west of TB), -0.14 d/yr (KP station), -0.02 d/yr (YPH station, oasis, west of TB), and − 0.01 d/yr (MF station), respectively, in spring, summer, autumn, and winter in TB.

3.3 Temporal variations

3.3.1 Interannual variations

Figure 12 and Table 1 show that the sand–dust, floating dust, sand blowing, and sandstorm days present decreasing trends from 1961 to 2015 in mountainous and oasis regions. The annual trend values are − 0.51, -0.38, -0.07, and − 0.09 d/yr (the trend is significant at the 99 % level), respectively in mountains, and − 1.23, -1.17, -0.32, and − 0.25 d/yr (the trend is significant at the 99 % level), respectively, in oases. However, the sand–dust, floating dust, and sand blowing present increasing trends from 1996 to 2015 in desert regions, with annual trend values of 4.00, 5.10, and 1.62 d/yr, respectively. It can be seen that the decreasing and increasing trends of floating dust are the most obvious during sand–dust events. In spring and summer, the trend values are larger, while in autumn and winter, they are smaller in mountainous and oasis regions. However, in deserts, the trend values of floating dust are larger in spring, summer, and autumn, and smaller in winter; the trend values of sand blowing are larger in summer, and smaller in other seasons (Table 1).

On average, the maximum values of sand–dust, floating dust, sand blowing and sandstorm days are 62.0 d, 51.3 d, 11.3 d, and 9.3 d, respectively, in 1978, 1978, 1975, and 1976 in mountains; 147.7 d, 133.6 d, 39.9 d, and 19.9 d, respectively, in 1979, 1979, 1980, and 1966, in oases; and 188 d, 172 d, 95 d, and 36 d, respectively, in 2010, 2010, 2009, and 1998, in deserts. The annual variations of sand dust, floating dust, sand blowing, and sandstorm in mountains are similar to those in oasis; that is, they were higher before 1985, and smaller thereafter. In other words, before the mid–1980s, it was the peak of sand–dust, floating dust, sand blowing, sandstorms, and after that, it was the low period.

Table 1 shows that the sand–dust is positively correlated with wind speed, air temperature, and relative humidity over different surfaces. A further analysis found that the annual and spring sand– dust shows a positive correlation between wind speed, air temperature and relative humidity in mountains. However, summer, autumn and winter sand–dust shows a positive correlation between relative humidity. Annual, summer and autumn sand–dust shows a positive correlation between wind speed, air temperature and relative humidity, relatively in desert. However, spring and winter sand–dust shows no correlation with wind speed, air temperature and relative humidity in desert. Interestingly, annual and seasons sand–dust shows a positive correlation between wind speed. Moreover, sand–dust shows a positive correlation between air temperature in oases in autumn.

Table 1

Trend of sand–dust, floating dust, sand blowing, and sandstorms, and the correlation coefficients between the various meteorological elements in mountains, deserts, and oases in terms of their annual values, and those during spring, summer, autumn, and winter.

		Annual	Spring	Summer	Autumn	Winter
Trend						
Sand-dust	Mountain	**-0.51****	**-0.08****	**-0.05****	**-0.03****	**-0.01****
	Desert	**4.00****	**0.78****	**0.67**	**1.00****	**1.00***
	Oasis	**-1.23****	**-0.51****	**-0.45****	**-0.24****	**-0.21****
Floating dust	Mountain	**-0.38****	**-0.31****	**-0.14****	**-0.10****	**-0.07****
	Desert	**5.10****	**2.00****	1.08	**1.00****	0.50
	Oasis	**-1.17****	**-0.42****	**-0.34****	**-0.20****	**-0.18****
Sand blowing	Mountain	**-0.07****	**-0.04****	**-0.06****	**-0.02****	**-0.01***
	Desert	**1.62****	0.20	**0.91****	0.09	**0.14**
	Oasis	**-0.32****	**-0.12****	**-0.14****	**-0.05****	**-0.04****
Sandstorm	Mountain	**-0.09****	**-0.06****	**-0.03****	**-0.02****	**-0.01****
	Desert	—	—	—	—	—
	Oasis	**-0.25****	**-0.13****	**-0.10****	**-0.02****	**-0.01****
Correlation coefficients between sand–dust and meteorological elements						
Wind speed	Mountain	**0.768**^{b}	0.684^{a}	**0.594**^{c}		
	Desert	0.647^{c}				
	Oasis	**0.695**^{c}	**0.807**^{b}	**0.752**^{b}	**0.603**^{c}	**0.466**^{b}
Air temperature	Mountain	0.801^{c}	**0.548**^{c}			
	Desert			0.472^{b}		
	Oasis				**0.715**^{b}	
Relative humidity	Mountain	**0.633**^{a}	0.645^{b}	0.646^{b}	0.453^{c}	**0.454**^{c}
	Desert				0.495^{b}	
	Oasis					

NB: Bold values indicate that the trend is significant at the 90 % level; Bold values and single star indicate that the trend is significant at the 95 % level; Bold values and double star indicate that the trend is significant at the 99 % level; Letter a indicate the three independent variables that comes into the regression equation; Letter b indicate the two independent variables that comes into the regression equation; Letter c is the one independent variable that comes into the regression equation.

3.3.2 Annual variations

Figure 13 shows that the numbers of sand–dust, floating dust, sand blowing, and sandstorm days above the different underlying surfaces in TB from January to December follow the ascending trend of deserts > oases > mountainous regions. Figure 13 also shows that sand dust, floating dust, sand blowing, and sandstorms mainly occur from March to October in TB, accounting for 90.9 %, 88.2 %, 89.0 %, and 87.0 %, respectively, in mountains; 86.7 %, 85.2 %, 95.6 %, and 97.8 %, respectively, in deserts; and 85.5 %, 84.5 %, 90.5 %, and 94.0 %, respectively, in oases.

Figure 13. Annual variations of sand–dust days, floating dust days, sand blowing days, and sandstorm days from 1961 to 2015 in mountainous regions, desert regions, and oasis regions in TB.

4. Conclusions

Using observational data obtained at 41 stations in TB, we analyzed the spatial and temporal distribution characteristics of sand–dust, floating dust, sand blowing, and sandstorms in mountains, oases, and deserts in this region. Our main conclusions are summarized as follows.

(1) Dust weather occurs frequently in southern regions of TD. The number of dust days (sand–dust, floating dust, sand blowing, and sandstorms) follows the order of deserts > oases > mountains. In the sand–dust event, the main is floating dust. The largest number of sand–dust, floating dust, sand blowing, and sandstorm days are at HT station (195.8 d), HT station (193.6 d), PS station (66 d), and XT station (38 d), all in oases, around TD. The fewest number of

sand–dust, floating dust, sand blowing, and sandstorm days are at TSKEG station (11.1 d), TSKEG station (6 d), TEGT station (0 d), and TEGT station (0 d), all in mountains, west of TD.

(2) Spring and summer represent the high–dust seasons in TD. In spring, the average maximum number of sand–dust, floating dust, sand blowing, and sandstorm days are 70.3 d, 69.6 d, 25.4 d, and 17.9 d, respectively, at HT station, HT station, PS station, and XT station (all oases). In summer, the average maximum number of sand–dust, floating dust, sand blowing, and sandstorm days are 65.7 d, 64.9 d, 28.9 d, and 22.9 d, respectively, at HT station, HT station, TZ station, and XT station (oases and deserts). In autumn, the average maximum number of sand–dust, floating dust, sand blowing, and sandstorm days are 36.3 d, 30.9 d, 10.3 d, and 4.4 d, respectively, at HT station, HT station, PS station, and XT station (all oases). In winter, the average maximum number of sand–dust, floating dust, sand blowing, and sandstorm days are 23.5 d, 23.2 d, 4.1 d, and 1.3 d, respectively, at HT station, HT station, MF station, and MF station (all oases).

(3) By the results of M–K analysis, from 1961 to 2015, 38, 40, 32, and 36 stations showed downward linear trends in sand–dust, floating dust, sand blowing, and sandstorm events in TB, passed 99% confidence level accounting for 100 %, 93 %, 72 % and 92 %, respectively. The largest annual average downward linear trend stations are QM station (-2.83 d/yr), QM station (-2.80 d/yr), TGLK station (-1.50 d/yr), and KP station (-0.87 d/yr), all of which are located in oases. In total, 36, 34, 34, and 0 stations in spring; 36, 33, 26, and 17 stations in summer; 34, 29, 19, and 4 stations in autumn; and 0, 32, 9, and 1 stations in winter showed downward linear trends in sand–dust, floating dust, sand blowing, and sandstorm events in TB. These downtrend sites are all associated with oases, while uptrend sites are located in oasis and deserts.

(4) The annual trend values of sand–dust, floating dust, sand blowing, and sandstorm are -0.51, -0.38, -0.07, and -0.09 d/yr, respectively in mountains, and -1.23, -1.17, -0.32, and -0.25 d/yr, respectively, in oases. However, the annual trend values of sand–dust, floating dust, and sand blowing are 4.00, 5.10, and 1.62 d/yr, respectively, in deserts. March to September is the peak season for dust events, accounting for 87.0 to 90.9 %, 85.2 to 97.8 %, and 84.5 to 94.0 %, respectively, of the whole year in mountains, deserts, and oases. The occurrence of sand–dust events is closely related to wind speed and relative humidity in mountains, and is closely related to wind speed in oases, while, is complex in desert.

Declarations

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Authors' contributions Participation of Qing He and Zhenjie Li included data collection; the participation of MingZai Deng and Alimabbas included drawing Figures 1–11; and the participation of Lili Jin included writing the article and helping to analyze the results.

Data availability The data used in this research are available from the corresponding author upon reasonable request.

Compliance with ethical standards Ethics approval

Ethics approval The authors confirm that this article is original research and has not been published or presented previously in any journal or conference in any language (in whole or in part).

Consent to participate and consent to publish The authors declare that they have consent consented to participate and consented to publish.

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Figures

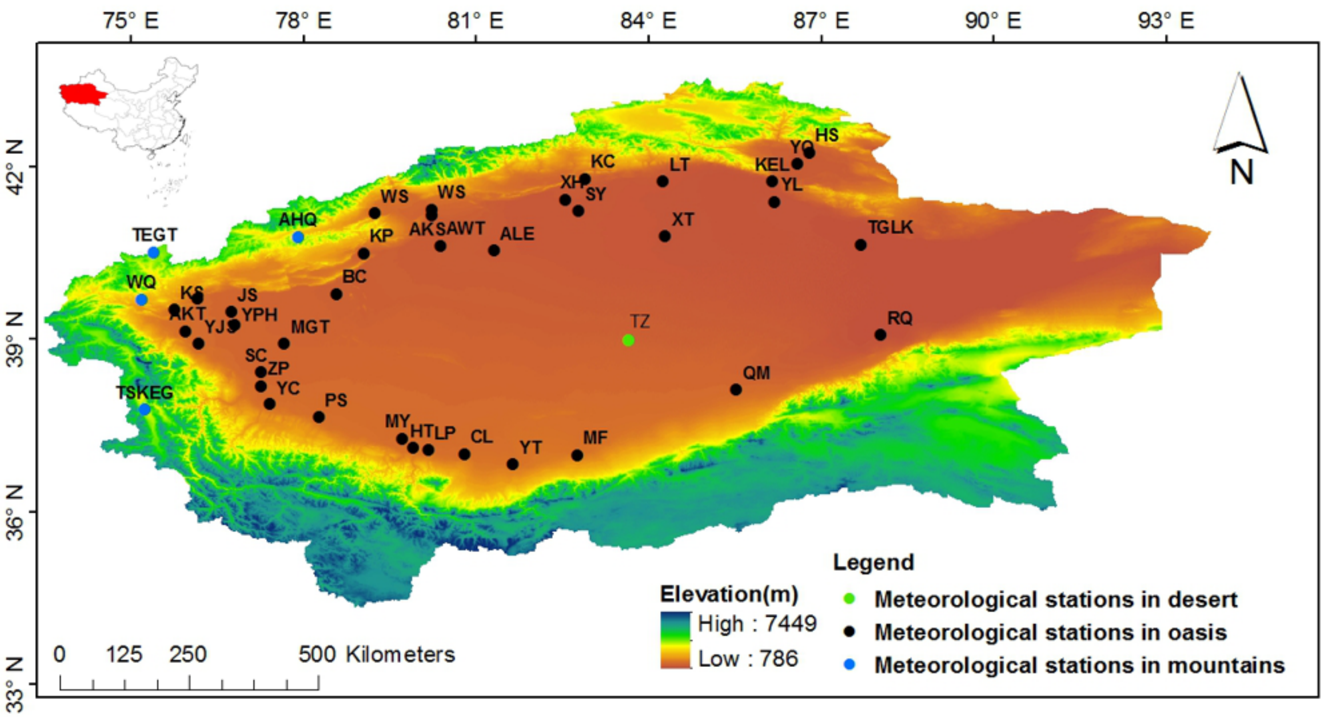

Figure 1

Spatial distribution of the meteorological stations in TB.

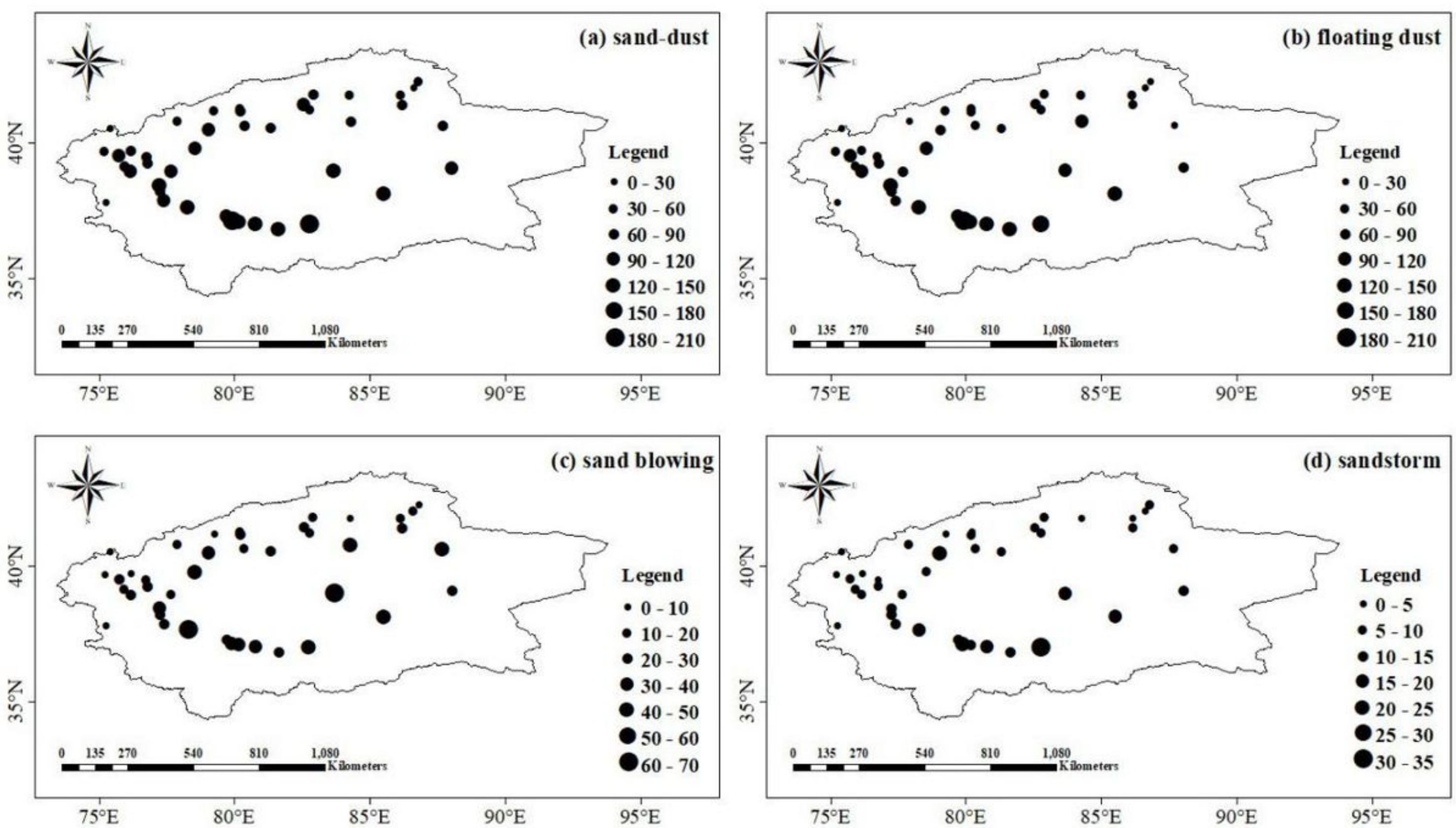

Figure 2

Annual average sand–dust days, floating dust days, sand blowing days, and sandstorm days from 1961 to 2015 in TB.

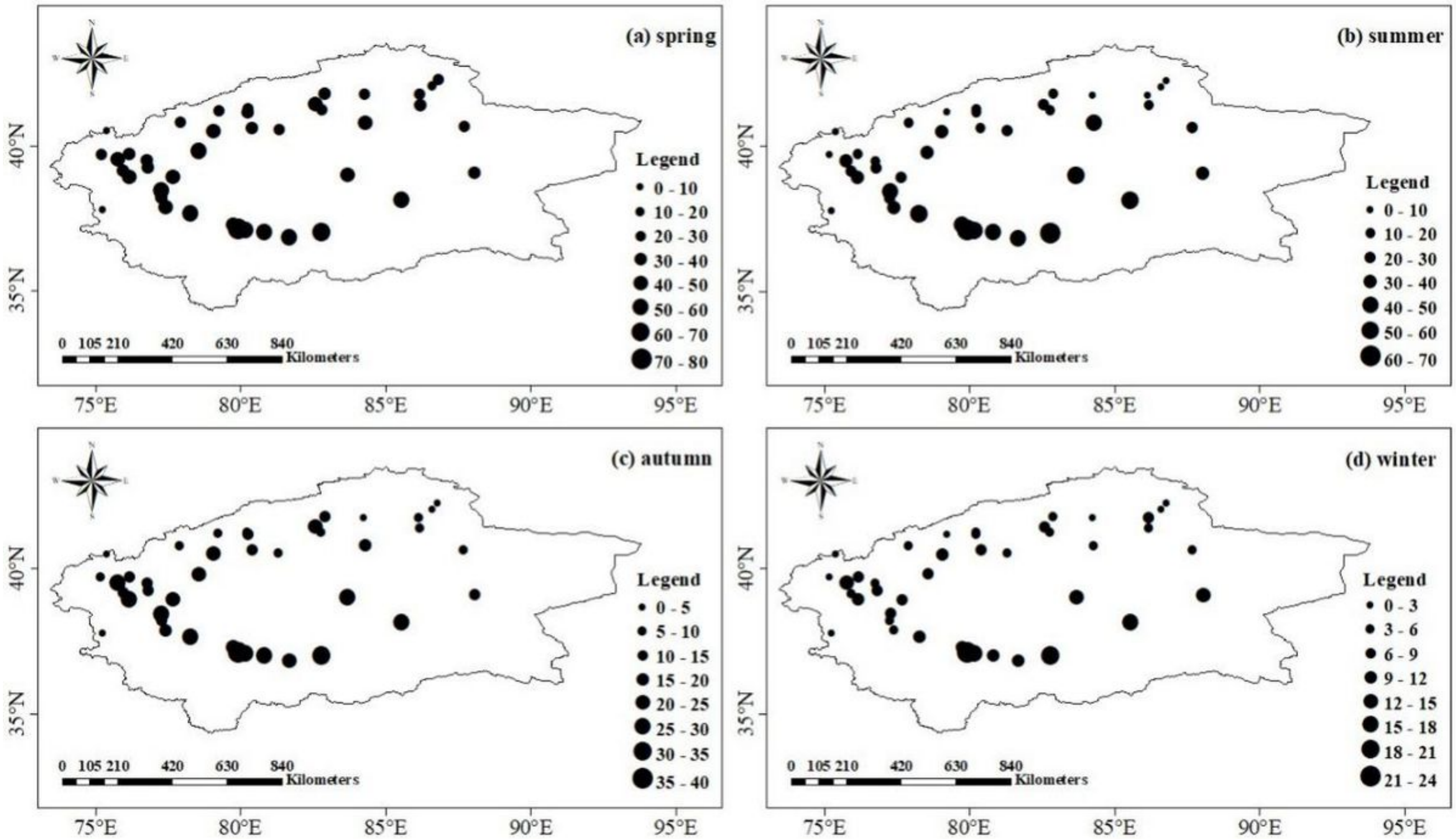

Figure 3

Seasonal average sand–dust days from 1961 to 2015 in TB.

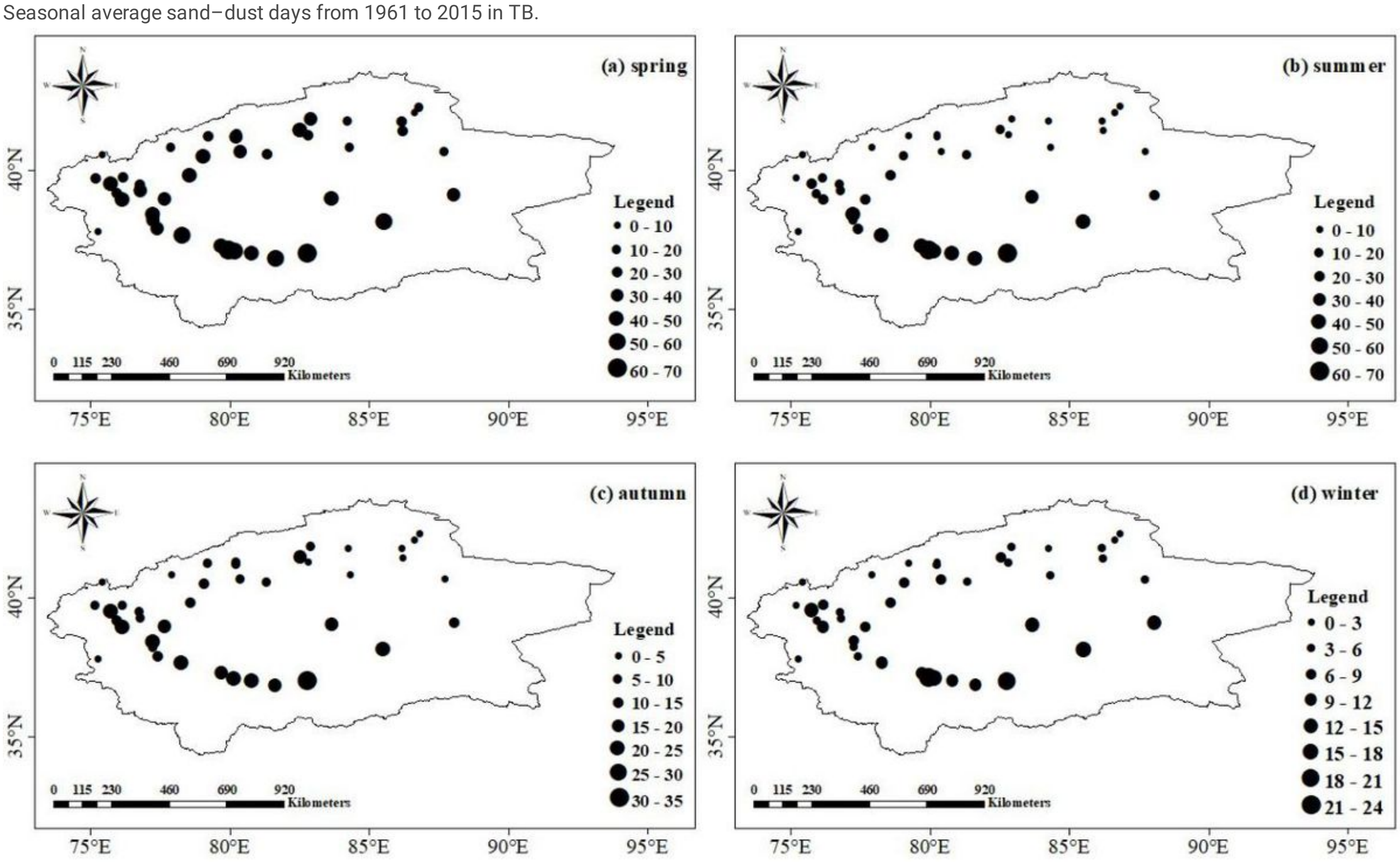

Figure 4

Seasonal average floating–dust days from 1961 to 2015 in TB.

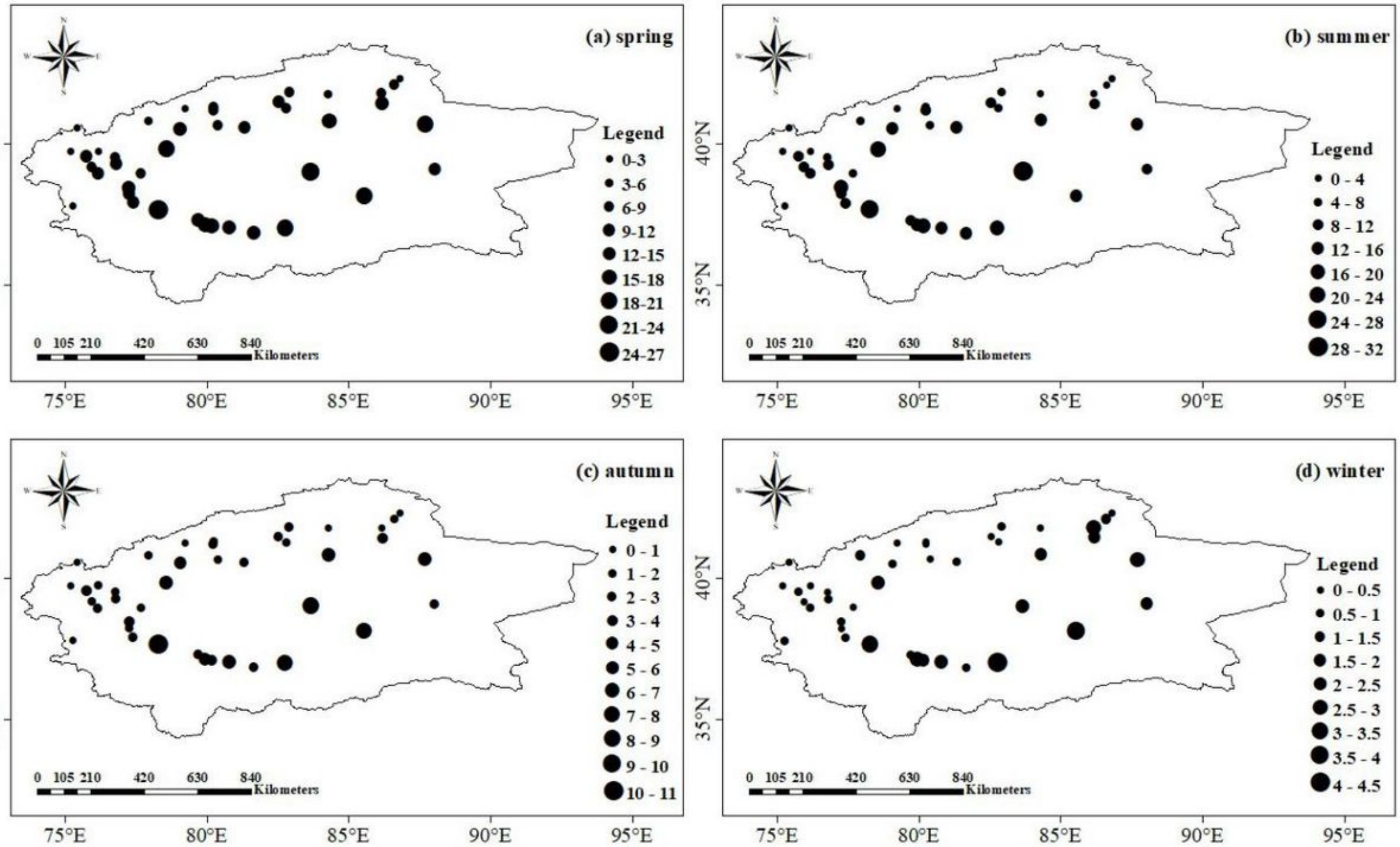

Figure 5

Seasonal average sand–blowing days from 1961 to 2015 in TB.

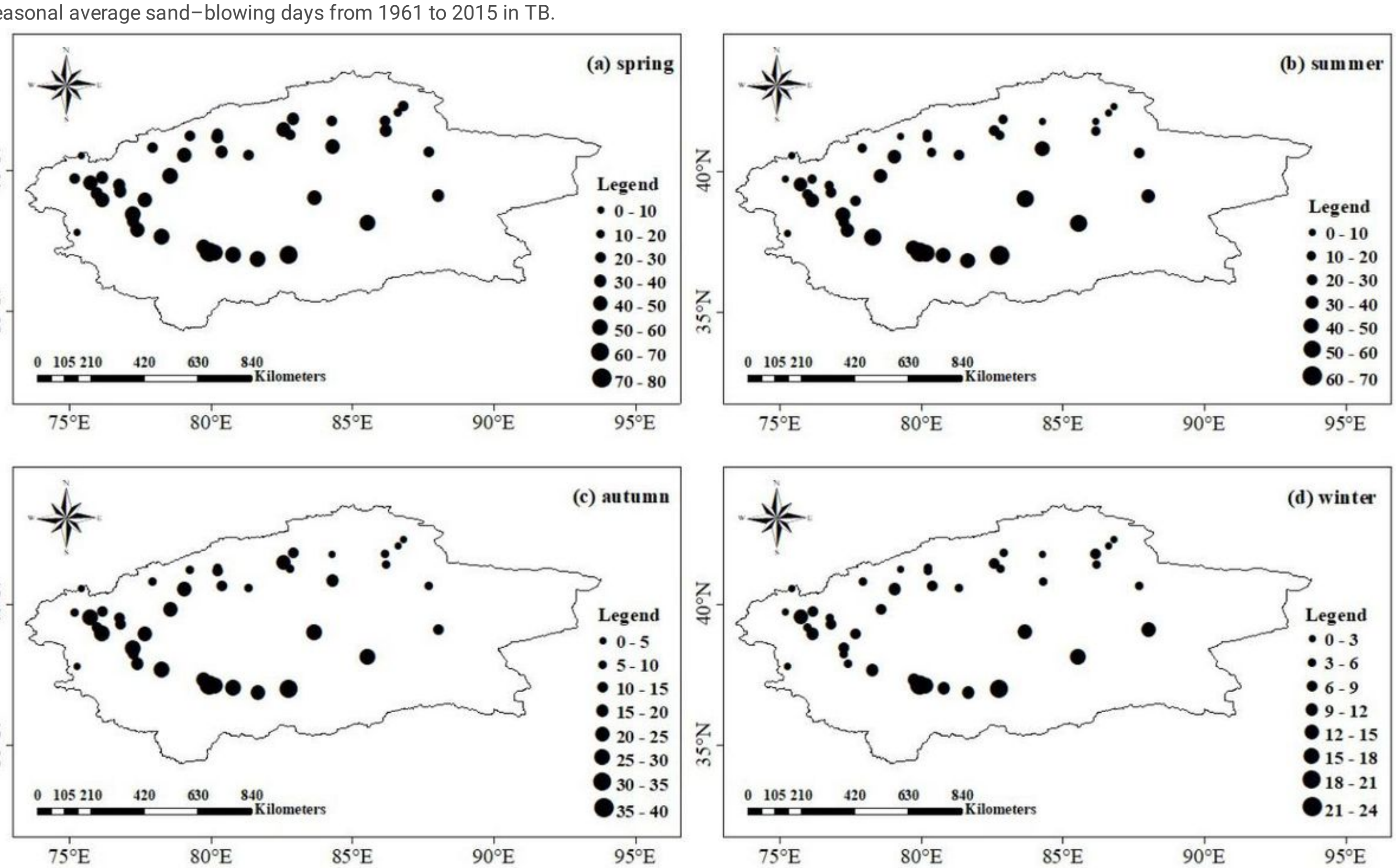

Figure 6

Seasonal average sandstorm days from 1961 to 2015 in TB.

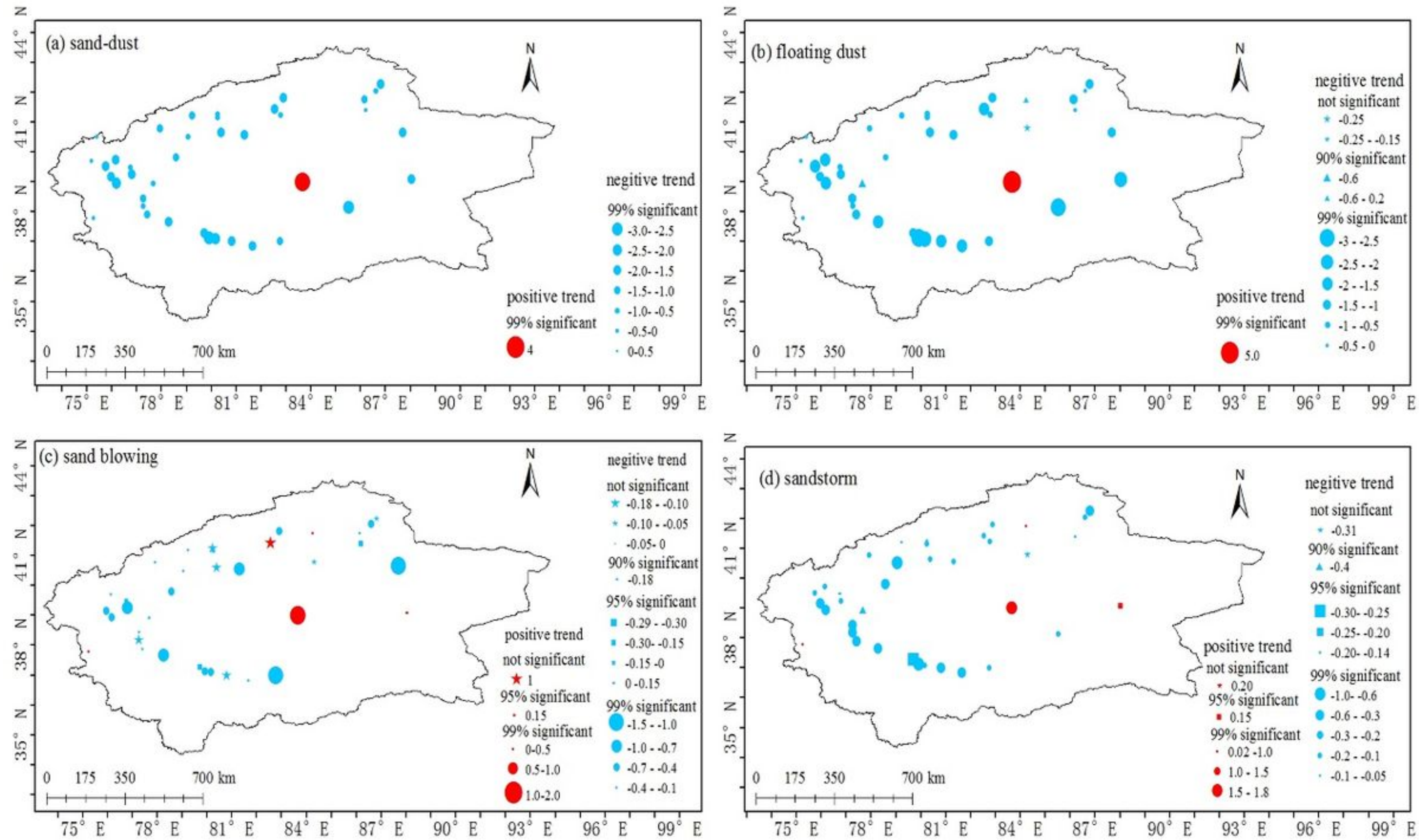

Figure 7

Annual average linear trend rates of sand–dust days, floating dust days, sand blowing days and sandstorm days from 1961 to 2015 in TB.

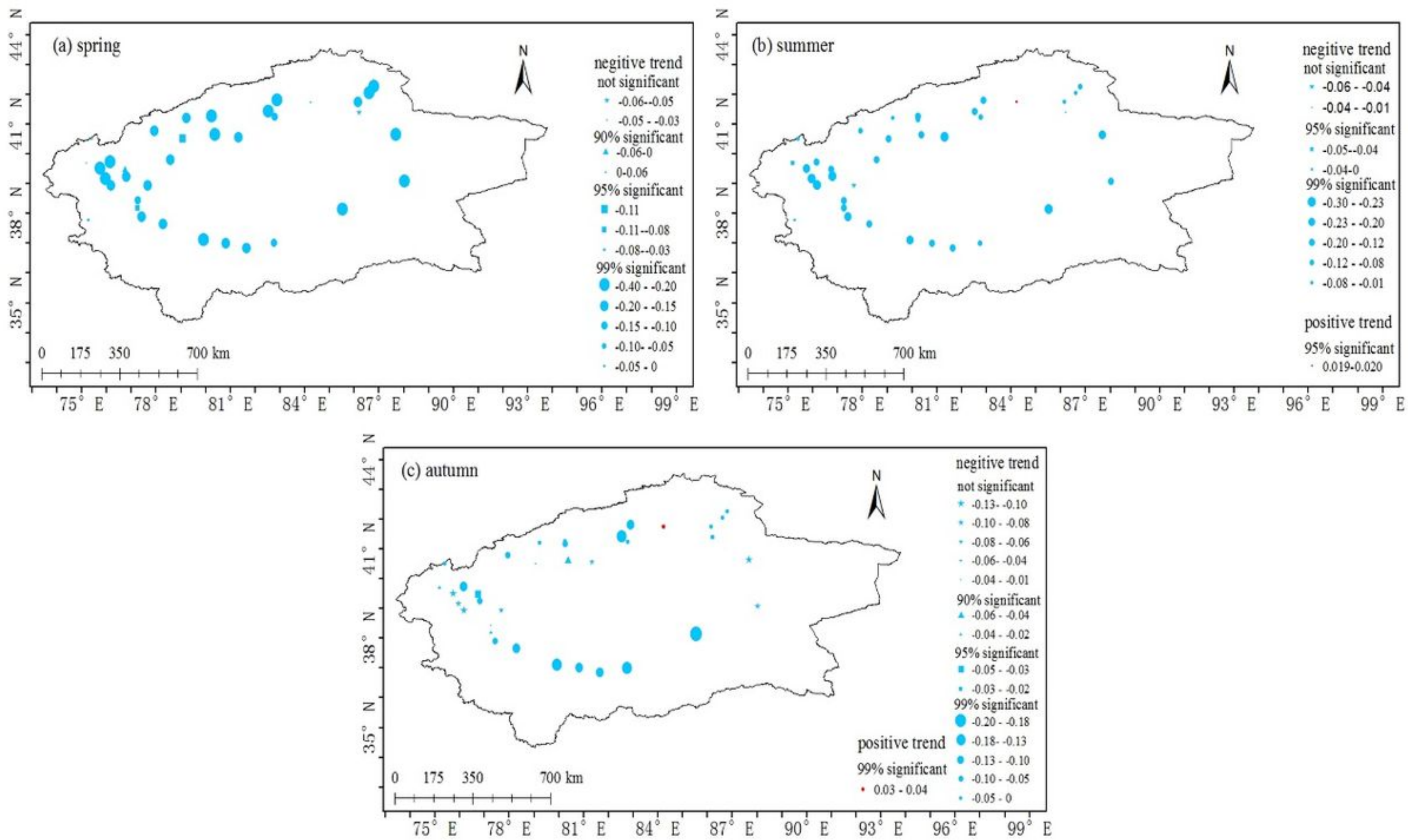

Figure 8

Seasonal average linear trend rates of sand–dust days from 1961 to 2015 in TB.

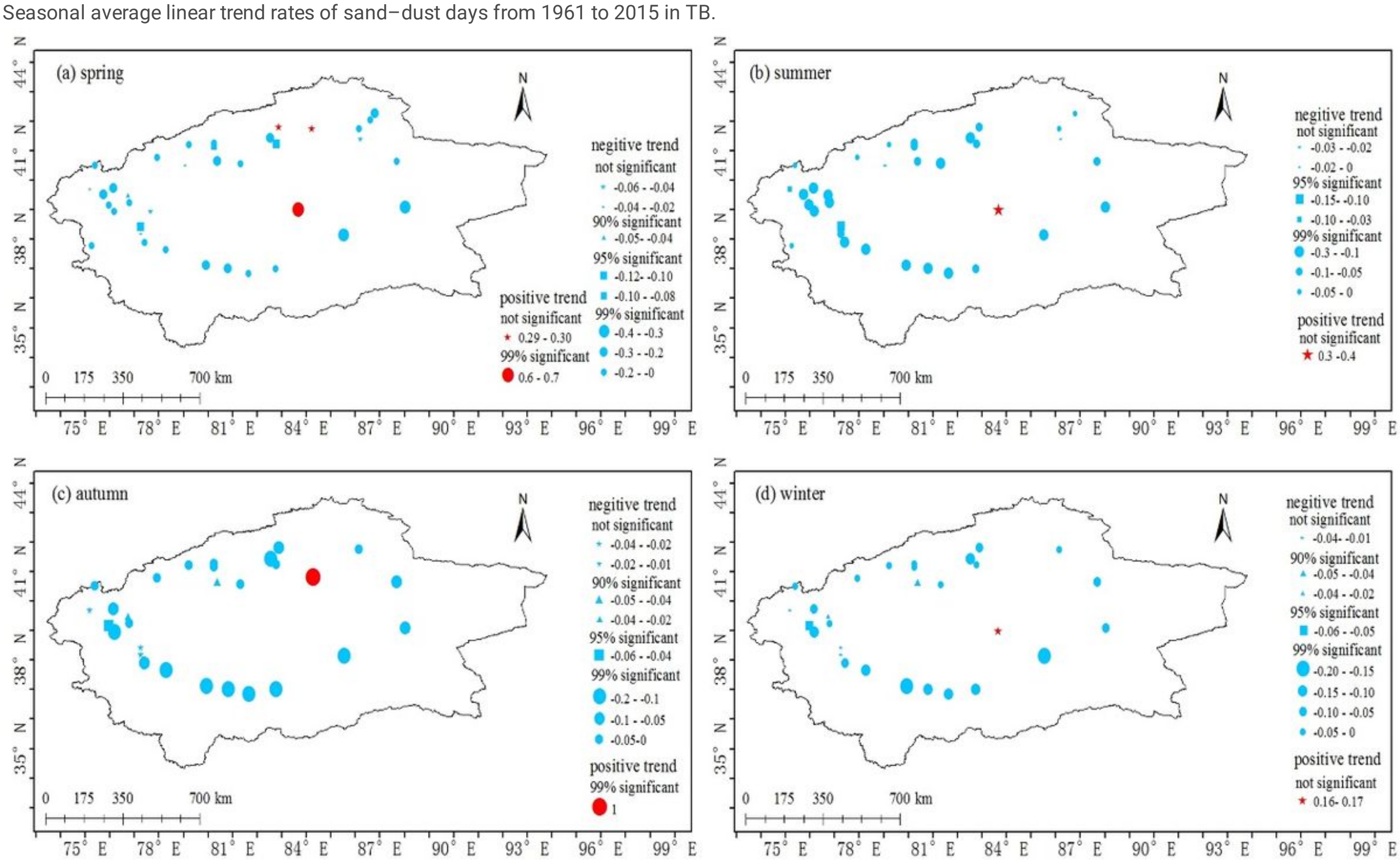

Figure 9

Seasonal average linear trend rates of floating–dust days from 1961 to 2015 in TB.

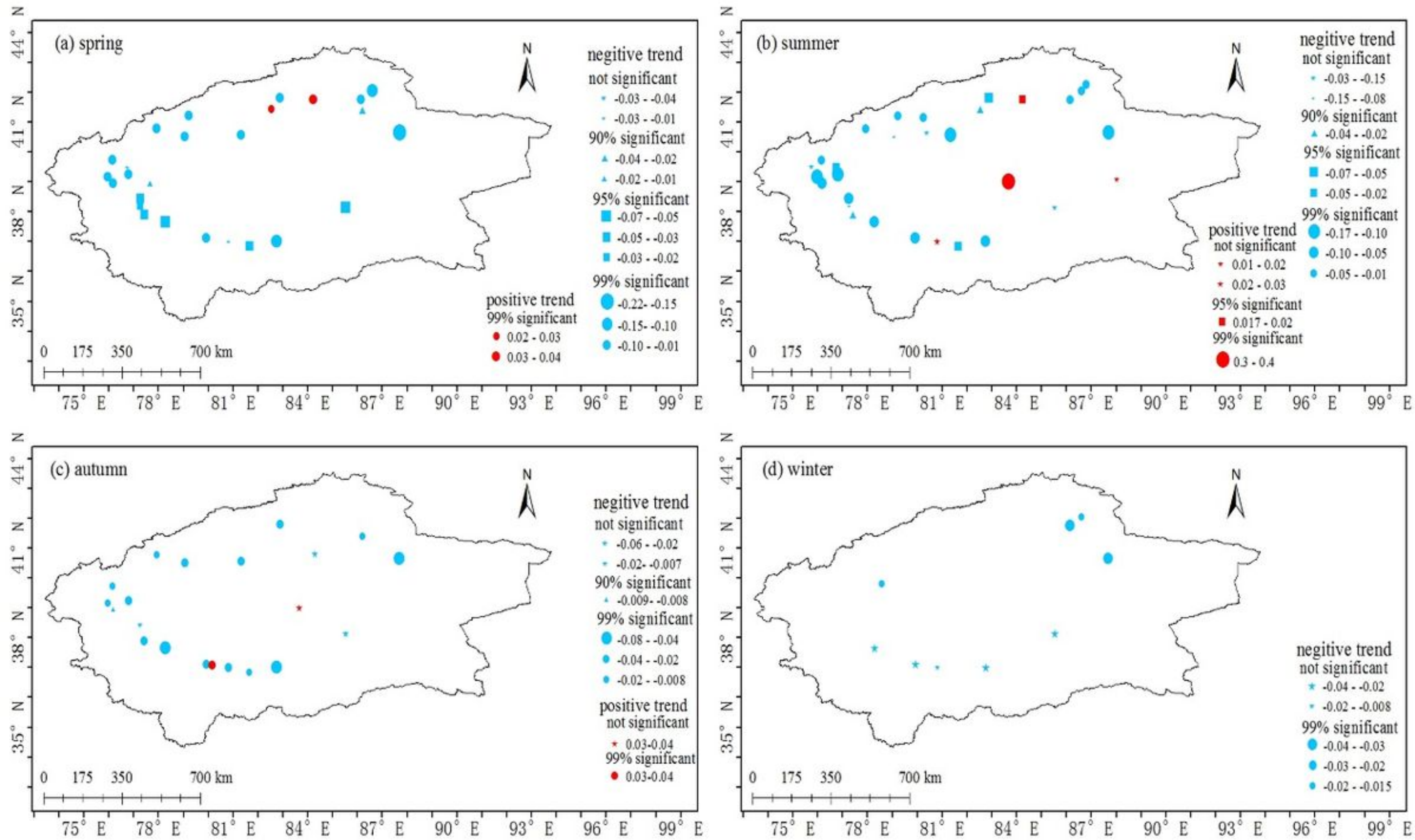

Figure 10

Seasonal average linear trend rates of sand–blowing days from 1961 to 2015 in TB.

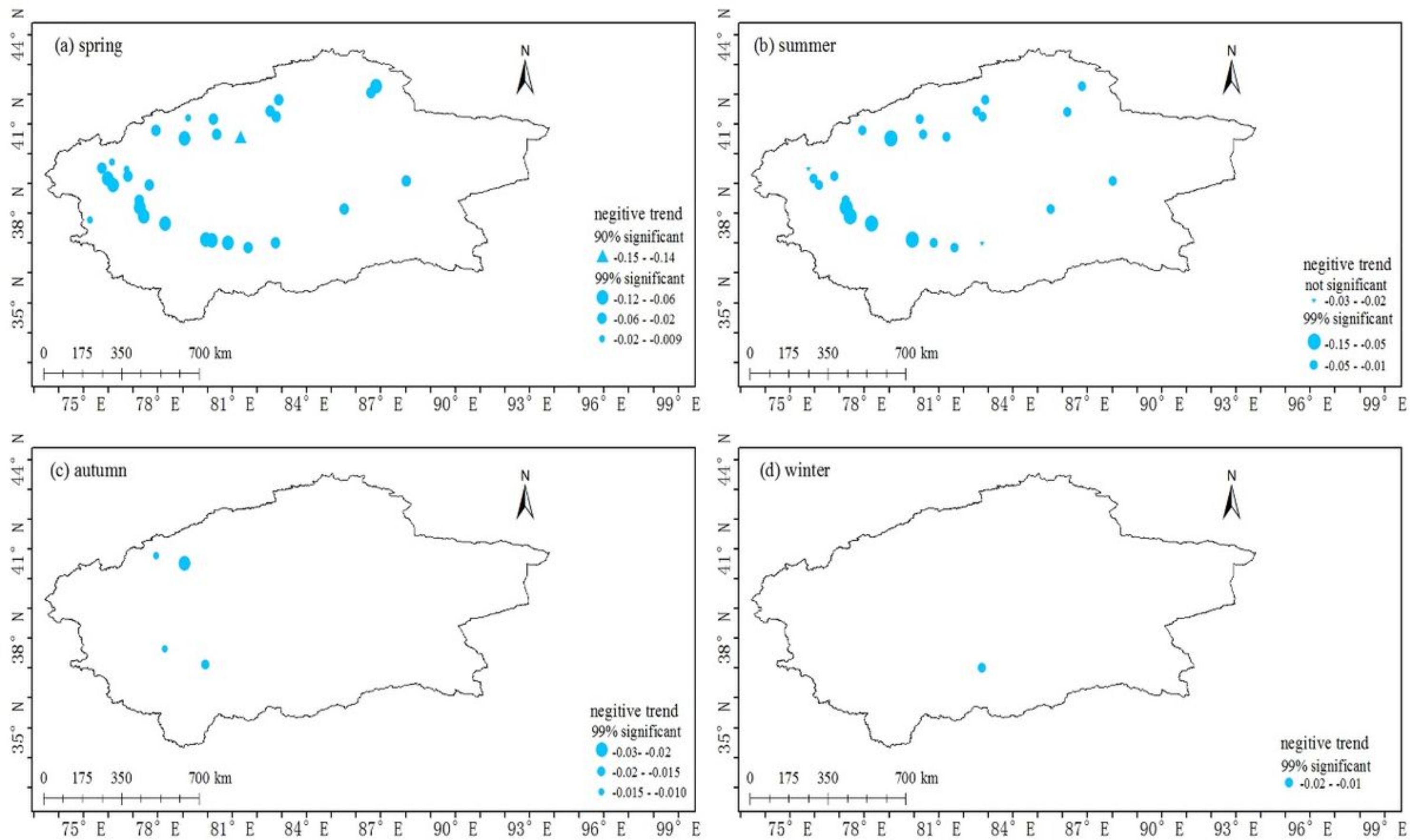

Figure 11

Seasonal average linear trend rates of sandstorm days from 1961 to 2015 in TB.

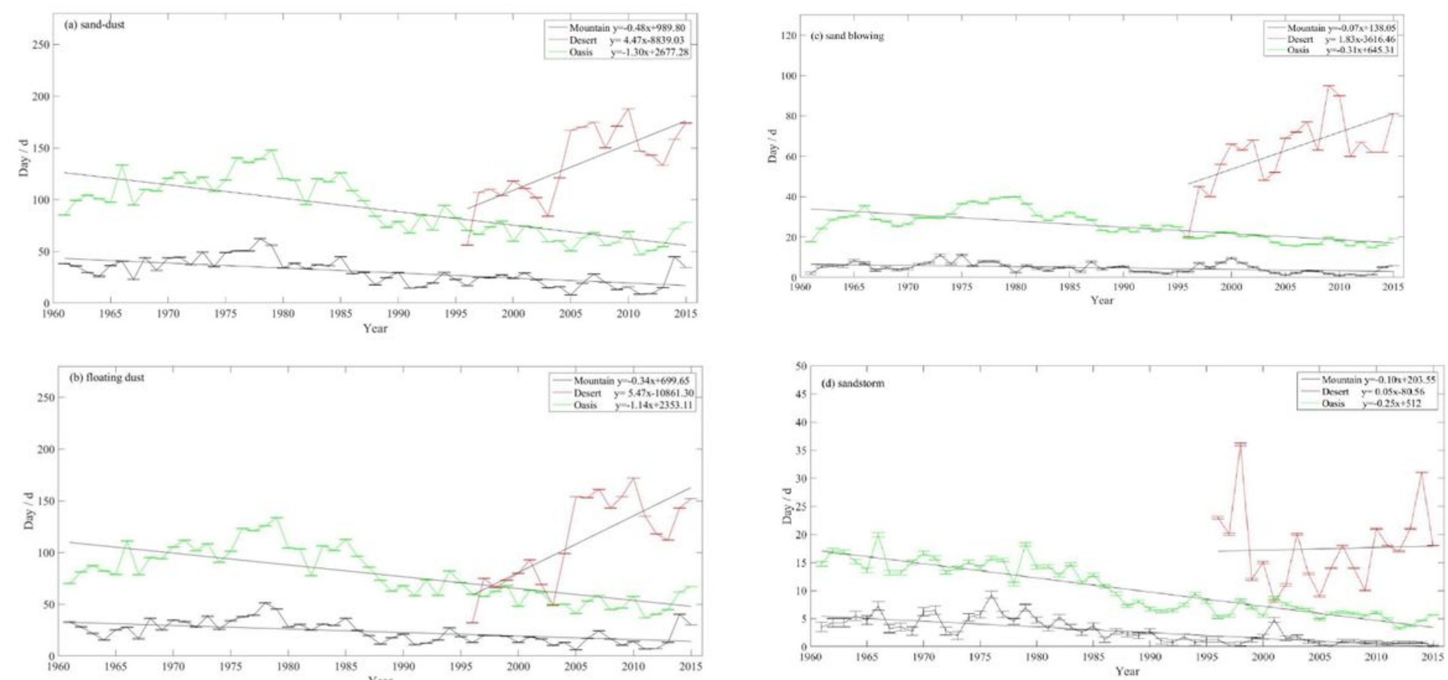

Figure 12

Interannual variations of sand–dust days, floating dust days, sand blowing days, and sandstorm days from 1961 to 2015 in mountainous regions, desert regions, and oasis regions in TB.

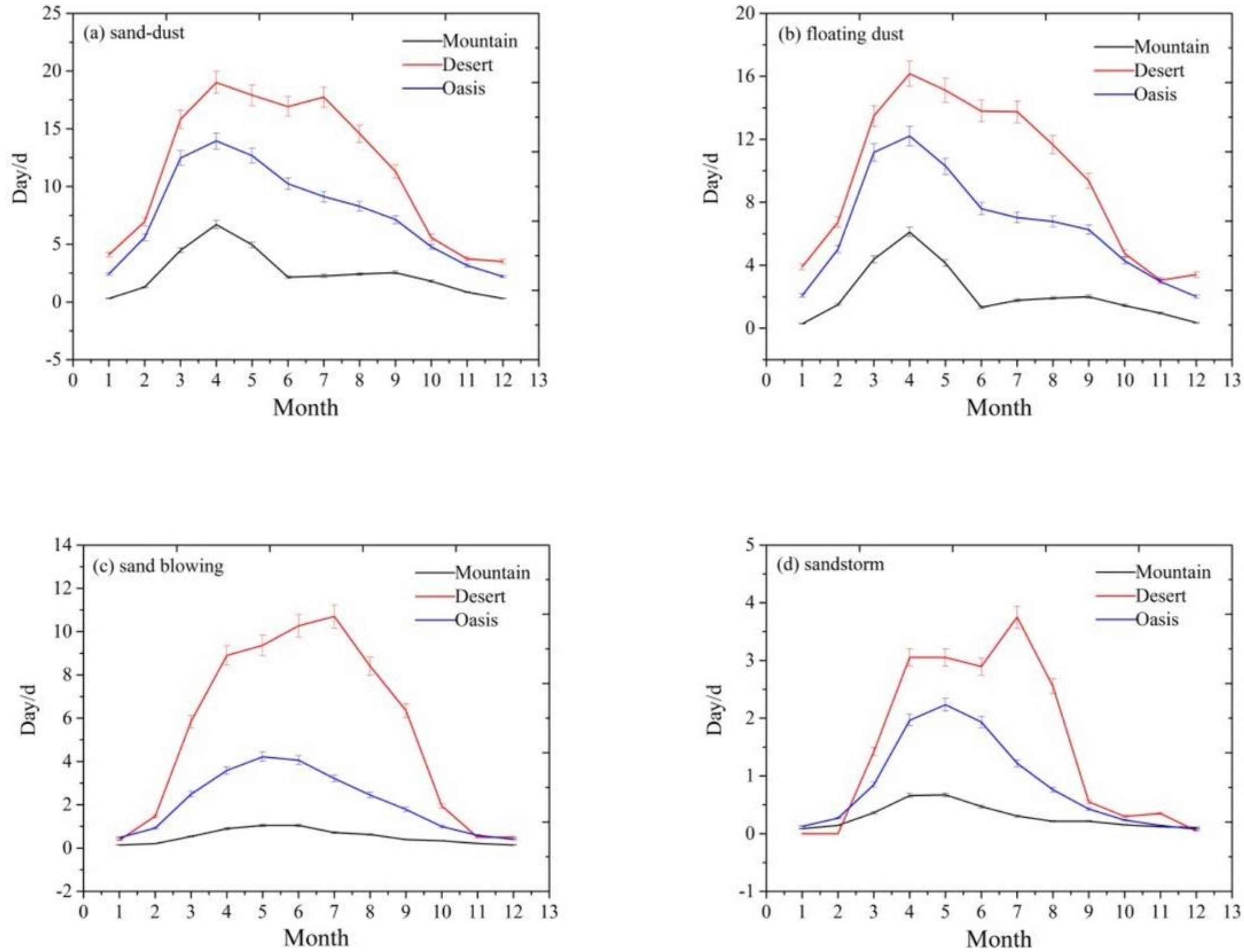

Figure 13

Annual variations of sand–dust days, floating dust days, sand blowing days, and sandstorm days from 1961 to 2015 in mountainous regions, desert regions, and oasis regions in TB.

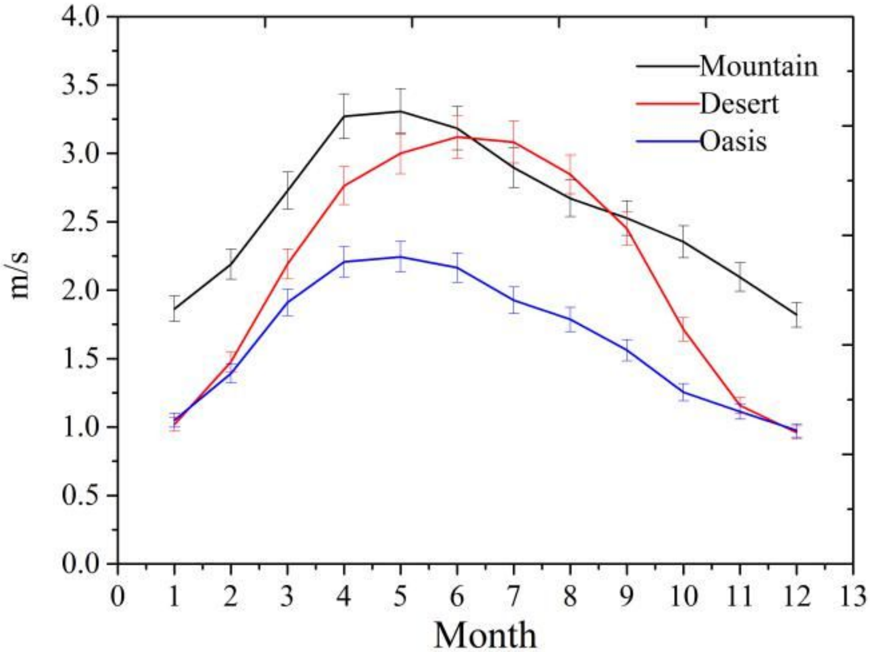

Figure 14

Annual variations of wind speeds from 1961 to 2015 in mountainous regions, desert regions, and oasis regions in TB.