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Dust emission factors for environment of Northern China

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Abstract

This paper gives the dust emission inventory in the Northern China where the climate is very dry and large desert areas exist. Before calculating the distribution of fugitive dust emission factors (emission rates of particles smaller than 0.05 mm in diameter) from natural surfaces with a US EPA formula, Chinese data of pedology and climatology were processed so as to suit requirements of the formula. The computed dust emission factors for this environment of Northern China are shown by contours, their distribution and seasonal variations are briefly discussed. The dust emission rate in the area increases from east to west by five orders. Also, the total amount of the dust emitted from natural surfaces of Northern China into the atmosphere is found to be some 43 million t yr^{-1}, with half of the emissions concentrated in the spring season (March–May). © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Fugitive dust; Emission factor; Emission inventory; TSP

1. Introduction

It has been recognized that most (perhaps 80% or more) of the matter suspended in the atmosphere is emitted from natural surfaces (Chow et al., 1994). Wang et al. (1981), for example, chemically analyzed the airborne particles sampled in the Beijing area and found that more than half of the suspended matter was from deserts and soil surfaces. However, we have seen many statistical studies on dust emission from industries (e.g. Klimont, 1994) and some on that from road traffic (e.g. Ji, 1993), but very few works published on fugitive dust emission from natural surfaces. It is well known that dust emissions in Africa and Asia have serious effect on the very important environmental problem, i.e. the global climate change. Also, scientists in the East Asia found that the alkaline content of the suspended dust can reduce the acidity of acid rain (Kang and Kim, 1995). Still, it is unlikely that we can effectively develop our knowledge of dust transportation and deposition process in the atmosphere, which is an important regional environmental problem, without knowing the dust emission inventory, i.e. the "source strength" of the fugitive dusts.

The mobilization of solid particles by wind forces is a complex process which is poorly understood theoretically. Through laboratory tests, a large number of factors affecting the dust emission process have been identified and some empirical or semi-empirical relationships established. However, when estimating dust emissions from natural surfaces, over much large spatial scale, scientists are facing a rather different situation. On the basis of the laboratory results, semi-empirical formulae, involving several kinds of soil and climatic parameters, have been established. It is difficult to decide which of the laboratory factors are important and should be selected into a formula as it is nearly impossible to directly measure the dust emission rate in atmospheric fields.

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According to Gillette (1979), the main factors of significance are the aerodynamic forces and the forces holding the particles in the soil. Those are wind speed, soil erodibility and its silt content, surface moisture, and some other factors concerning terrain and plant (snow) covers. Some of the semi-empirical formulae have been recommended by US EPA for calculating the dust emission factor from open surfaces, e.g. OAPQS of US EPA (1977).

There is a huge belt in the world map from Central Eurasia to the Far East, i.e. Kazakhstan, Mongolia and Northern China which is defined as, in this paper, the soil regions II and III in Fig. 1. The natural environment is very poor in the belt. Climate is very dry and there exist loess lands, deserts and "gobi deserts" which are widely distributed along with deserts in the North-West, i.e. the west sub-region of Northern China and, sometimes, completely covered by pebbles of, e.g. some 10–20 cm or more in diameter (Zhao, 1985). Every year in the region, millions of tons of fugitive dusts are released into the atmosphere, being transported east by winds of middle latitude and deposited on East Asia. Fig. 1 shows the eleven famous deserts distributed in Northern China (Zhao et al., 1991). There are also some large "gobi-deserts" and some other smaller deserts in between. Also, there is the huge Loess Plateau south from the Mongolian Plateau, ranging from east longitude 102°–114°. However, up to now, no one has studied the fugitive dust emissions in these parts of China and Chinese pedologists and climatologists have no such necessary soil and climatic data for using the US EPA formula. So, we had to calculate the necessary soil and climate parameters with available (formally published) data of pedology and climatology of China before computing the dust emission factors with the US EPA formula. The computed fugitive dust emission inventory is comparable with previous works in Sahara Desert on its order of magnitude. Also, it seems to be reasonable when compared with the observations of the "aeolian sand–dust phenomenon" in Northern China on its spatial distribution and with the chemical analyses of aerosols above the Japan Sea on its

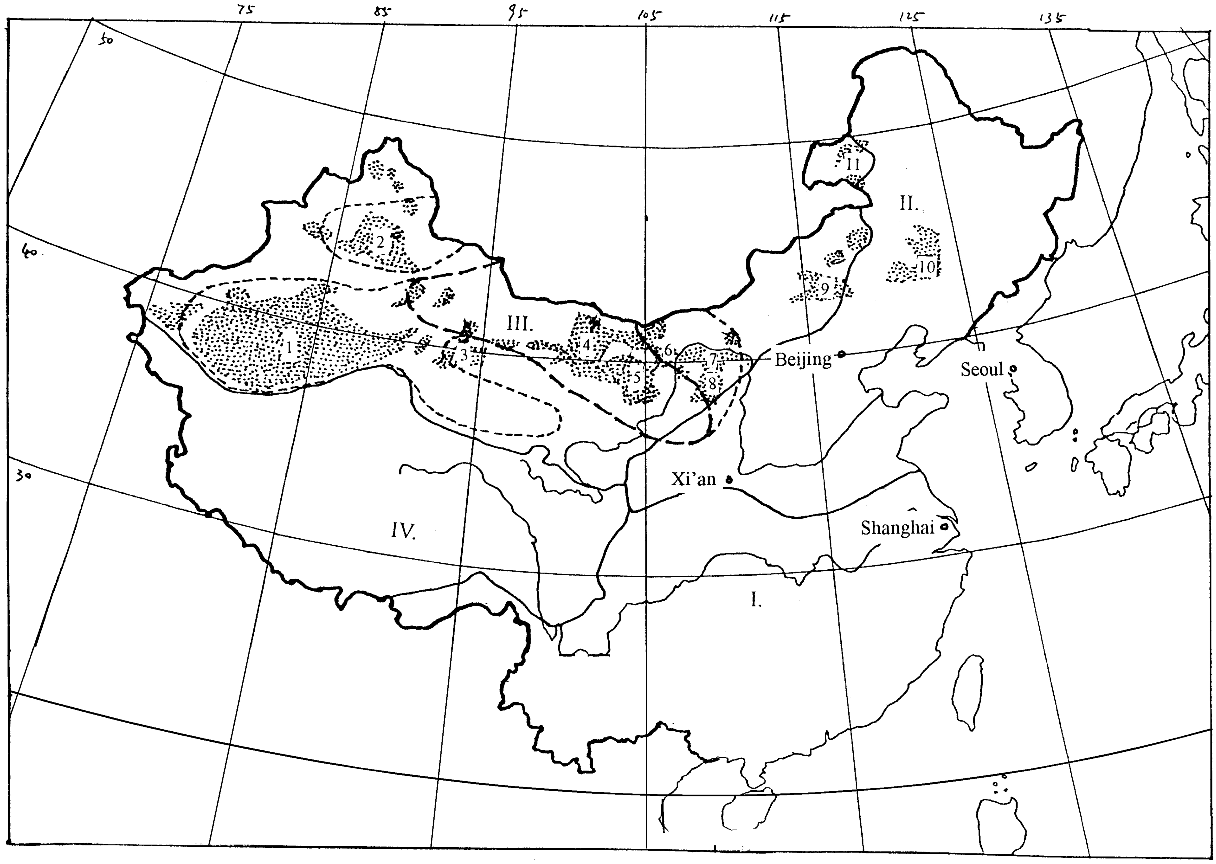

Fig. 1. Soil regionalization, deserts and sand-storm areas. Soil regions: 1. Allitic greatsoil region; II. Stallitic great soil region; III. Arid great soil region; IV. Alpine great soil region. Deserts: 1. Takelamagan desert; 2. Guerbantonggute desert; 3. Kumutage desert; 4. Badanjilin desert; 5. Tenggeli desert; 6. Wulanbuhe desert; 7. Kubuqi desert; 8. Maowusu sand-land; 9. Hunshandage sand-land; 10. Keerqin sand-land; and 11. Hulunbeier sand-land. Sand-storm areas: – – frequent sand-storm area; – more frequent sand-storm area.

seasonal variations. However, it is a great natural process that dust particles are emitted from deserts of central Eurasia and carried east by prevailing winds of middle latitude and deposited to the ground in the East Asia even the east seas of China. A famous example is the huge Loess Plateau formed by millions of years of dust depositions. So, the study of the dust emission inventory is of great significance even larger than the scale of environmental problems such as acid rain and global climate change.

2. Methodology

2.1. US EPA formula and determining factors

The following equation is of those recommended by US EPA (1977):

$$Q = ceKC\mathrm{LVA}, \tag{1}$$

where Q denotes the annual emission quantity, t yr^{-1}, from the surface of A hectares; c the TSP content, i.e. the weight ratio of the suspended particles (diameter less than 0.05 mm) over the total erodible soil particles; e the erodibility index of the soil type (t ha^{-1} yr); K the surface roughness factor, 1 or 0.5 for smooth or rough surfaces, respectively; C the climatic factor, $C = 0.504\, u^3/\mathrm{PE}^2$; here u is the annual mean wind speed (m/s) and PE the Thornthwaite's precipitation–evaporation index (see below); L the unsheltered field width factor, 0.7 or 1.0 for fields of width 300 m (or less) or 600 m (or more), respectively; and V denotes the vegetation cover factor, 1.0 if no vegetation.

So, according to Eq. (1), the main climatic factors are annual mean wind speed, u, and surface moisture parameter, i.e. the Thorthwaite's precipitation–evaporation index, PE, noticing that the emission rate is proportional to the third power of wind speed and the aridity of

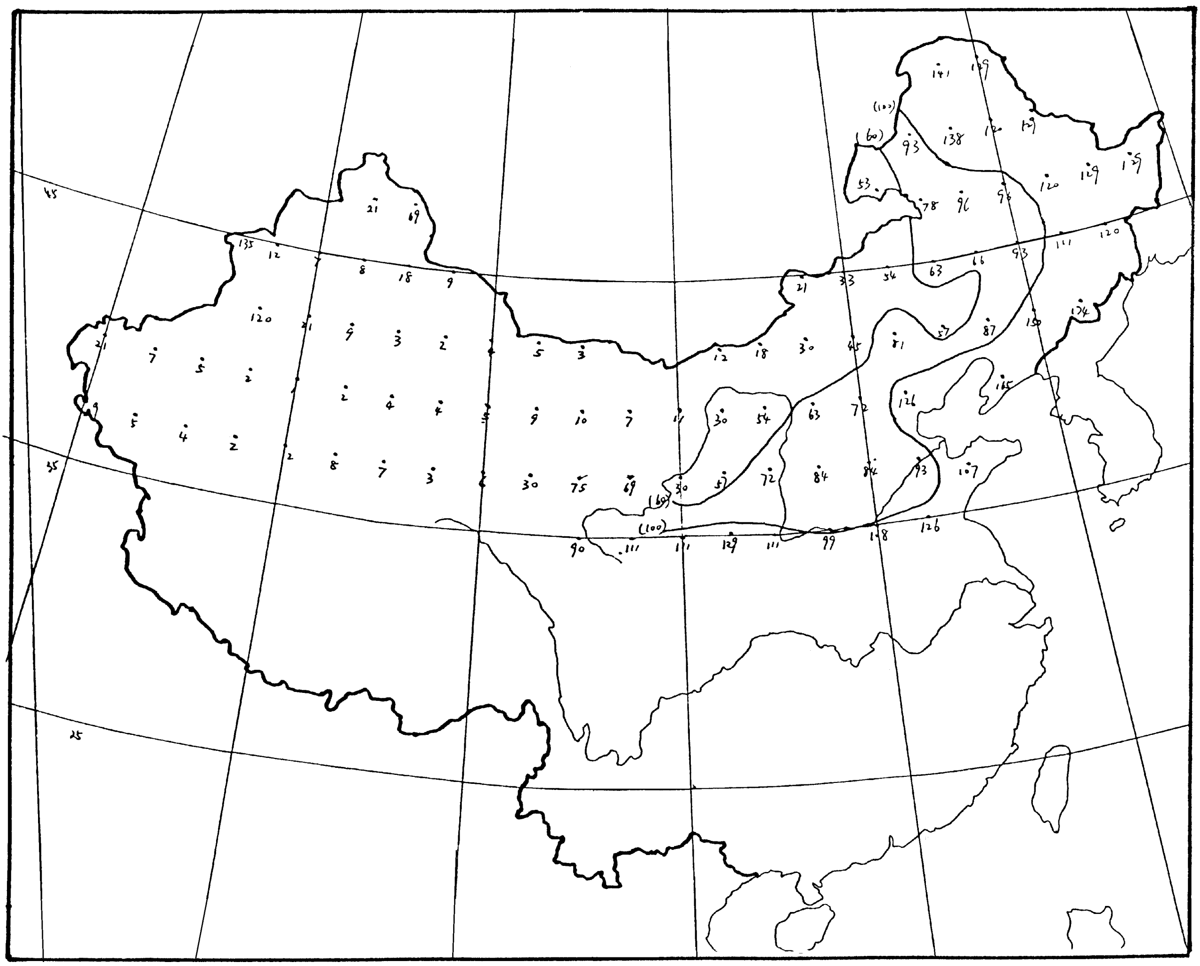

Fig. 2. Thornthwaite's precipitation–evaporation index.

ground surfaces, on which the amount of suspendible loose soil particles depends, is mostly relevant to the budget of precipitation and evaporation of the surfaces. As it is well known that there is a threshold wind speed, U_t, for a certain type of surface, below which no obvious particle movement (creeping) is observed, the semi-empirical equation implies that the effect of threshold wind speed can be included in that of the erodibility index, e, and the mean wind speed, u. So, the equation suggests that, among many factors affecting dust emission process, above four, u, PE, c, and e, are the principal factors determining the dust emissions from natural surfaces and the other three parameters, K, L and V, should also be included into considerations.

Following are discussions for evaluating the three parameters. K representing the surface roughness, we suggest that its value equals 0.5 since smooth surfaces can seldom be seen in natural environment. Since we now apply Eq. (1) to surfaces of a kilometer scale (to estimate the dust emissions in vast natural area), the width parameter, L, represents the effect of terrain in the present case. Terrain modifies the wind speed field (Moralse, 1979), making different emission rates from different parts of the surfaces, e.g. it is commonly seen in deserts that most sand and dust are blown up on the windward side of sand dunes. As a preliminary estimate, we let the terrain parameter, L, be equal to 1.0 everywhere. Nonetheless, in mountain areas which take a high area percentage of Northern China, the complex terrain is of serious effect. The most uncertain factor is the vegetation cover parameter, V. This parameter represents, in our case, the effect of nonerodible elements such as bushes, boulders, bare rocks, and consolidated clods. Gillette (1979) emphasized the effect of these nonerodible elements very much. An interesting example is that the mountains in gobi-deserts consist usually of bare rocks without soil cover. Such bare stone hills even exist in the Loess Plateau as all of the soil cover has already eroded out by wind and water (The Integrated Scientific Research Team of Loess Plateau of Chinese Academy of Sciences, 1991). While in the North-China and the North-East (the other two sub-regions of Northern China), the vegetation cover is usually higher than 50% in summer-half-year. Also, the snow cover lasts more than 3 months in the North-East. Thus, the surfaces covered by vegetation, bare rocks and any other nonerodible matters should be considered as minor or insignificant dust source areas. With an arbitrariness, I suggest from field data that this nonerodible cover parameter, V, ranges from 1/8 to 1/2 and the lower limit value, 1/8, was used in following calculations. The uncertainty will not be well solved until we obtain enough data to estimate the nonerodible cover parameter, V, in different places.

Table 1
Erodibility and TSP content

No.	Soil	Erodibility index e (t ha^{-1} yr)	TSP ratio c
1.	Sand	544	0.009
2.	Loamy sand	331	0.010
3.	Sandy loam	213	0.021
4.	Clay	213	0.008
5.	Silty clay	213	0.008
6.	Loam	138	0.066
7.	Sandy clay loam	138	0.066
8.	Sandy clay	138	0.010
9.	Silt loam	116	0.041
10.	Clay loam	116	0.025
11.	Silty clay loam	94	0.041
12.	Silt	94	0.008

Table 2
Soil texture classification of China

Soil No.	Particle composition (%) Sand (1–0.05 mm)	Coarse silt (0.05–0.01 mm)	Clay (< 0.001 mm)
(2) Coarse sand	> 70	–	
(3) Fine sand	60–70	–	
(3) Very fine sand	50–60	–	
(9) Sand silt	> 20	> 40	< 30
(12) Silt	< 20		
(6) Sandy loam	> 20		
(11) Loam	< 20	< 40	
(8) Sandy clay	> 50	–	> 30
(5) Silty clay	–	–	30–35
(5) Loamy clay	–	–	35–40
(4) Clay	–	–	> 40

2.2. Determining factors in Northern China

The total desert area in Northern China is 63.7 million ha and the total area of gobi-deserts is 45.8 million ha (Zhao et al., 1991). All of the deserts are of temperate zone deserts, among which the Takelamagan desert in south Xinjiang Province is the second largest desert of the world, after the Sahara desert which is known as a typical hot desert.

We calculated values of the four factors, u, PE, e and c, and then calculated the dust emission rate, Q_e, in 94 different locations of Northern China, most of which are 2.5° apart in both longitude and latitude (see map of, e.g. Fig. 2).

We obtained the data of annual mean wind speed, u, as well as those of precipitation, p, and evaporation, E, in corresponding contour figures of the "Atlas of Climatic Resources in China" compiled by the China State Meteorological Bureau (1994), in which all of the contours are drawn with the meteorological observation data of 30 yr (1951–1980) averaged. An interpolation method was used to obtain the values of different points between contours. Chinese meteorologists use other aridity parameters, instead of Thornthwaite's precipitation–evaporation index, to describe the arid degree of a climatic region. Nevertheless, Pan et al. (1992) successfully computed the climate change in the North-China with the Thornthwaite's index. According to the authors, the Thornthwaite's potential evaporation, E^*, can be expressed as the following semi-empirical equation in the North-China:

$$E^* = (0.5949 + (0.1189 \times T_a)) \times 365 \tag{2}$$

where T_a denotes the diurnal mean temperature of the air. The Thornthwaite's precipitation–evaporation index, PE*, is then defined in the present case as

$$\mathrm{PE}^* = 100 \times (p/E^*). \tag{3}$$

The equation is a kind of definition for Thornthwaite's index, in which the retention of moisture on soil surfaces is not taken into account as we concern the mobilization

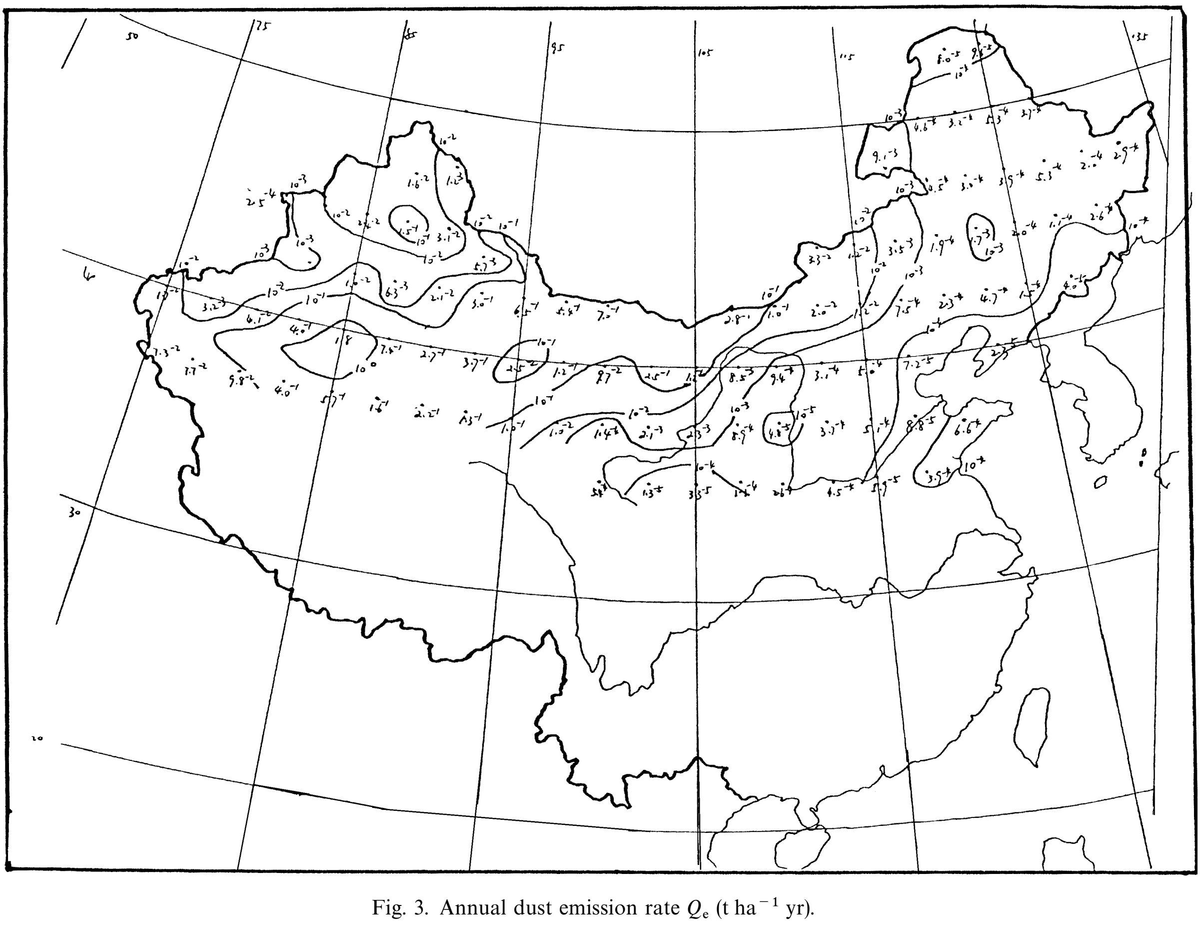

Fig. 3. Annual dust emission rate Q_e (t ha^{-1} yr).

of loose particles at surfaces. As we had to compute the index, PE*, in larger area, i.e. the whole Northern China and we preferred using observed evaporation data, E, an alternative equation was developed. Firstly, the Thornthwaite's potential evaporation, E^*, was calculated in different points of the North-China and compared with the observed evaporation, E, so that following empirical relationship was found:

$$E/E^* = 2.5\text{–}4.6, \tag{4}$$

and, the mean value of the ratio, E/E^*, was 3.0. So, supposing the ratio is universal in the whole Northern China, the ultimate equation used in our computation was

$$\mathrm{PE} = 300 \times (p/E). \tag{5}$$

Fig. 2 shows the calculated PE values in Northern China. It is interesting to notice that the contour of PE $= 60$ is nearly the same with the line of demarcation between the East Monsoon Region and the North-West Arid Region. According to its definition, the PE value of 100 is the critical one dividing arid and moist climates. So, with the contour of PE $= 100$, it is demonstrated that nearly the whole Northern China is of dry climate.

The soil factors, e and c, which scientists and engineers in the United States have precisely tested for different soil types (see Table 1, from Jutze et al., 1976) are considered next.

The quantitative study of soil erosion by wind has just started in China (Yang et al., 1996), i.e. there is no data of erodibility, e, and TSP content, c, available. Fortunately, the criteria for classification of soil textures are very similar in the two countries and a precise map of soil textures in China has been published (Institute Of Soil Science of Academia Sinica, 1986). It was thus possible to calculate the dust emissions with the available American wind erosion data and the Chinese soil texture map. The Chinese classification of soil textures is tabulated in Table 2 (Xiong, 1990), the first column of which shows the corresponding (the most similar in texture, referring to Gillette, 1979) American soil type numbers in Table 1. Reading soil types of the 94 places in the Chinese soil

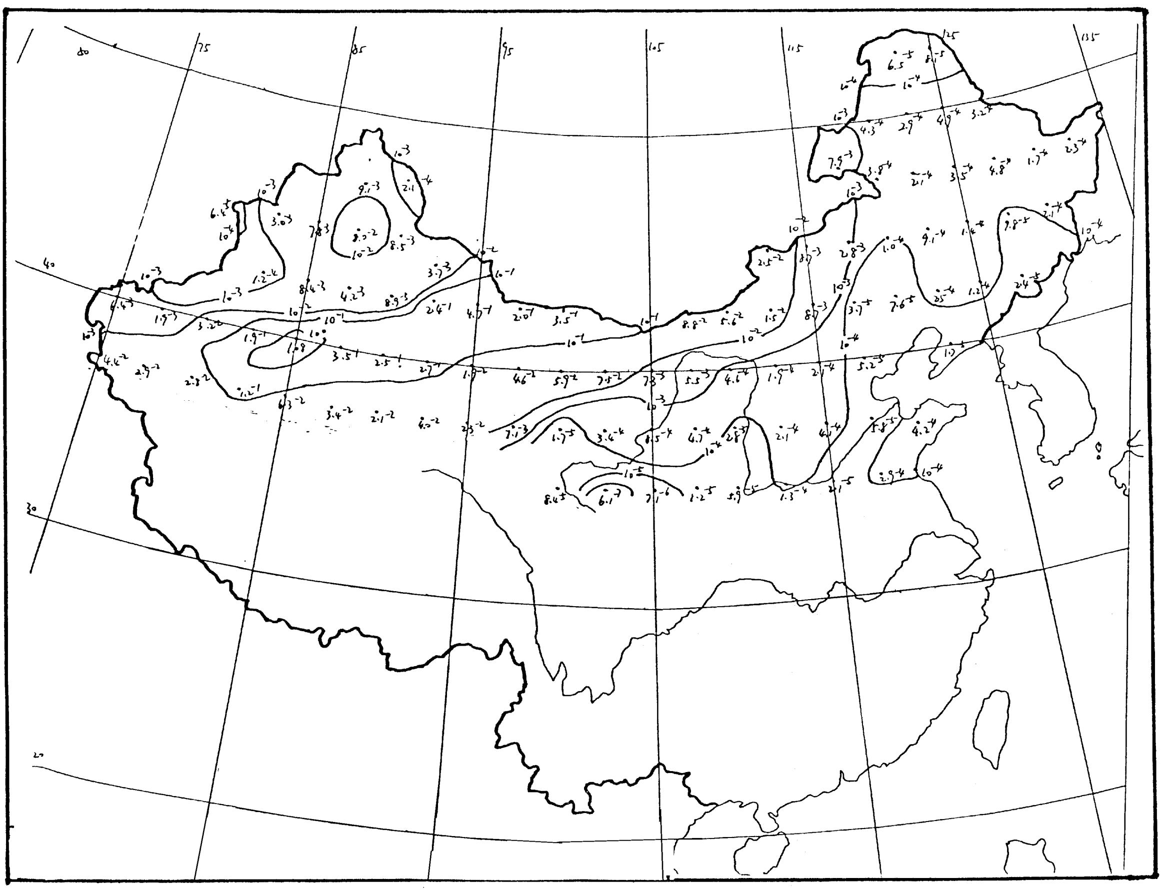

Fig. 4. Dust emission rate in spring Q_1 (t ha^{-1} spring).

texture map, we then obtained the values of the two soil factors, e and c, through Tables 2 and 1.

2.3. Computation of dust emission rate

Applying the factors calculated above to Eq. (1), we first calculated the annual dust emission rates of 94 places and then drew the contours which are shown in Fig. 3. In order to investigate seasonal variations of the dust emission rates, we also calculated the rates in four seasons: the spring (March–May), the summer (June–August), the autumn (September–November) and the winter (December–February), respectively, by changing of the climatic factors, u and PE. So, we first read seasonal mean wind speed, u', as well as the precipitation, p', and the evaporation, E', and then calculated the Thornthwate's precipitation–evaporation index, PE′, in the same way for annual calculations. Then, we calculated the climatic factor, $C' = u'^3/\mathrm{PE}'^2$, of different places in different seasons. Finally, the annual quantity of the rate, Q_e, was divided into four seasons, Q_1, Q_2, Q_3 and Q_4, respectively, on percentage of its climatic factor, C'. Figs. 4–7 show the dust emission contours for the four seasons.

3. Results and analyses

It can be seen that most of the contours in Fig. 3 roughly run from northeast to south-west and the value of the dust emission contours increases from southeast to north-west. The difference of dust emission rates between maximum and minimum values is as large as 10^5. The pattern of distribution is important and reasonable as the rainfall decreases from south-east to north-west. The most serious area of dust emissions includes the west part

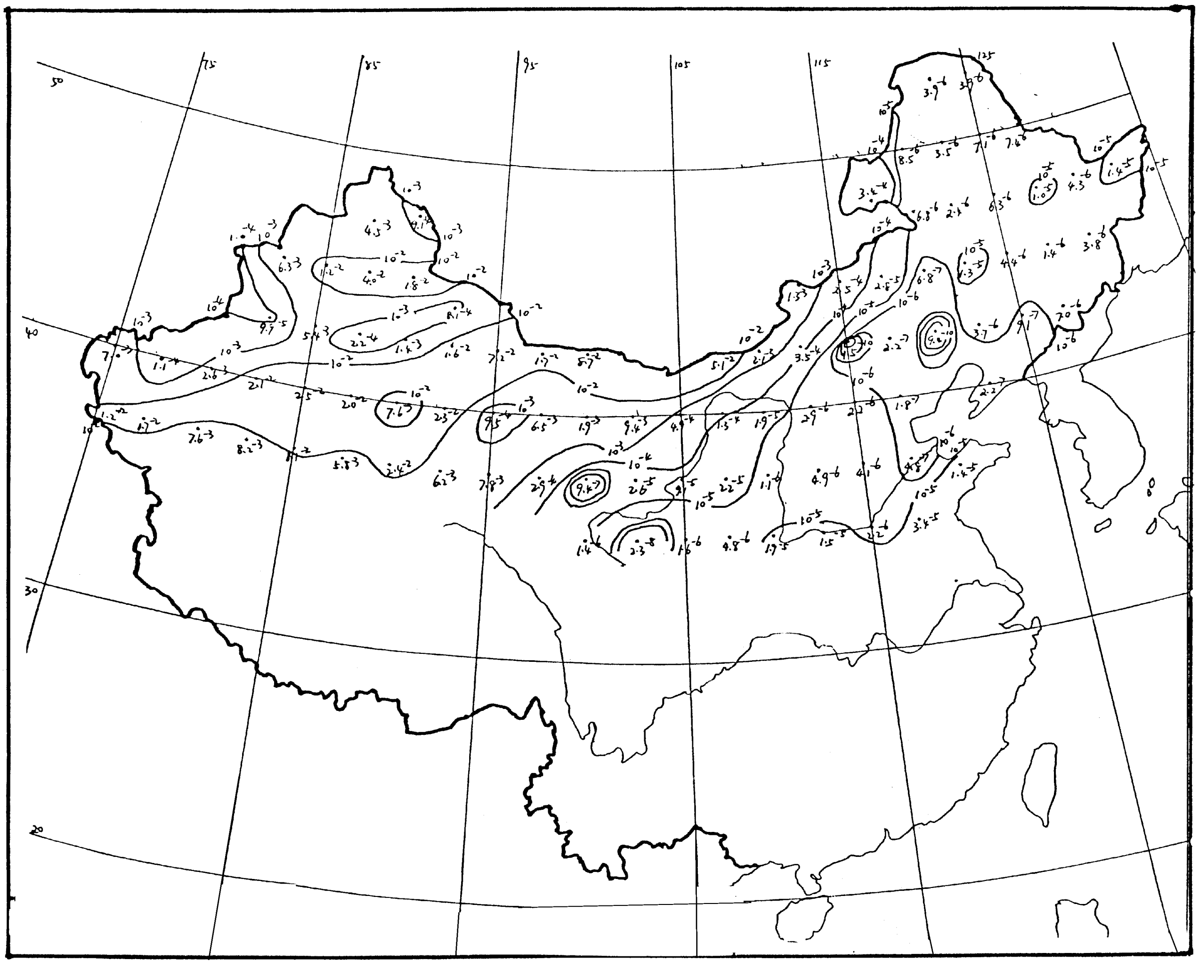

Fig. 5. Dust emission rate in summer Q_2 (t ha^{-1} summer).

of the Inner Mongolia Plateau, the Chaidamu Basin (north part of the Tibet Plateau) and the Talimu Basin of South Xinjiang Province, i.e. the Takelamagan desert. There appears a maximum value of dust emission rate, which equals 1.8 $\mathrm{t\,ha^{-1}\,yr^{-1}}$, in the center of the Takelamagan desert. There are similar distributions in all of the four seasons (see Figs. 4–7). This distribution of fugitive dust emission rates is very similar to the distribution of strong sand-storms shown also in Fig. 1 in which dashed lines show the frequent and most frequent sand-storm areas (Xu, 1996). Other authors reported that sand-storm strengths seem to be strongest in two areas: one located south to the border with Mongolia and the other in the desert of south Xinjiang (Geng, 1985). Incidentally, some Chinese meteorologists suggested from their investigations that the former is, in fact, the southern part of a larger frequent sand-storm area, whose center is located on the other side of the Sino-Mongolian border (Zhao, 1990). Obviously, the good agreement comes from the very close relationship between fugitive dust emissions and sand-storms, both of which involve the same physical process, i.e. the mobilization and transportation of solid particles by natural winds. The agreement also means that our calculations are trustworthy.

Comparing Figs. 4–7, we can see a general pattern of seasonal variation of dust emission rate, i.e. in spring, when the ground surfaces are very dry and strong winds coming from the Arctic Ocean blow through the vast area, dust emission is the strongest; while in summer, when the precipitation is highest, dust emission is the weakest. Also, the second strongest dust emission season seems to be winter except for the Takelamagan desert where autumn is the second strongest. It is interesting to notice the report from Japanese scientists that the elements Al and Ca in aerosols above the Japan Sea show highest concentration in spring season with these elements are well recognized from Northern China (Tsunogai et al., 1988). The seasonal variation is in good agreement with our computation results.

Based on the calculation of dust emission rates, we have calculated the total amount of dust emissions in

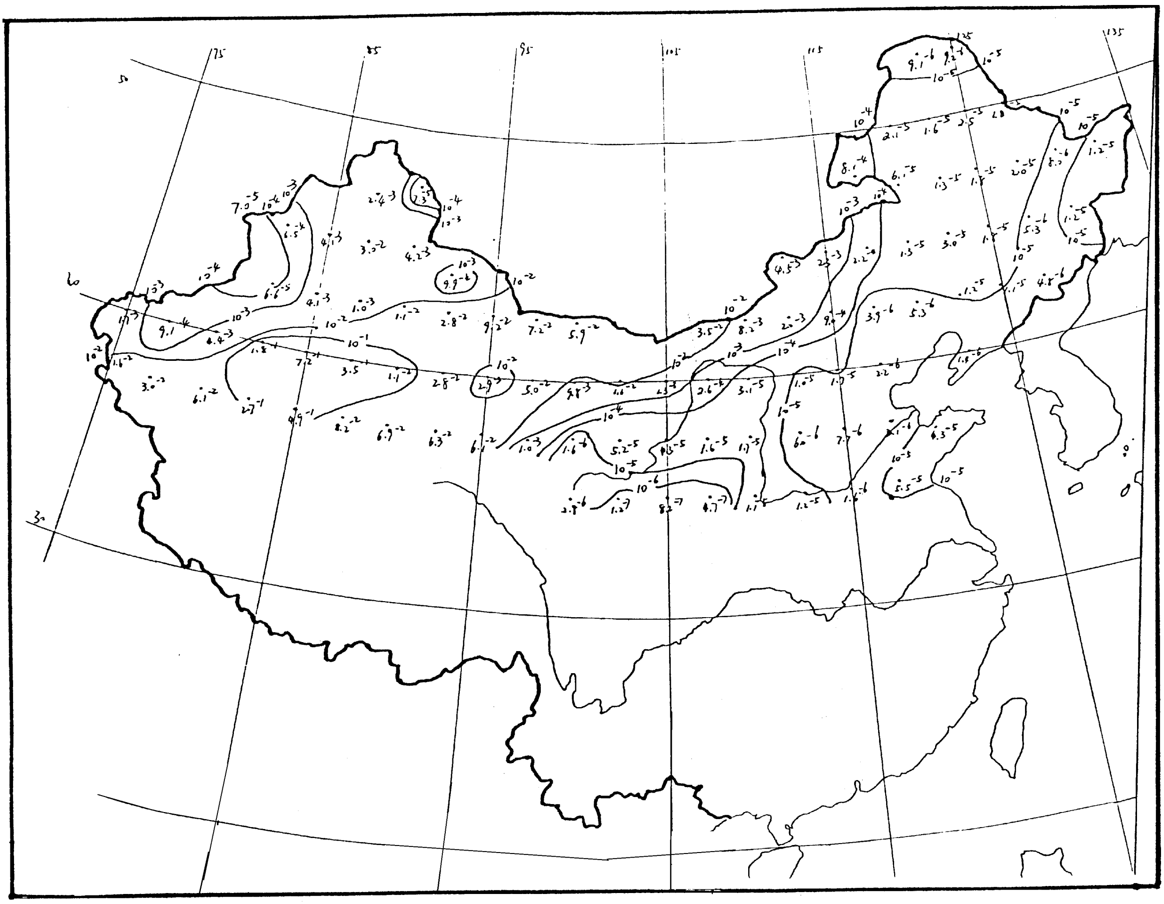

Fig. 6. Dust emission rate in autumn Q_3 ($\mathrm{t\,ha^{-1}}$ autumn).

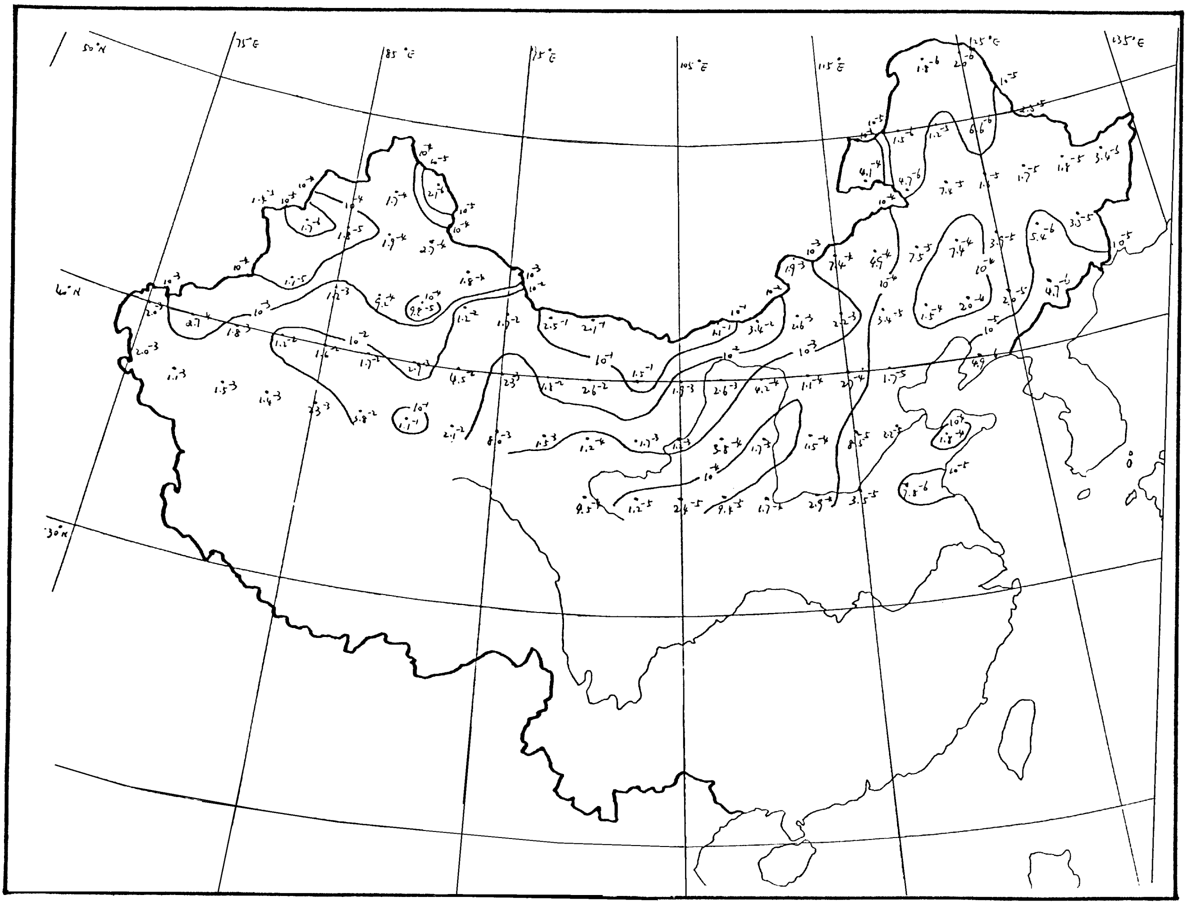

Fig. 7. Dust emission rate in winter Q_4 (t ha^{-1} winter).

Northern China, the result is: some 43×10^6 t yr^{-1} and, out of it, 25×10^6 t in spring, 2.5×10^6 t in summer, 8.6×10^6 t in autumn and 7.4×10^6 t in winter. The results seem comparable with the data of Sahara Desert (Junge, 1979), i.e. the dust (particles smaller than 0.05 mm in diameter, the same size with our computation) emitted into the atmosphere from the Sahara Desert is estimated about 60–200×10^6 t yr^{-1} while the total dust emission amount from the other sources in the north-hemisphere is some 150×10^6 t yr^{-1}.

Direct measuring dust emission rates in atmospheric fields is nearly impossible. And, we know little about the particle mobilization process theoretically. So, we have to use empirical formulae which are much different from each other for estimating the rates. Obviously, a great uncertainty (a great error) exists in the estimating procedure, e.g. the uncertainty factor for previous Saharan dust emission data is usually 2–3 (Junge, 1979). I think that my calculation is much better in error, nevertheless, I still cannot quantify the total error because some formulae and data used in my calculating procedure were officially published with no error information supplied. However, at the most an error of 100% should be supposed when one uses my calculation results.

4. Conclusions

(i) The fugitive dust emission rate in Northern China increases from east to west by as much as 5 orders.
(ii) There are two strong emission centers: the south Xinjiang Province, i.e. the Takelamagan desert and the west part of the Inner-Mongolia Plateau.
(iii) Spring is the most serious dust emission season.
(iv) The annual dust emission amount is some 43 million t, and the dust emission in the spring season accounts for a half of this.

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