Journal of Environmental Sciences Vol.13, No.1, pp.14—21, 2001 ISSN 1001—0742 CN11—2629/X

Article ID: 1001-0742(2001)01-0014-08 **CLC number**: X14 **Document code**: A

Climate controls on dust storm occurrence in Maowusu Desert, Inner Mongolia, North China

HUANG Fu-xiang, GAO Qiong

(Laboratory of Quantitative Vegetation Ecology, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China. E-mail: hfx1121@sina.com)

Abstract: Dust storms occurring in arid and semi-arid regions play a main role in the evolution of landscapes. Climate is generally regarded to be important factors influencing the occurrence of dust storm, however, the way of climate controlling dust storms had been poorly understood. In this paper, we present the *Ew* Index model to describe the relationship between climate variables and dust storm frequency using the available meteorological data from three meteorological stations in Maowusu Desert. This index model explains 83.6%, 69.5% and 65.09% of the variance of dust storm frequency in three regions from the north to the south, respectively and this difference is probably caused by the difference of the human disturbance. The *Ew* Index model is an effective predictor of dust storm frequency and provides us a quite good understanding on the occurrence of dust storms in Maowusu Desert.

Key words: dust storm; wind erosion; P-E Thornthwaite Index; Maowusu Desert

Introduction

Dust storms, which remove large quantities of topsoil, play a main role in the evolution of landscapes in arid and semi-arid lands. Occurrence of dust storm depends on a number of environmental factors, including sediment availability, soil erodibility and wind erosivity. In recent years, there is a growing awareness of the importance of climate effects on dust storms (McTainsh, 1989; 1990; 1998). Climate factors such as rainfall, evaporation and temperature are considered to be very important influential factors on soil moisture vegetation cover, and therefore, the erosion hazard, and the strong wind is considered to be the erosion power (Yu, 1993). However, the role of climate factors is less clearly apparent and has only recently received attention. In the past few years, many researchers have done a lot in this aspect (McTainsh, 1998).

Studies of the climatic controls upon dust storm occurrence have been developed from early models used in the USA. (Chepil, 1956; Fryrear, 1981), using annually averaged data on wind velocity and effective soil moisture (McTainsh, 1990). To improve those models, climate data averaged over shorter time intervals were used in following work (McTainsh, 1998). In China, however, up to date, few researchers have done research work about the climate controls on the occurrence of dust storm.

Ranging from 37°30′ to 39°20′ northern latitude and from 107°20′ to 111°30′ east longitude, Maowusu Desert in Inner Mongolia, northern China, is a transitional ecotone from agricultural crop fields in the southeast to grasslands for animal husbandry in the northwest. Maowusu, with a typical grassland climatic condition, has once been a luxuriant grassland with very dense vegetation coverage, however, now has shifted to be a sandland with mobile and semi-mobile sand dunes as the dominant landscape (Zhang, 1994).

In this shift, human misuse of land combining the climatic influence is commonly regarded as the main cause, but "to what extent, this shift should contribute to the natural and human aspects?" is a puzzle to be solved. In fact, this is a valuable question both of theoretical and practical. To do this, the first step is to get a much better understanding for the role of climate

Foundation item: The Chinese Academy of Sciences (No. KZ951-B1-108); The Excellent Youth Found of the National Natural Science Foundation of China (No. 39725006)

playing in dust storm occurrence.

In this paper, we present the *Ew* Index model developed from that of McTainsh *et al*. (McTainsh, 1998) using monthly averaged meteorological data to describe how wind speed and soil moisture interact through time to influence dust storm occurrence. To explain the difference of dust storm frequency at different region, we choose three typical meteorological stations from the north to the south in Maowusu Desert. These three stations not only play a role of the climate data source, but also provide different climate and land use background, so that we can understand the actual cause of dust storm occurrence completely.

1 Data and methods

Since this study aims to describe pattern of dust storms and climate, the major climate data requirements therefore are longevity and spatial breath. Three meteorological stations, Uxin Ju (UJ), Uxin Banner (UB) and Henan (HN) (Fig. 1), from the north to the south in Maowusu Desert, are chosen, where climate data from 1951 to 1981 are available (Inner Mongolian Meteorological Station, 1982). We calculate monthly averaged dust storm frequency and wind velocity on the base of these climate data (Table 1, Table 2).

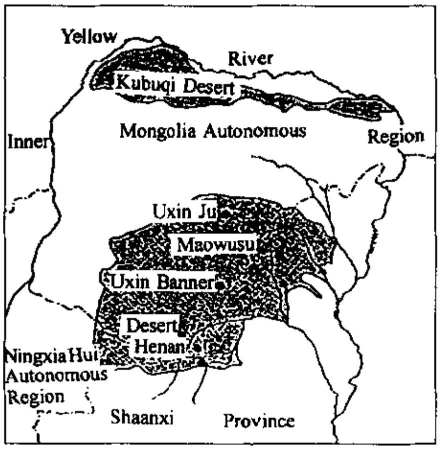

Fig.1 Maowusu Desert and the location of the three meteorological stations

Here, we use the term of dust storm frequency to mean the daily averaged times of dust storm, i.e., dust storm frequency = mean monthly times of dust storm/days of a month.

Table 1 Dust storm frequencies averaged monthly between 1951—1981

Station	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
UJ	0.0533	0.04	0.09	0.1333	0.1	0.04	0.0067	0	0.01	0.0067	0.0333	0.0367
UB	0.05	0.05	0.1033	0.17	0.1167	0.0833	0.03	0.0067	0.01	0.0133	0.03	0.0333
HN	0.05	0.05	0.13	0.18	0.1467	0.0633	0.02	0.0067	0.0033	0.0067	0.0167	0.0367

Table 2 Mean monthly wind velocities between 1951 – 1981, km/d

Station	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
UJ	138.24	146.88	159.84	190.08	185.76	155.52	146.88	138.24	125.28	133.92	151.2	142.56
UB	138.24	146.88	159.84	181.44	181.44	155.52	142.56	138.24	125.28	120.96	138.24	138.24
HN	95.04	108.00	133.92	151.20	151.20	129.60	120.96	108.00	95.04	99.36	103.68	90.72

The *Ew* Index model presented in this paper is developed from the previous work by McTainsh *et al*. (McTainsh, 1990; 1998). Following improvements are made: (1) mean monthly precipitation and evaporation data are used to produce precipitation-evaporation (P-E) Index (Thornthwaite, 1931) directly instead of using precipitation and temperature to approximate soil moisture (Table 3); (2) since wind run can underestimate wind erosivity in gust wind environment by averaging out infrequent high windspeed events, but wind velocity usually provides a better measure (McTainsh, 1998), in this paper, wind velocity data instead of wind run are used; (3) temperature in the winter is extremely low in Maowudu Desert (Table 4). The freezing

Table 3 Mean monthly effective soil moisture (*P-E*) between 1951—1981

Station	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
UJ	0.46	0.48	0.51	0.63	0.53	0.86	3.1	4.24	3.14	1.74	0.67	0.25
UB	0.31	0.45	0.45	0.60	0.57	0.70	2.52	3.54	2.73	1.45	0.72	0.24
HN	0.32	0.43	0.51	0.79	0.72	0.91	2.04	4.02	3.11	1.85	1.12	0.32

temperature affects the occurrence of dust storm in a completely different way, because it makes the topsoil solid and difficult to erode. To solve this problems, the variable of (*P-E*) is used instead of (*P-E*)^2 used in those papers by McTainsh *et al.* (McTainsh, 1990; 1998) for the winter months from November to February; (4) McTainsh *et al.* (McTainsh, 1998) used a wind run threshold in their model to separate those months with very low wind speed from other months. The determination of wind run threshold is, however, quite difficult and arbitrary. So, in this paper, no wind velocity threshold is set for any month.

Table 4 Mean monthly temperature in the winter in Maowusu Desert

Station	Jan.	Feb.	Nov.	Dec.
Uxin Ju	-11.4	-7.6	-1.8	-9.8
Uxin Banner	-10.5	-6.8	-1.4	-9.0
Henan	-9.9	-6.2	-0.4	-8.4

2 The *Ew* Index model

Fig. 2 compares the monthly pattern of dust storms frequency within each of the three regions, in relation to monthly soil moisture (measured by the *P-E* Index) and wind velocity. Fig. 3 compares the monthly pattern of wind velocity and effective soil moisture in Uxin Ju (the northern station). A general rule is that periods of high dust storm frequency correlate well with the period of low soil moisture and high wind velocity, and high wind velocity months correlate quite well with the low soil moisture months (Fig. 2, Fig. 3). In this paper, the *Ew* Index model uses wind velocity and soil moisture data to simulate dust storm frequencies.

2.1 The basic structure of the model

The basic model describing annual average relationships between soil moisture, wind velocity and dust storm frequency was first presented by McTainsh *et al.* (McTainsh, 1990).

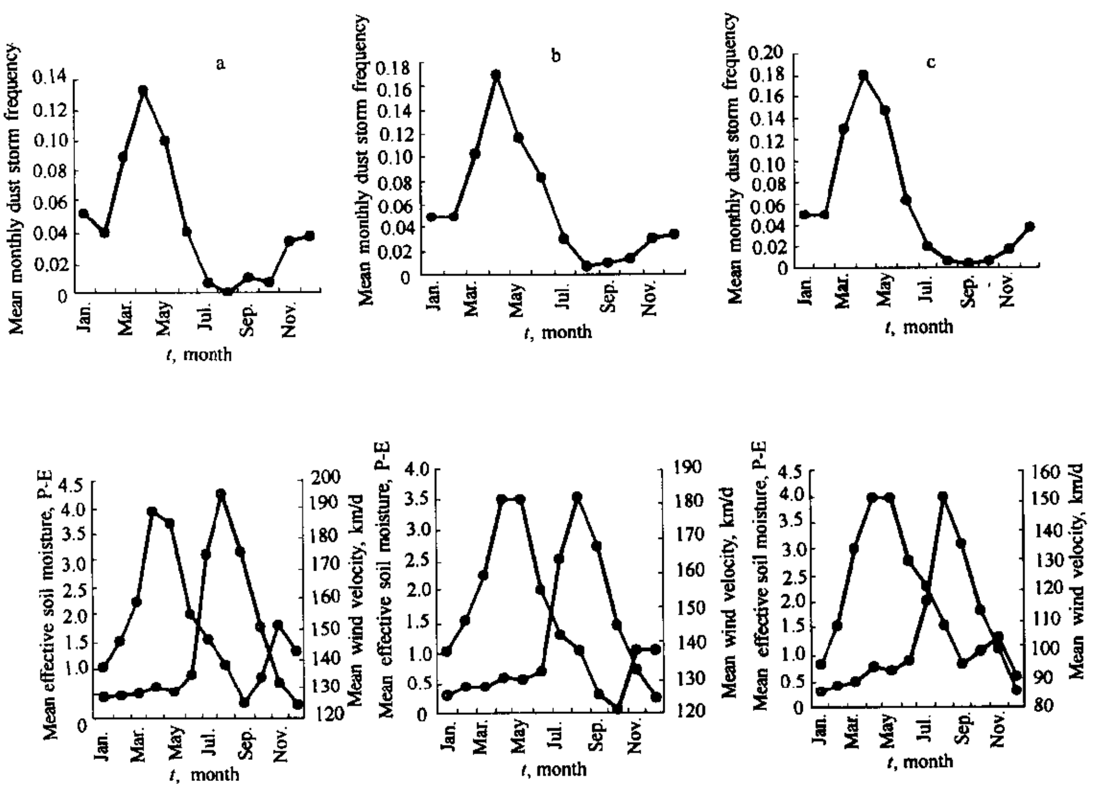

Fig. 2 Dust storm frequency(●), effective soil moisture(○) and wind velocity (●) in (a) the Uxin Ju Station, (b) the Uxin Banner Station and (c) the Henan Station

$$Ew = \frac{w}{(P - E)^2}, \quad (1)$$

where Ew is the index to discribe the effects of climate on dust storm frequency, W is the mean annual wind run and P-E is Thornthwaite's Index (Thornthwaite, 1931).

This model is not, however, a good predictor of average monthly dust storm frequency because it does not adequately describe the effects of variations in wind velocity and antecedent soil moisture conditions upon dust storms (McTainsh, 1998). In the following paper, McTainsh *et al*. improved the Ew model in those aspects. To separate those months with very low wind speed from other months, a threshold of wind run was set (McTainsh, 1998).

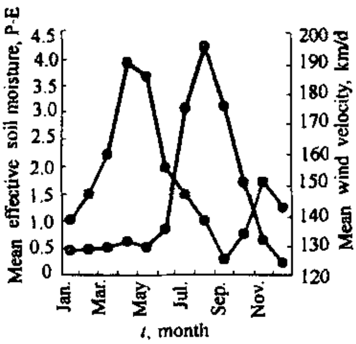

Fig.3 Structure of the Ew Index for the Uxin Ju Station. (○) for mean monthly Effective soil moisture and (●) for mean monthly wind velocity.

However, this improvement by McTainsh *et al*. (1998) is still not perfect. The main shortcomings include: (1) only considering the potential effects of the previous month moisture is not enough. Extremely cold weather reduces the dust storm frequency sharply because it freezes the topsoil hard to be eroded; (2) although antecedent soil moisture condition affects the present month's dust storm occurrence, in fact, this effect is noticeable only when the moisture is relatively low. When the soil moisture is quite high, this effect is negligible; (3) determining the threshold of wind run is quit difficult and to some extent, arbitrary. Those aspects restricts the application of the model in practice.

In this paper, the basic structure of the Ew Index model conveyed by Equation (1) is used as the basis of the Ew Index model. Following aspects are improved in a much sound way. (1) Mean monthly climate data instead of annual data are used in this paper. (2) At the same time of considering effects of antecedent soil moisture on the present month's dust storm occurrence, pay a close attention to the size of the moisture. (3) No arbitrary wind speed threshold is appointed. (4) Mean monthly precipitation and evaporation data, instead of the temperature, are used to produce the P-E Index directly (Table 3). (5) Mean monthly wind velocities, instead of wind run, are used to measure wind erosivity and (6) in the freezing winter, effects of the extremely cold weather on the dust storm occurrence are paid special consideration.

2.2 Effect of antecedent soil moisture

Without considering the effect of antecedent soil moisture on dust storm occurrence in the present month would under- or overestimate wind erosion rates depending on whether the soil moisture in the preceding month was dryer or wetter. Antecedent soil moisture conditions are described in two ways. If the preceding month is drier (the soil is getting wetter through time) the Ewt Index is used (Eq. 2). If the preceding month is wetter (the soil is getting drier through time) the Ewd Index is used (Eq. 3) (McTainsh, 1998). This improvement is a quite good simulation of the actual dust storm occurrence, and we adopt it in this paper.

The Ewt Index expressed in Equation (2) allows for the effect of antecedent soil moisture conditions in a wetting curve situation. The potential of wind erosion in the present month is increased by the previous month's relatively low effective soil moisture. This effects is prominent especially in months during the soil moisture is relatively low.

$$Ewt = \frac{W}{(P - E)^2} + (P - E)^* \frac{W}{(P - E)^2}, \quad (2)$$

where W and (P-E) are climate variables in the present month and $(P\text{-}E)^*$ is the previous month's effective soil moisture. In the three regions of Maowusu Desert, five months April, June, July, February and August are period when soils moisture are becoming wetter. However, the Ewt Index only applies in April, Júne and July but does not apply in February and August. This is caused by the following reasons. In February, Maowusu is in the freezing winter when the extremely cold temperature is the most important influential factor on the dust occurrence, in which case, the effects of antecedent moisture is negligible. August is the month when the moisture is the biggest and soil moisture in July is also in a quite high level. In this case, the soil moisture of July has no remarkable influence on the dust storm in August.

The *Ewd* Index expressed in Equation (3) considers the effect of antecedent soil moisture condition in a drying curve situation by subtracting the inverse of the previous month's relatively high effective soil moisture. By this way, the antecedent higher soil moisture reduces the dust storm frequency in the present month.

$$Ewd = \frac{W}{(P-E)^2} - \frac{1}{(P-E)^*}\frac{W}{(P-E)^2}, \tag{3}$$

where W and $(P\text{-}E)$ are climate variables in the present month and $(P\text{-}E)^*$ is the previous month's effective soil moisture. In Equation (3), the inverse of $(P\text{-}E)^*$ is used, because of the inverse proportion relationship between the potential wind erosion and soil moisture, i.e., as the soil moisture decreases ($P\text{-}E$ gets smaller) the potential for wind erosion increases.

In Fig.2 and Fig.3, May, September, October, November and December are months when soil moisture getting drier, but only October applies the *Ewd* Index in Maowusu Desert. The reason of September not apply the *Ewd* Index is that soil moisture is very high in August and September which influences the occurrence of dust storm so sharply that the change of moisture makes little influence on the dust storm occurrence. May does not apply the *Ewd* Index because the change of soil moisture between April and May is not big enough. November and December are excluded applying the *Ewd* Index because of the freezing temperature in those two months. In Maowusu Desert, the freezing temperature is the most important influential factor in the winter. The influence of the soil moisture in winter months will be discussed in the following text.

2.3 Effect of the freezing winter

In the winter months, from November to February of the next year (November, December, January and February), Maowusu Desert is at its extremely cold period (Table 4). In those months, the freezing temperature makes the topsoil of sand to be solid and hard to erode. In this way, the very low temperature reduces dust storm frequency sharply and becomes to be the most important role to control dust storm. To simulate the climate controls on dust storm occurrence, a new index is needed. In this paper, we present the *Ewf* Index expressing in Equation (4) for winter months.

$$Ewf = \frac{W}{P-E}, \tag{4}$$

where W and $P\text{-}E$ are the climate variables in the present month. In Maowusu Desert, the *Ewf* Index applies in November, December, January and February.

2.4 The *Ew* Index model

For months of March, May, August and September, the index of *Ew* in the basic model are applied. Now, we have got the *Ew* Index model in Maowusu Desert for every month.

$$Ew = \begin{cases} Ew \text{ (Mar., May, Aug., Sep.);} \\ Ewt \text{ (Apr., Jun., July);} \\ Ewd \text{ (Oct.);} \\ Ewf \text{ (Nov., Dec., Jan., Feb.).} \end{cases} \tag{5}$$

3 Results

3.1 The *Ew* Index for every month in Maowusu Desert

We calculate the *Ew* Index for every month for the three regions respectively, by using the model expressed by Equation (5) (Table 5).

Table 5 *Ew* **Index of every month in the three regions**

Station	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
UJ	329.6	246.4	616.8	722.8	654.6	319.6	15.3	7.7	12.7	30.1	204.6	225.8
UB	445.9	326.4	777.2	739.5	554.6	504.0	22.5	11.0	16.8	36.6	192.0	576.0
HN	297.0	251.2	505.1	366.6	292.7	266.9	29.0	6.7	9.8	19.8	92.6	283.5

By using these indexes of the three regions in Maowusu, we obtain the relationships between the *Ew* Index and the actual dust storm frequency (Table 6).

Table 6 Results of regression for the three regions

Region	Regression model	R	R^2	F	Sig.
UJ	$Y = 0.0001x + 0.0007$	0.914	0.836	304.6	0.000
UB	$Y = 0.0001x + 0.0067$	0.834	0.695	23.1	0.001
HN	$Y = 0.0003x - 0.0014$	0.807	0.6509	18.8	0.001

3.2 Statistical test of the *Ew* model

Fig. 4 (a, b, c) shows graphical relationships between the *Ew* Index and mean monthly dust storm frequency in the three regions in Maowusu. The models explain 96.8%, 69.8% and 65.3% of the variance in the dependent variable dust storm frequency for the three regions from the north to the south, respectively.

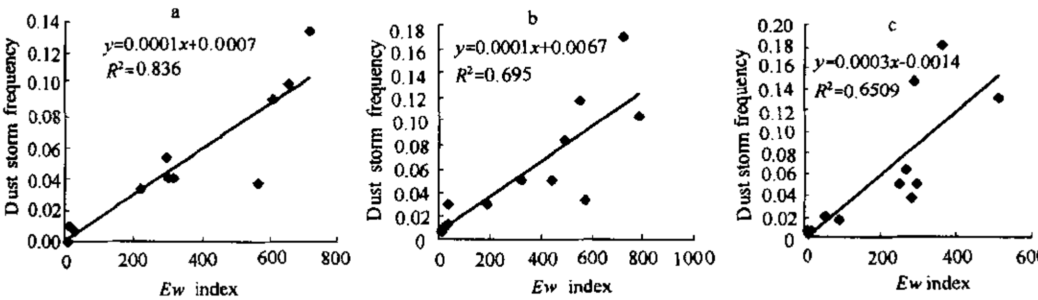

Fig. 4 Relationship between the *Ew* Index and dust storm frequency for (a) Uxin Ju, (b) Uxin Banner and (c) Henan Station

In Fig. 5, the predicted dust storm frequencies are compared with the actual dust storm frequencies for the three regions respectively. In Uxin Ju (in the north of Maowusu), the predicted fits the actual quite well. But in Uxin Banner and Henan, the calculated frequency curves do not fit the actual curves so well. In the spring months (March, April and May), the predicted values are generally smaller than actual ones.

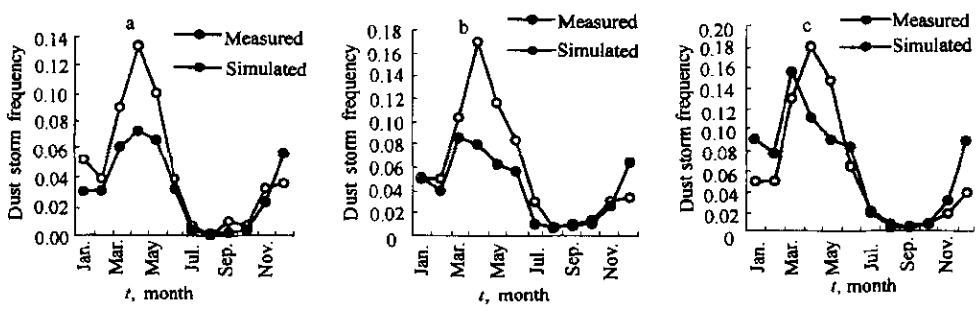

Fig. 5 Temporal pattern of measured and simulated of dust storm frequency for (a) Uxin Ju, (b) Uxin Banner and (c) Henan Station

3.3 Explanation of the pattern of dust storm in Maowusu

Generally, the dust storm frequency is proportional to the *Ew* Index. So, the *Ew* Index model is a quite good predictor of the dust storm frequency.

Table 1 and Fig.2 show that dust storm is most frequent in the spring months (March, April, May and June). In the winter months (November, December, January and February), the frequency is lower than in the spring but higher than in the summer. Summer (July, August, September and October) is the season when dust storm frequency is the lowest. We can explain the dust storm pattern using the *Ew* Index model presented in this paper. Spring is the season when the wind speed is the highest with the lowest soil moisture and therefore there is the most frequent dust storm. Summer is the season when the wind speed is the lowest with the most abundant rain, therefore, there is no strange that dust storm frequency is the lowest in the summer. In the winter, the freezing temperature is the most important factor controlling the occurrence of dust storms. Although the freezing temperature reduces the dust storm occurrence sharply, with the quite high wind speed, the dust storm frequency is relatively high (Fig.2). Generally, coinciding with the order of *Ew* indexes, spring > winter > summer, the order of dust storm frequency is spring > winter > summer.

4 Discussion

4.1 The probably cause of the difference in fitting dust storm frequency

Fig.4 shows us that there is noticeable difference when we use the *Ew* Index model to explain the variance in the dependent variable dust storm frequency. In Uxin Ju Station, 83.6%, while in Uxin Banner Station, 69.5% and in Henan Station, 65.09%. Besides stochastic factors influence, if there exist any other cause to make this difference? If so, what is main cause to make the noticeable deference?

Factors influencing the occurrence of dust storm include the climate and human land-use. In this paper, when we use the *Ew* Index model to describe the climate control on dust storm occurrence in Maowusu Desert, we do not consider the effects of human land-use. Human land-use affects the occurrence of dust storms by changing the pattern of land-cover what plays a protective role to the topsoil in wind erosions. In Maowusu Desert, the difference of effects by human land-use is probably the main cause of the difference in predicting the dust storm frequency. Henan Station, locating in the south of Maowusu, has a quite better water condition and a much longer history of cultivating than the other two regions. Long period of human cultivating destroyed the land- cover markedly, which increases the potential of dust storm occurrence sharply. Uxin Banner Station locates at the capital of Uxin Banner, which also makes this region affected severely by human land-use. Uxin Ju is a traditional mobile pastoral region. In this way, climate factors is almost the sole determinant factor of dust storm frequency in Uxin Ju Station, but in Uxin Banner Station and Henan Station, besides the climate factors, human land-use effects also play an important role in controlling the occurrence of dust storm. Different degrees of human land-use on dust storm frequency are the probably causes of the difference in fitting dust storm frequency using the *Ew* Index model.

4.2 The possible wind velocity threshold for dust storm

Since wind erosions occur only when the wind speed is big enough (there is wind speed threshold for wind erosion; Bagnold, 1941), there should exist wind speed threshold in dust storm occurrence. In this meaning, the setting of wind run threshold in the paper by McTainsh *et al*. (McTainsh, 1998) to separate months with low wind speed from other months is reasonable. Because the determination of wind speed threshold is quite difficult and arbitrary, this is not adopted in our model. To improve the fit degree of predicting dust storm frequency, we should determine the correct wind speed threshold for dust storm occurrence in using the *Ew* Index model. Obviously, the wind velocity threshold for dust storm is quite different from that for wind erosion.

4.3 The consideration of soil moisture condition in applying the *Ew* Index model

In considering effects of antecedent soil moisture on dust storm frequency in the present month, we should pay close attention to the condition of the soil moisture in the present and previous months. Change of soil moisture in the two successive months should be big enough to soil moisture in the present month. Otherwise, this change will make no noticeable influence on the occurrence of dust storm and indexes considering effect of antecedent soil moisture will not apply. This is the very reason that August does not apply the *Ewt* Index, May and September do not apply the *Ewd* Index in this paper.

References:

Bagnold R A, 1941. The physical of blown sand and desert dunes [M]. London: Methuen.
Burgess R C, McTainsh G H, Pitblado J R, 1989. Australian Geographical Studies [J], 27(1):98—110.
Chepil W S, 1956. Proceedings Soil Science Society of America [J], 20:288—291.
Fryrear D W, 1981. Transactions of the American Society of Agricultural Engineers [J], 24:991—994.
Inner Mongolia Meteorological Station, 1982. Meteorological data of Ih Ju League [R]. China: Inner Mongolia.
McTainsh G H, Burges R C, Pitblado J R, 1989. Journal of Arid Environments [J]. 16: 11—22.
McTainsh G H, Lynch A W, Burgess R C, 1990. Australian Journal of Soil Research [J], 28:323—339.
McTainsh G H, Lynch A W, Tews E K, 1998. Journal of Arid Environments [J], 39: 457—466.
Thornthwaite C E, 1931. Geographical Review [J], 21: 633—655.
Yu B, Hesse P P, Neil D T, 1993. Journal of Arid Environments [J], 24:109—124.
Zhang X S, 1994. Acta Phytoecologica Sinica [J], 18(1):1—16.

(Received for review October 28, 1999. Accepted January 9, 2000)