PART I

PHYSICS, MECHANICS AND PROCESSES OF DUST AND SANDSTORMS

Field observations and wind tunnel laboratory research have helped to explain the physical process of sand and dust blowing under the force of wind and moving over the land surface in arid and semi-arid zones. When the wind force reaches the threshold value, the sand and dust particles are transported from the surface and start to move.

Soil erosion by wind has two broad dimensions: transport and accumulation. Studies on sand-dust storms cover both aspects, because each is damaging in its own way and each contributes to the problem of desertification in the world's drylands.

The literature dealing with wind erosion and dust-sandstorms amounts to tens of thousands of articles, research papers and books. The two articles in this section introduce the essential issues.

Chapter One

DUST AND SANDSTORMS: AN EARLY WARNING OF IMPENDING DISASTER

Victor R. Squires
International Dryland Consultant
Adelaide University, Australia

Key Words: coping strategies, traditional technologies, land-use, policy, drought, socio-economics, Dust Bowl, entrainment, transport, dunes, dust storm, sandstorm, early warning, disaster

SYNOPSIS

Drylands occupy more than 40% of the world's land surface. They are home to about 1 billion people. Dust storms are a symptom of poor land management and a constant reminder of the interaction between people, the land they use and the climate. When land management is inappropriate as a result of government policies or because the traditional technologies are no longer able to cope with burgeoning populations and the shrinking resource base, wind erosion will occur. This chapter considers the relationship between weather, climate and dust storms and examines the mechanisms by which dust and sand are transported. The regional transport of dust in the atmosphere is also considered.

KEY POINTS

1. *True deserts are rarely the source of dust storms because of the way in which particles are entrained and transported. The desert margins are more often the principal source of damaging dust storms that periodically (or regularly) sweep across the landscape wreaking havoc as they roll by.*

2. *The mechanism of transporting sediments (sand, dust, and organic matter) by the action of wind has been well studied and is understood. The challenge is to create a situation on the ground where entrainment and transport is unlikely.*

3. *The socio-economic aspects (human dimension) of dryland degradation need to be given more attention. The emphasis should be on the people who use the land, not only on the land they use.*

1. INTRODUCTION

Sand and dust storms are natural events that occur widely around the world in arid and semi-arid regions, especially in subtropical latitudes. The vast distribution and existence of desert landscapes (*see Figure 1*) indicates that these regions are a very important source of dust storms in historical time but in more recent times the action of humans has created another source on the desert margins in semi-arid areas that previously were stable. The major dust storms occur where anthropogenic land disturbances exist in drylands under severe drought. Several areas of the world are contributing to large-scale storms. These areas correspond to areas undergoing accelerated desertification.

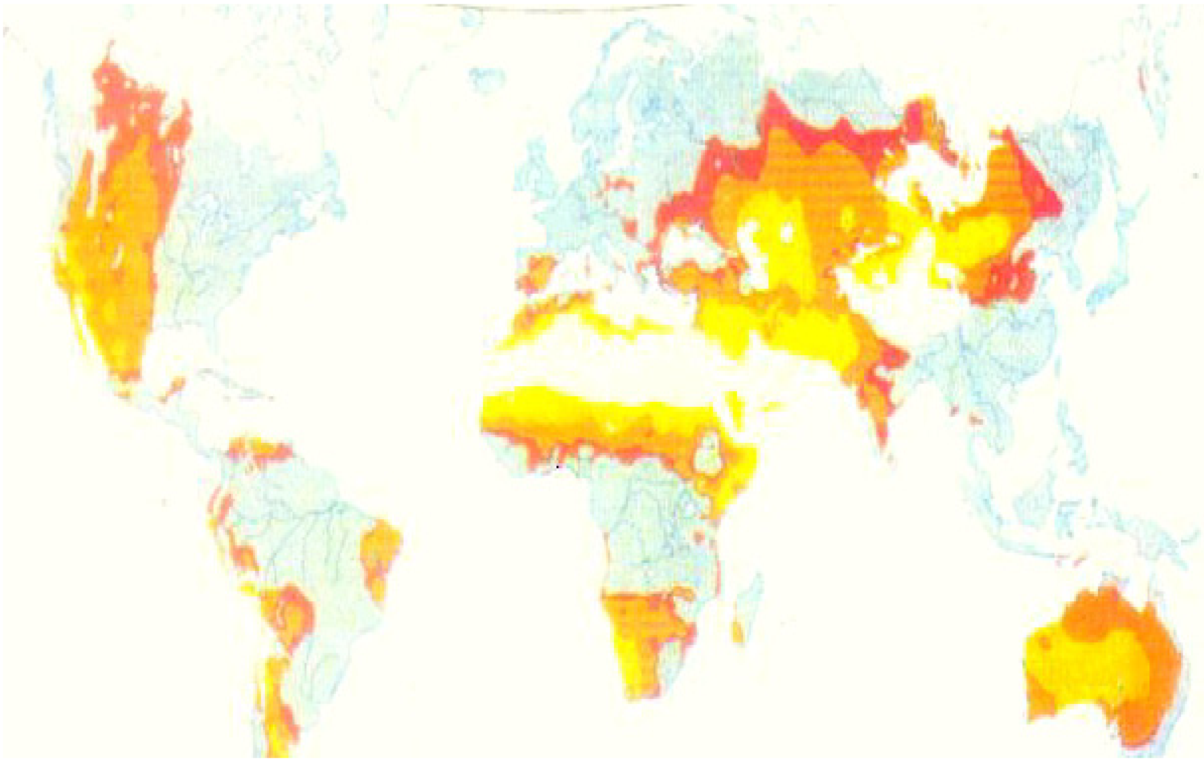


Figure 1: Vast distribution and existence of desert landscapes

Yaalon (1996) has indicated that North Africa is a source of dust for southern European dust deposition. Mattson and Nilsen (1996) indicate that the Sahara region is the main source of aeolian dust in the world. Dust is transported westwards over the Atlantic Ocean and Sahara region and northwards over several cycles of transport and deposition. Pease et.al. (1998) suggests that arid and semi-arid regions around the Arabian Sea are one of the principal sources of global dust. India, Pakistan, Iran and the Arabian Peninsular contribute to Arabian Sea dust deposition (*Figure 2*). Dust from China contributes to sediment in the Pacific (*see cover*).

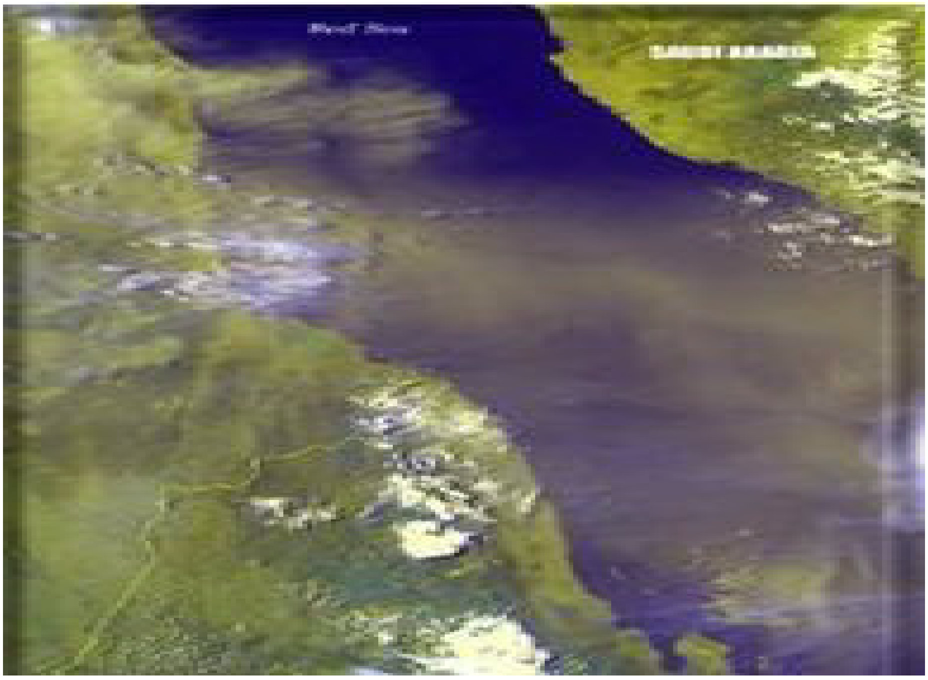


Figure 2: Satellite image of dust over the Red Sea. Saudi Arabia on the right of the image

2. SAND AND DUST STORMS – TERMINOLOGY

Conventionally, *"sand"* describes soil particles in an approximate size range of 0.6-1 mm, while *"dust"* describes particles <0.6 mm. In practice only those dust particles below 0.1 mm can be carried by suspension (see below) and be manifested in a dust storm. Thus dust storms are a product of mass transportation of soil particles by wind. Dust storms are typically a form of dry deposition. Often the fine fraction that is richer in nutrients and organic matter is entrained into the air upon which dust particles become condensation nuclei. These small particles may be deposited subsequently as a wet deposition through rain or snow.

The transport, suspension and deposition of dust particles in the atmosphere mainly manifest itself as a dust storm. Major storms occur when prolonged drought causes the soil surface to lose moisture and there is a co-occurrence of strong winds.

3. HOW DOES DUST BECOME AIRBORNE?

Field observations and wind tunnel laboratory research allow us to understand the physical process. Consider a surface made up of separate particles that are held in place by their own weight and some inter-particle bonding. At a low speed wind, there will be no indication of motion, but when the wind force reaches the threshold value a number of particles will begin to vibrate. Increasing the wind speed still further, a number of particles will be ejected from the surface into the airflow. When these injected particles impact back on the surface, more particles are ejected, thus starting a chain reaction. Once ejected, these particles move in one of three modes of transport depending on particle size, shape and density of the particle. These three modes are designated *suspension*, *saltation* and *creep*. Its size and density determine movement pattern of sand-dust particles (*Table 1*).

The *suspension mode* involving dust particles of less than 0.1 mm in diameter and clay particles of 0.002 mm in diameter are small in size and light in density. These fine dust particles may be transported at altitudes of up to 6 km and move over distances of up to 6,000 km. These red-coloured and alkalized dust particles are 0.1 mm in diameter and suspended high in the atmosphere and contribute to general loss of visibility, but do not manifest as a real dust storm. The research results of the Geology Faculty of Oxford University in the UK show that

Great Britain has suffered dust storm disasters 17 times since 1900. About 10 million tons of dust particles has been transported and brought to Great Britain from the Sahara Desert during a single dust storm.

Saltating particles (i.e. those between 0.01-0.5 mm in diameter) leave the surface, but are too large to be suspended. The remaining particles (i.e. above 0.5 mm) are transported in the creep mode. These particles are too large to be ejected from the surface and are therefore rolled along by the wind and impacting particles. Coarse sands of 0.5-1.0 mm in diameter move along in a rolling movement. Medium-sized sands of 0.25-0.5 mm in diameter encroach in the form of a jumping movement. As these particles impact upon the land surface, they initiate movement of other particles. About 50-80% of all soil being transported is carried in this mode. Due to the nature of this mode the heights carried are rarely more than 30 cm and the distance traveled rarely exceeds a few metres.

Sand particles, transported by saltation and by creep will accumulate to form new sand dunes when they are blown out, graded and transported for a distance (*Figure 3*). Sands of 2.0 mm in diameter will be left on land surface when fine materials are blown away (*Figure 4*).

Table 1: Movement of soil particles under a wind force of 15 metres/second*

Particle size (mm)	Period of suspension (time)	Comment/description
0.1	0.3-3.0 seconds	Fine sand
0.01	0.83-8.3 seconds	Dust. Can go up to 700 m high
0.001	0.95-9.5 years	Fine clay can go up to 77 km high

*The threshold wind velocity (15 cm above ground surface) that can lift up and transport dust grains of 0.05-0.1 mm in diameter is 3.5-4.0 m/s. Data from (Qian Ning, 1983).

Figure 3: Sand and small gravel remains after the finer particles, including organic matter, have been blown away. The wind is constantly moving the sediments, leaving a typical windswept surface

Figure 4: Sand dunes form when sand is moved along by the wind (*see text*)

4. INTERACTIONS BETWEEN CLIMATE, WEATHER[1] AND DUST STORMS

Reference has already been made to the role of prolonged drought in exacerbating the severity and frequency of dust storms. This is due to several causes. The most obvious are the reduction of plant cover and the drying of the soil. Bare, dry soil is more susceptible to the actions of the wind. Plant cover reduces wind velocity at the soil surface and moisture improves cohesion between individual soil particles. However, the major effect of prolonged drought seems to be to force land-users to take greater risk and impose greater pressure on an already stressed environment.

One important aspect of the discussion about drought is the difference between aridity and drought. Coughlan and Lee (1978) state:

> "Aridity implies a high probability of rainfall for a given period below a low threshold. Drought implies a low probability of rainfall for a given period below a relatively low threshold."

Drought can be thought of as a meteorological phenomenon but it is more than that. The whole question of drought perception is a vexed one and the implications for governments and for individuals in learning to live with drought are quite profound.

Drought is defined by meteorologists as a period of rainfall in the lowest decile (Gibbs and Maher, 1978). This means that droughts occur in all climatic regions with the same frequency i.e. 10% of the time. This definition says little about the severity or duration of the drought. If droughts are perceived to occur more frequently than 10% of the time then it is because land management is inappropriate for the climatic variability so that the land is under stress in periods with rainfall well above the tenth decile; i.e. management is inappropriate for the normal climatic variability. It is not the climate that is at fault, but human perception of the land as being better than it is.

[1] Weather refers to the environmental conditions being experienced on a day-to-day (even hour-by-hour) basis, but climate is the pattern of these occurrences over a long time period. Weather can be conducive to the advent of dust storms on some days or at certain times of a given day.

Many people associate desertification with droughts. While it is true that land degradation commonly proceeds more rapidly during drought, the real causes of desertification are:

i. Inappropriate land management both during droughts and between droughts.
ii. Management which does not take cognizance of the normal climatic variability .
iii. The inherent capabilities and limitations of the land.

In effect, drought (however defined) is one of the risks associated with human occupation of arid lands characterized by a variable and largely unpredictable climate. Drought (especially severe drought) is often regarded as an abnormal event. But in fact it is a natural recurring feature of all arid environments. It is often said that the climate in a particular region is *"characterized by frequent droughts"* but this is nonsense and furthermore it is dangerous to think it, because it tends to reduce human responsibility for land degradation.

From a practical viewpoint drought is intrinsically related to climatic zones and the resistance of plants to water shortage. Thus, establishing whether there is, or is not, a drought in progress is less meaningful for arid zones since the prospects of it remaining dry are significantly higher than in more abundant rainfall zones.

In low rainfall regions, the amplitude of rainfall variation is relatively greater than in higher rainfall regions (i.e. rainfall in the lowest decile is relatively much lower than average or higher deciles) and individual periods in the lowest decile are longer. These are factors that need to be taken into account in land management systems; especially where cropping and herding are the major land-uses.

For example, an analysis of drought in Australia shows that the likely pattern of drought across the Australian continent (7,600,00 km^2) in any 100-year period can be summarized as:

i. 21 years are likely to be free of major droughts.
ii. 62 years will have a drought that covers less than 20% of the continent.
iii. 15 years will have drought covering 20-40% of the continent.
iv. 2 years will have drought covering more than 40% of the continent.

These figures give some idea of the return periods, but not the severity of those periods.

Droughts are normal components of climate variability, though their effects are seriously worsened by human factors such as population growth that forces people into drier and drier regions and inappropriate cropping and herding practices. The impacts of drought are likely to become ever more severe as a result of development processes and population increases.

Drought is a time of crisis, for the land, its animals and its people. It is a critical testing time for sustainability of land management systems and will often determine whether the enterprise will survive and whether the productivity of the land on which it depends will be maintained. The crisis can be averted or diminished with careful planning and management. No two droughts are the same and the responses to them need to differ because the nature, extent and degree of risks are constantly changing. This means that to best cope with drought, management must be closely attuned to climatic conditions, land resource conditions, financial and forage reserves, and prevailing economic conditions in the affected region or country.

The practical problems of dealing with drought are that we do not know when it starts, and we do not know how long it will last. Unlike other natural disasters such as cyclones and wildfires, drought (at least at the outset) has no obvious physical presence. It is this insidious nature which has made drought management so complex.

Droughts often stimulate sequences of actions and reactions leading to long-term land degradation. Droughts may also trigger local food shortages, speculation, hoarding, forced liquidation of livestock at depressed prices, social conflicts and many other disasters associated with famines that may catastrophically affect numerous groups and strata of local populations. In some instances however, droughts may contribute to the emergence of social strategies that enhance sustainable land productivity while protecting local livelihoods. The lessons learned from those countries/regions that have experienced severe drought and its attendant land degradation problems need to be more widely disseminated and put into practice in today's situation (*see Chapter 2*).

The majority of dryland human populations struggle daily with persistent and almost universal poverty in their struggle to scrape a living from a harsh environment where periodic drought is a common phenomenon, soil fertility is low, and productivity is very low. In addition, traditional technologies have not kept up with the present rate of population growth and increased demands for food, fuel and shelter. The end results are poverty, hunger and malnutrition (*Table 2*). Unable to survive with scarce land and water resources, these poor populations are often forced to become environmental refugees that migrate to neighboring lands and urban centers in search of relief, employment and refuge (*see Chapter 6*).

Traditional coping strategies are frequently unable to deal with accelerated land degradation associated with over-use of diminishing resources in a fragile environment. Abuse of a natural resource base by its traditional users is seldom due to carelessness or ignorance, but results from survival mechanisms under harsh conditions. Droughts often stimulate sequences of actions and reactions leading to long-term land degradation.

5. IMPACTS OF DUST STORMS – PHYSICAL AND ENVIRONMENTAL

The environmental impacts from dust storms are wide ranging, impacting on source, transport and deposition environments.

6. SOURCE ENVIRONMENTS

The impact on source environments is primarily a consequence of soil loss. During dust storm generation, nutrients, organic matter and thus soil fertility are exported out of the source ecosystem. Consequently there is a loss of agricultural productivity.

6.1. Transportation environments

During dust transportation, many young plants are lost to the sand blasting nature of the process at ground level, resulting in a loss of productivity. However, major dust storms have most of their impact within the atmosphere. The most noticeable effect is the reduction of visibility. This is of course dependent on the severity of the dust event (*see Chapter 7*). It could range from a slight haze to a major dust cloud. In the worst cases, visibility can be reduced to only a few metres. This loss of visibility can be a major hazard to aircraft and in some cases to motorists (*see Chapter 12*).

Dust particles are thought to exert a radiative influence on climate directly through reflection and absorption of solar radiation and indirectly through modifying the optical properties and longevity of clouds (*see Chapters 2 and 8*). Depending on their properties and in what part of the atmosphere they are found, dust particles can reflect sunlight back into space and cause cooling in two ways. Directly, they reflect sunlight back into space, thus reducing the amount of energy reaching the surface. Indirectly, they act as condensation nuclei, resulting in cloud formation (Pease et al, 1998). Cloud formation raises the albedo of the globe, causing more solar radiation to be reflected back into space.

However, dust particles can also cause an indirect heating effect of the atmosphere through cloud formation. Clouds act as an *"atmospheric blanket,"* trapping long wave radiation within the atmosphere that is emitted from the earth. Thus, dust storms have local, national and international implications concerning global warming, and land degradation. They also impact human health.

6.2. Deposition environments

Mineral dust, it has been suggested, has an important role to play in the supply of nutrients and micronutrients to the oceans and to terrestrial ecosystems. Iron in the minerals composing this desert dust is a vital nutrient in oceanic regions that are deficient in iron. Further, more research has shown that the canopy of much of Central and South American rainforest derives much of its nutrient supply from dust transported over the Atlantic from the Sahara region of North Africa. Sahara dust occasionally reaches the State of Florida in the US, causing a high-altitude haziness that obscures the sun. Dust from China's deserts is transported to the waters near Hawaii in the south Pacific. As the dust settles in the waters around Hawaii, the primary productivity of the plankton in the water column increases (NOAA, 1999). This research suggests that dust transport processes form an integral part of the global ecosystem.

Yet, nutrient deposition can have negative effects. Many arid region rivers and lakes have been slowly eutrophied by ongoing dust deposition. As the dust cloud moves downwind it inevitably passes through populated areas, contributing to urban air pollution. As the dust settles over a populated area and people breath in these tiny dust particles, those with asthma and other respiratory disorders will suffer. Dust particles have been shown to cause a wide range of respiratory disorders including chronic bronchitis and lower respiratory illness. More sinister are the health related problems in areas where the dust is salt laden or is contaminated by *toxins (see the Aral Sea experience reported in Chapter 8*).

7. SOCIAL AND ECONOMIC IMPACTS OF LAND DEGRADATION

The human aspects are related to both population pressure and land-use technologies that are not sustainable, as they have not developed alongside the rapid population growth that is being witnessed in the Third World but whose negative effects hit the drylands most. The best known of these land-use technologies is the fallow system that in earlier times involved the resting of exhausted land long enough to allow fertility recovery through secondary revegetation. This original time span has been shortened and is almost non-existent now as a result of land pressure, especially in the African drylands (*see Chapter 6*). Clearing of vegetation, rapid abandonment of exhausted cropland, expansion of cropping into more and marginal land set up a vicious cycle that is hard to break. *Figure 9* is a flow chart showing the typical sequence contributing to this cycle of poverty.

As much as the inherent ecological fragility of the drylands, coupled with recurrent droughts, increase the degree of susceptibility to human-related land degradation processes, so do the latter affect the impact of drought through the weakening of the resilience of the system and the ability to return to equilibrium. Devastating dust storms are a common symptom of the rapidly deteriorating ecological situation (*see Chapter 8*).

Land degradation through loss of vegetation and soil cover contributes to global climate change by increasing land surface albedo, increasing the potential and decreasing the actual evapo-transpiration rate, changing the ground surface energy budget and adjoining air temperature, and adding dust and carbon dioxide to the atmosphere.

Impacts of land degradation on the natural resource base with direct effect on human populations include:

i. Reduction of perennial and annual livestock forage in rangelands.
ii. Reduction of available fuelwood material.
iii. Reduced biodiversity.
iv. Reduced water availability due to a drop in the water table.
v. Sand encroachment on productive land, human settlements and infrastructure.
vi. Increased flooding as a result of sedimentation of water bodies.
vii. Reductions of yield or crop failure in irrigated or rainfed farmland.

All these factors may ultimately lead to disruption, in various degrees, of human life due to deteriorating life-support systems that are expressed by:

i. Increase in the spread of poverty and hunger due to loss of land resources and consequent inability to provide sufficient food and shelter to growing populations, leading to a reduction in the nutritional and health status of the affected populations, especially the young and the elderly.
ii. Migration in search of relief and refuge as a result of economic and political stress as populations struggle to survive on the diminished water and land resources.
iii. An influx of environmental refugees that puts enormous pressure on the physical environment, economy and stability of societies in the immediate neighborhood, often exacerbating political differences and in some cases civil strife.

The solution to desertification, if there is to be one, is to shift the emphasis from the land to the people. Desertification control should be about the people who use the land not only the land they use.

As the case studies presented in this volume show, there are many regions where dust storms and drifting sand are real problems faced on a day to day basis by local populations and by government land management specialists and advisors. Experience in the Dust bowl of North America should be both a warning and a source of comfort. Faulty land-use practices, poor farming/herding methods and inappropriate government policies can lead to an acceleration of land degradation in drylands (*Figures 5 and 6*). The good news is that something can be done if the problem is properly analyzed and if there is a serious attempt to mobilize all the stakeholders in finding a solution. The solution may well be to relocate people and abandon attempts to crop or graze the badly degraded areas. The National Action Plans of each signatory to the UNCCD should reflect all options and develop a programme with verifiable targets and an agreed time frame that is known to the public.

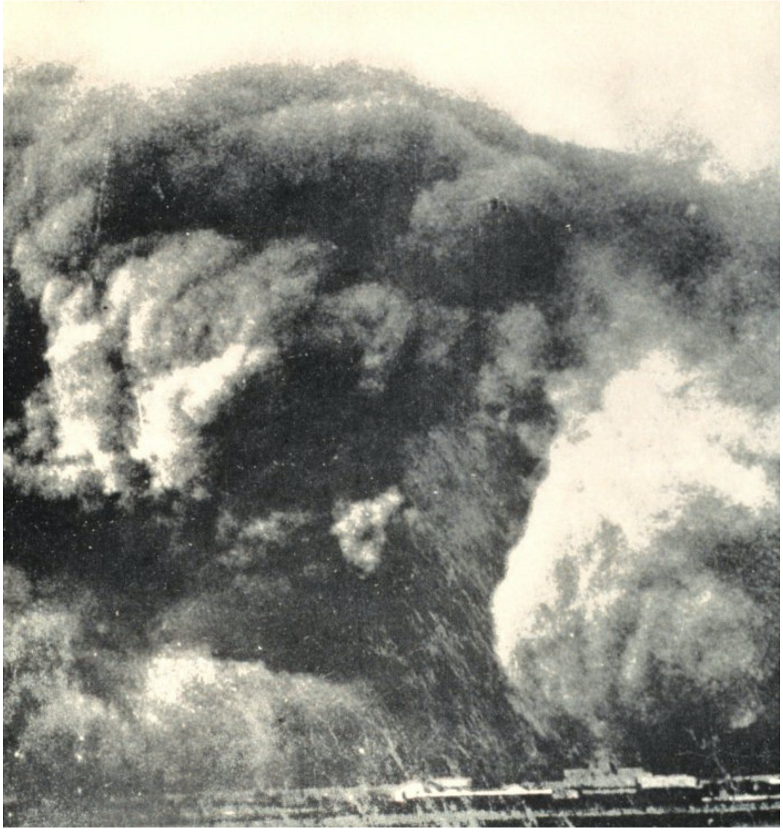


Figure 5: Black blizzards like the one experienced in North America during the Dust Bowl era can develop when poor land management, short sighted policies and drought combine

Figure 6: Dust storms have a serious impact on people's wealth, health and spirit. They can destroy whole communities and impose high economic costs on a region or a nation

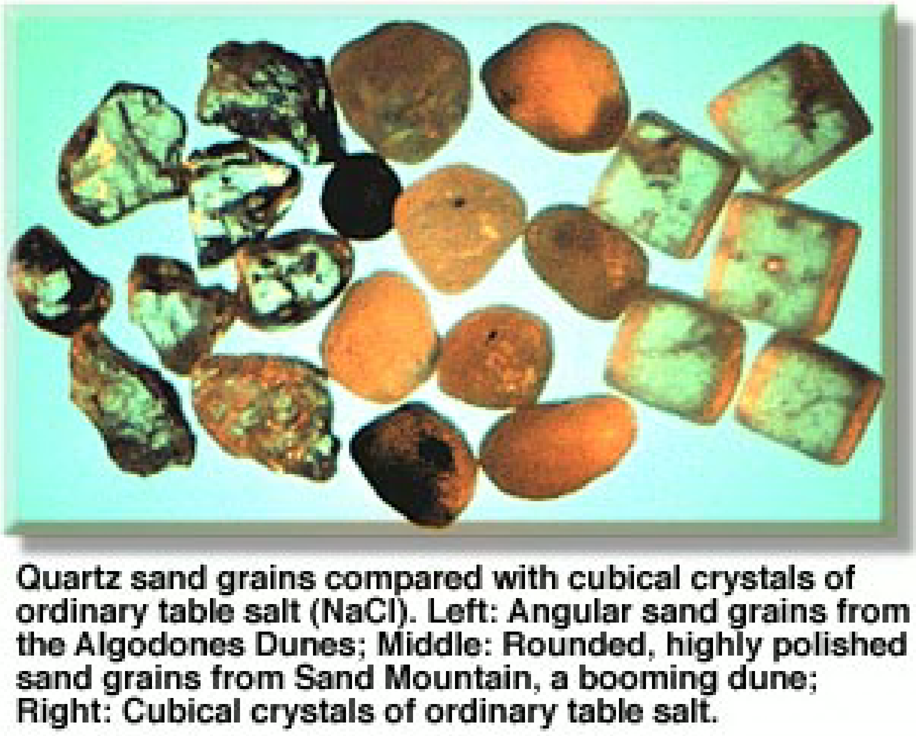


Figure 7: Sand grains are not all the same. The size and density will determine the behavior of sand particles when subjected to wind

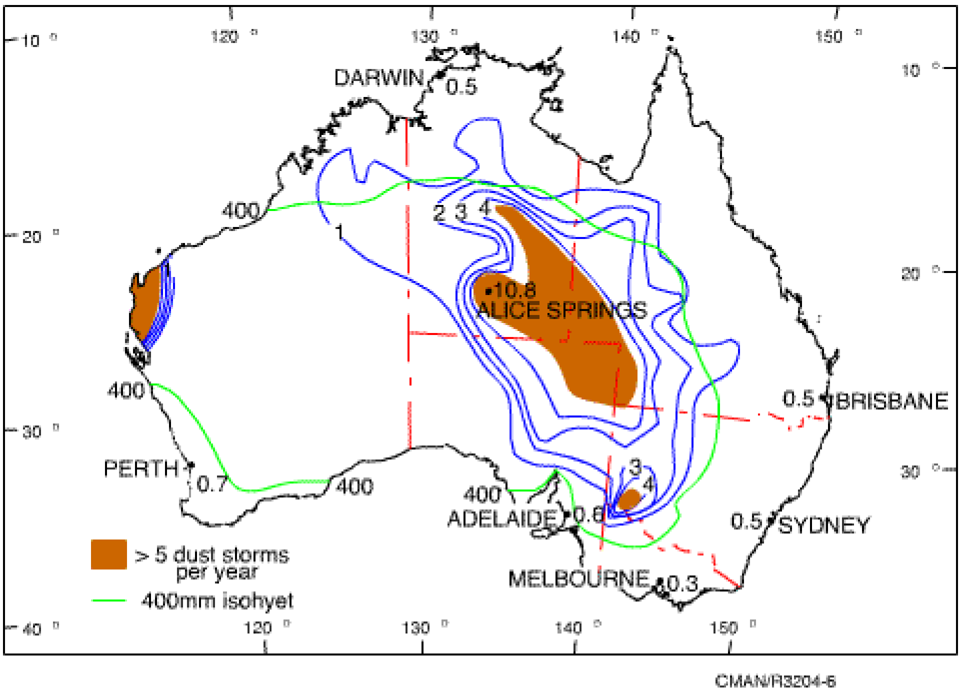
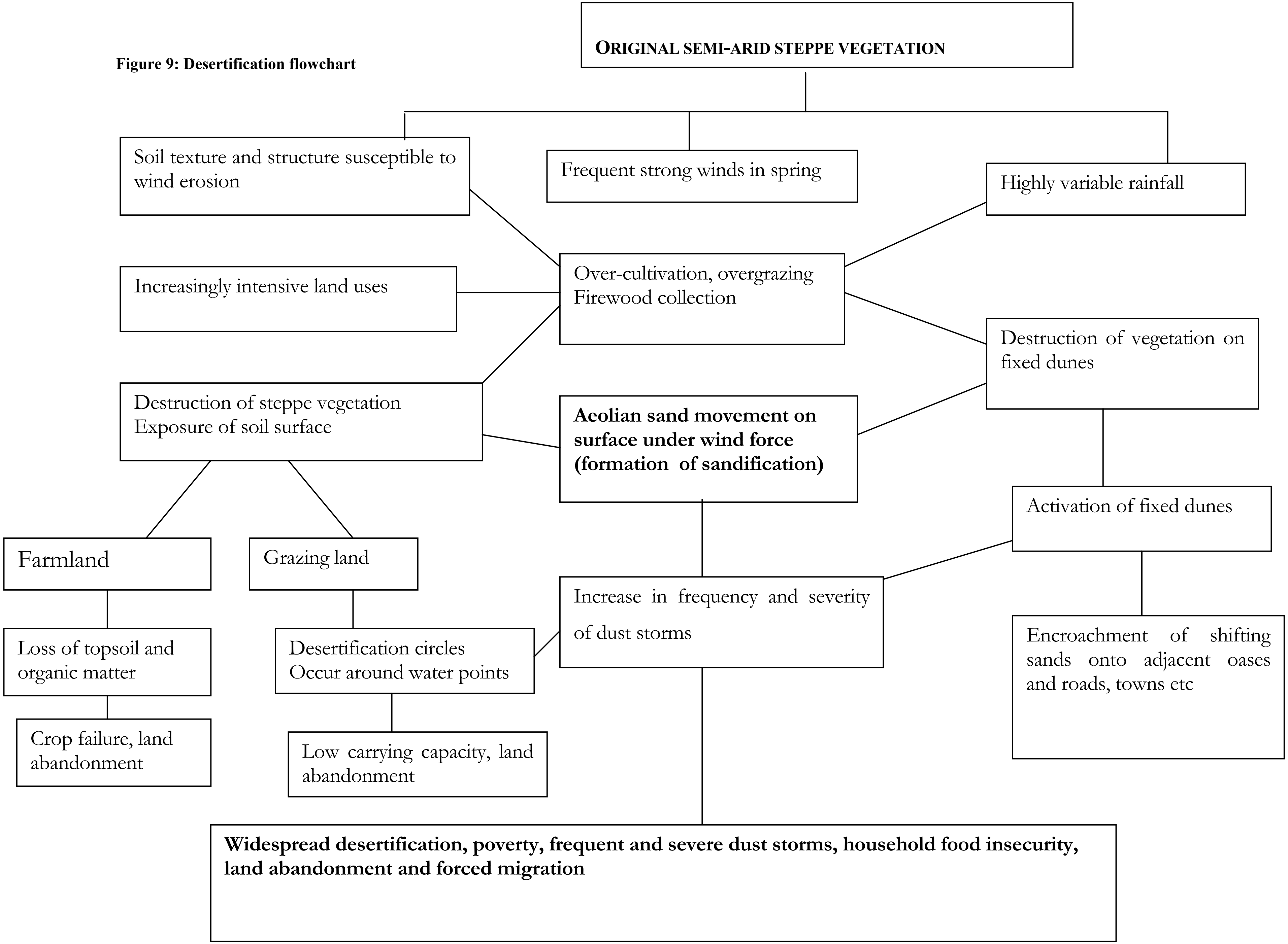


Figure 8: Frequency and distribution of dust storms in Australia (Data from Middleton, 1984)

Table 2: Some common manifestations of desertification

ECONOMIC MANIFESTATIONS	ECOLOGICAL MANIFESTATIONS	SOCIAL MANIFESTATIONS
Economic loss in cash	Loss of diversity in terms of wildlife, plants, and ecosystems	Migration of population off affected areas
Decreased crop yields	Loss of inland lakes	Rural poverty
Loss of farmland due to desertification	Loss of topsoil in terms of organic matter, N, P, and K nutrients	Influx of ecological refugees into urban areas
Loss of rangeland due to desertification	Decreased ground water level, increasing salinity of water	
Decreased grazing capacity in terms of the number of livestock	Increased frequency of sandstorms and associated loss of human life and livestock	
Abandoned farmland		
Abandoned rangeland		
Drifting sand affects railway lines and highways		
Increase in suspended load raises river heights and increases flood problems		

Figure 9: Desertification flowchart



8. REFERENCES

Coughlan, M.J. and Lee, D. H. *The assessment of drought risk in Northern Australia. "Natural Hazards Management in North Australia"* Aust. Nat. University, Canberra; 1978.

Gibbs, W.J. and Maher, J.V. *Rainfall deciles as drought indicators*. Bulletin no. 8 Bureau of Meteorology, Australia; 1978.

Mattson, J.O. and Nilsen, J. *The transport of Saharan dust to southern Europe: a scenario*. Journal of Arid Environments; 1996; 32: 111- 119.

NOAA; As reported on the web-site on 09-12-99 (http://www.noaa.gov/); 1999.

Pease, P., Vatche, P., Tchakerian, N. and Tindale, N.; *Aerosols over the Arabian Sea: geochemistry and source areas for aeolian desert dust. Journal of Arid Environments*; 1998; 39: 477-496.

Yaalon, D. *Comments on the source, transportation and deposition of Saharan Dust to Southern Europe*. Journal of Arid Environments; 1996; (36): 193-196.

Chapter Two

PROGRESS OF RESEARCH ON UNDERSTANDING SAND AND DUST STORMS IN THE WORLD

Wang Shigong, Dong Guangrong, Shang Kezheng and Chen Huizhong *Translated by Yang Youlin*
Department of Atmospheric Science, College of Resources and Environment
Lanzhou University, China

Key words: seasonality, periodicity, frequency, severity, satellite imagery, optical qualities, weather, particulates, trace elements, air pressure, forecasting, monitoring, research

SYNOPSIS

Sand-dust storm is the generic term for sand and dust storms. Sand-dust storms are hazardous weather events often associated with extreme calamity. The occurrence and development of sand-dust storms is either an important process of the acceleration of land desertification, or to a certain extent a consequence of the spreading of desertification. Strategies for preventing sand transport and reducing sandstorm disasters can be developed from an analysis of the causal factors in the formation of sandstorms.

This paper reviews the relevant recent research and studies on sandstorms in China and abroad. It intends to raise awareness of the severity of sandstorms and its impacts, to promote detailed studies on sandstorms and to enlarge the effective channels for exploring strategic measures against sand-dust storms.

KEY POINTS

1. *Desertification is one of the major global environmental issues and constitutes one of the three modern frontier research topics closely related to global climate change and biodiversity. It is well known that desertification is a consequence of natural factors (mainly climatic elements) and human elements. As one of the manifestations of desertification, sand-dust storms are both an important process of acceleration of desertification and a consequence of land desertification. Therefore, further integrated and systematic studies of sand-dust storms will promote understanding of the dynamics and mechanics of the desertification processes.*

2. *Sand-dust storms are hazardous weather events often associated with extreme calamity. They occur most commonly in desert and adjacent areas. Since the 1920s and 1930s, institutions abroad have started their studies on the spatial and temporal distribution, formation, causes and structure of sand-dust storms, and*

sand-dust storm disaster monitoring and controlling strategy. Since the 1970s, China started research on sand-dust storms but the attention given to it increased after a major dust storm in May 1993.

3. *On May 5th 1993, a unique strong sand-dust storm took place in Northwest China and serious attention from both research institutions and government was paid to the issue ever since. Emphasis was on promotion of further studies of sand-dust storms. In September 1993, the "First National Seminar on Sand-Dust Storm Weather" was sponsored in Lanzhou, the capital of Northwest Gansu Province. On November 29th 1993, the State Commission of Science and Technology convened a Reporting Meeting and the research programmes of sand-dust storms and dust storms were incorporated into the "Tackle Key Problem Programmes" of the State's Eighth Five-Year Plan of Science and Technology.*

4. *Since 1994, the State Natural Science Fund has financed more research programmes on sand-dust storms and some scientific agencies of provincial governments have also allocated budgets for carrying out research topics on sand-dust storms and dust storms. Particularly since the spring season of 2000, due to the rapid increase in the number of sand-dust storms and dust devils, alarm bells began to ring and nationwide concerns were expressed about the deterioration of the eco-environment. Attention is now being paid to the serious issue of sand-dust storms. Therefore, the central government of China and its agencies (like the Ministry of Science and Technology and others) strengthened the research capability to carry out further studies and approaches to control sand-dust storms.*

5. *This paper reviews the relevant recent research and studies on sandstorms in China and abroad. It intends to raise awareness of the severity of sandstorms and its impacts, to promote detailed studies on sandstorms and to enlarge the effective channels for exploring strategic measures against sand-dust storms.*

1. FUNDAMENTAL CHARACTERISTICS AND HAZARDS OF SAND-DUST STORMS

1.1. Definition, terminology and classification

Sand-dust storm is the generic term for sand and dust storms. It is a serious phenomena of wind and sand which brings sand particles and dust silts into the sky and turns the air turbid (horizon visibility is less than 1 km). Sandstorm refers to the strong sand-carrying windstorm at force 8 (Beaufort scale) that blows up great quantities of sand particles from the surface into the air. Dust storm refers to the strong dust-carrying windstorm that blows up great quantities of dust and other fine grains into the atmosphere (Zhao Xingliang, 1993).

Terminologically, different countries or regions term sand-dust storm differently; for instance, in the Northwest region of India, the convection sand-dust storm that occurs in the season preceding the monsoon is named *Andhi*. It is called *Haboob* (Joseph et al., 1980) in Africa and Arabic countries. It is titled *"phantom"* in some regions: namely it means *"devil"* (Wolfson et al., 1986).

In general, two indicators, wind velocity and visibility, are adopted to classify the grade of intensity of sand-dust storms. For instance, Joseph has classified the sand-dust storms occurring in the Northwest part of India into three grades. Namely, the feeble sand-dust storm develops when wind velocity is at force 6 (Beaufort) degree and visibility varies between 500-1,000 m. The secondary strong sand-dust storm will occur when wind velocity is at force 8 and visibility varies 200-500 m. Strong sand-dust storms will take place when wind velocity is at force 9 and visibility is <200 metres. In China, a sand-dust storm is defined similarly to the above. The only difference is that the category of strong sand-dust storms is defined again into two grades, namely strong sand-dust storms and serious-strong sand-dust storms. When wind velocity is 50 metres per second (m/s) and visibility is <200 metres, the sandstorm is called a strong sand-dust storm. When wind velocity is 25 m/s and visibility is 0-50 metres, the sandstorm is termed a serious sand-dust storm (some regions name it Black windstorm or Black Devil) (Xu Guochang et al, 1979).

1.2. Statistic features of spatial and temporal distribution

1.2.1. Spatial Distribution

As consequences of land desertification, sand-dust storms frequently occur in four regions throughout the world: Central Asia, North America, Central Africa, the Sahel and Australia (Yan Hong, 1993). Sand-dust storms occurring in China belong to one part of the Central Asia Sandstorm region, mainly in Northern China. General characteristics of sandstorms in China are that sandstorms prevail in Northwest China and Northeast China, more frequent in plain (or basin) areas than in mountain areas and occurring much more in desert or at desert fringes than other districts. Most sandstorms are concentrated in two large regions. One is the Taklimakan Desert in Tarim Basin where there are two sub-centre areas from Maigaiti to Keping via Bachu and average sandstorm frequency is 20-38.8 days annually. The other sub-centre area is from Sache to Qiemo via Hetian and average sandstorm frequency is 25-35 days annually.

Another large region with frequent sandstorms is the vast area from the eastern edge of the Baidan Jilin Desert to the Kubqi Desert via the Tengger Desert, the Ulan Buh Desert and Mu Us Sandy Land. Its boundary in the southern part is the Hexi Corridor in West Gansu Province (*see Chapter 11*). This vast belt is a region with frequent sand-dust storms in Northwest China and its centre is located in Minqin County at the southern fringe of the Tengger Desert, with average annual frequency of sand-dust storms being 37.7 days. The second largest area with frequent cases of sand-dust storms is situated in Hangjin County in the northern part of the Kubqi Desert and Dingbian County in the southern part of Mu Us Sandy Land, with annual frequency of sand-dust storms averaging 27 and 25.9 days respectively (Wang Shigong et al, 1995). Statistic analysis of case studies of strong and serious-strong sandstorms and dust devils in Northwest China (He Huixia et al, 1993) has indicated that the most serious sandstorm in Northwest China originates potentially from the vast belt areas from the Turpan and Hami regions in the west and extends to the Great Bay Area of the Yellow River crossing the thousand kilometres long Hexi Corridor of Gansu Province and the Alxa Plateau in West Inner Mongolia. In addition, there are three local sandstorm occurring and prevailing areas in Northwest China. They are the Kelamayi Region of North Xinjiang, the Hetian Region of South Xinjiang and the Northwest part of Qinghai Province.

1.2.2. Temporal change

According to the measurements of deep-sea lithologic core and glacial cover sediments, sandstorms occurred before the end of the Cretaceous period, dating back 70 million years ago. In light of the local chronicles, sandstorms had occurred in Wuwei of Gansu province in 351 AD and some collapsed houses and human and animal casualties had been recorded.

Over long-term geological history, periodic changes of sandstorms were significantly indicated and sandstorms were closely related to climate change in geological periods and the growth and decline of land surface sand materials. Meeting with warm and wet climate, vegetation on land surface grew dense and eco-environment conditions were favorable and the frequency of sandstorm occurrence was low. On the contrary, in the cold and dry climate period, the frequency of sandstorm occurrence was high (Xia Xuncheng et al, 1996). Since the early 1950s, the detailed records of modern sandstorms began.

In Northwest China, the frequency of sandstorms during the last five decades is characterized by the following facts: the frequency of sandstorms in the 1950s was highest and a slight decline of frequency took place in the first half of the 1960s, with maximum reduction particularly in 1967 and 1968. It increased slightly again in the 1970s and dropped down in the 1980s. Since the early 1990s, a certain increase occurred and a remarkable growth of sandstorm frequency again took place. There is a certain difference of sandstorm frequency in various arid climate zones. The situations in extreme arid zones, central arid zones and semi-arid zones are fundamentally similar to the general situation of entire Northwest China. Yet there is a significant difference in the arid zone in the northern part of Xinjiang, namely, it was constantly at a negative anomaly since the later 1950s to early 1970 and was constantly at a positive anomaly since the later 1970s to the end of the 1980s. Sand and dust storms occur mainly in spring season, which covers half of the total frequency of sandstorms (particularly the serious-strong sandstorm occurring in spring season). The summer season is the next in line, and autumn (winter season in Xinjiang) is the season with minimum frequency of sandstorms. In terms of months in which sandstorms occur, April is the dangerous month with high frequency, March and May are lower and September (December and January in Xinjiang) is the month with minimum frequency (Wang Shigong et al, 1996). Liu Jingtao et al (1998) have studied the situation in central and western Inner Mongolia and analysis shows that the frequency of sandstorms in April is maximum and sandstorms in the spring season (March to May) occupy 73% of the total cases of sandstorm.[2]

Sand-dust storms are also characterized by their significant daily change. Wang Shigong et al (1995) analyzed the daily change of the frequency of sandstorms in April 1994 in Northwest China and their results show that most sandstorms took place mainly in the period from afternoon toward evening, occupying 65.4% of the total number of sandstorms. The sandstorms occurring in the period from early morning to midday occupy only 34.6% of the total frequency. In the Hexi Corridor of West Gansu Province, most dust storms or black devils occurred during the period from 12:00-22:00 o'clock (Fu Youzhi, 1994).

1.3. Variation characteristics of meteorological factors

The peak of serious sand or dust storms moves quickly eastward as a black wall from the west (or southeastward from the northwest). The weather conditions change severely before or after the transit of windstorms and sand-dust storms. Before the transit of sandstorms, the temperature is very high, air pressure is very low, weather is fine and wind velocity is low. When the sand-dust storms occur, strong wind sweep across, sand and dust flies upward, air pressure ascends immediately and air temperature drops suddenly. On April 22nd, 1977, a black windstorm took place in the Hexi Corridor of West Gansu Province. It was recorded that ten minutes later, after the sandstorm in Zhangye, air pressure rapidly increased 2.8 hpa (hectopascals[3]), temperature declined 6.8°, wind direction changed northwestward and west from east wind and mean wind

[2] In Mexico City, the most frequent cases of sandstorms took place in March (that normally receives less than 13 mm of rainfall in three months) and minimum frequency took place in September (Jauregui, 1989). In Northwest India, sand-dust storms occur mainly in April-June and this fact coincides with the reality frequency of sandstorms in Xinjiang of China.

[3] Hectopascals: a measure of pressure

velocity increased up to 20 m/s, while maximum wind speed exceeded 30 m/s (Xu Guochang, et al, 1979). On May 5th 1995, a serious black sand-dust storm originated from Jinchang City in West Gansu Province. It was recorded that the air pressure heightened suddenly to 3.1 hpa in a span of ten minutes in Jinchang. In Yongchang City neighboring Jinchang, the air pressure increased 2 hpa in two minutes and the air pressure curve was manifested by phenomena of *"air pressure nose"* after jump reductions of air pressure (Chen Minglian, et al, 1993).

Joseph (1980) studied the convection sandstorm of *"Andhi"* in Northwest India and results show that visibility can be reduced quickly from 1,000 metres to 200 metres, and even 100 metres, while a strong sandstorm or dust storm sweeps across. Wind velocity can be increased up to 20 m/s from 4 m/s. Air temperature can be reduced about 5° and relative humidity can increase 10% or more. On May 20th 1976, a sandstorm took place in India and the visibility at New Delhi Airport was reduced to 280 metres from 4,000 metres in a span of two minutes. Air temperature declined from 38-25°, relative humidity increased rapidly from 31-70% and wind speed was 73-80 km/hr. Research (McNaughton, 1987) on the spring sandstorm/dust storms in the Arabian Gulf and adjacent Gulf countries indicates that the above-mentioned meteorological factors possess similar variation characteristics.

1.4. Satellite image and optical characteristics

Zheng Xinjiang et al (1995) studied and interpreted the images of sandstorm weather, and research results show that the serious-strong sandstorm of May 5th 1993 in Northwest China was clearly indicated on the NOAA images. Sandstorms occurred in the gray-white areas between cloud masses and peak cloud belts. The reflection of light was characterized by the well-distributed top structure of sandstorm occurring areas and some stripes can be seen along with the wind direction. These stripes were light gray and some shadows of high clouds were visible. There was a big difference between rate of reflection of light at the top peak of sandstorms and the rate of reflection of light on land surface. The rate of reflection of light on land surface was lowered nearly 15% and the rate of reflection of light on the top windstorm peak was reached 24%. The reflection of light of cloud masses was highest reaching 51%. On the infrared images, significant differences of temperatures between sandstorms, cloud masses and land surface are visible. Here, the temperature of clouds is minimum and centralized around -54°, the temperature of sandstorm areas is secondary and centralized around -3° and the temperature of land surface is at a maximum and reaches +39°. According to the characteristics of temperature and air data, it can be determined that the peak of the serious-strong sandstorm on May 5th 1993 in Northwest China was as high as 2,100 metres above ground.

Xu Xihui (1997) studied the characteristics of satellite images of sandstorm weather in desert regions (Taklimakan Desert) and her research shows that, on the visible satellite images, there were water bodies and rain-traces on the land surface and the rate of reflection of light of forest coverage is minimum and manifested in black colour. The rates of reflection of light of crops, forages and desert steppe vegetation are manifested in dark gray or gray colours. In arid climate zone deserts, due to the scarcity of vegetation, the rate of reflection of light is high and manifested in gray or light gray colours. The rate of reflection of light of clouds and alpine snow is highest and manifested in gray-white or white colours. The feather-shaped masses formed by sand or dust storms are similar to the low clouds and coloured in gray-white. The only difference between the sandstorms and low clouds is that the boundary of low clouds is clear and its shape is uncertain or undulating, impacted by agitation. The boundary of sandstorms is unclear and its shape is well-distributed feather-like and dispersed and scattered under the cloud masses and it is easier to be classified with the cloud masses. The distribution of feather-like sandstorms is due to topographic orientation and its borderline often coincides with the margin of the basin. Yang Dongzheng, et al (1991) interpreted the satellite images of sandstorm occurrences in the Beijing region in April 1988 and his analysis shows that the sandstorm developing area is coloured in light gray on the satellite images.

Jiang Jixi, et al (1995, 1997) analyzed the causes of the serious-strong sandstorm that occurred from afternoon to nighttime on May 5th 1993 in Gansu and Ningxia, by utilizing the GMS-4 digital stretch infrared data, and concluded that the Medium Convection System (MCS) of the head section of the medium-strong cold front and the squall line formed during the serious-strong sandstorm, can be interpreted by using satellite image data. The resolution of the Meteorological Satellite is high, yet all the weather systems with different (space-time) spatial and temporal scales, from planet to weather scale, medium scale and windstorm convection body scale, can be seen on one sheet of image. Even the dynamic and thermal processes, which occur and develop in the weather system, can be revealed. Therefore, the combined use of satellite image data and normal data will help increase the recognition of the occurrence and development mechanism of sandstorm weather systems and the characteristics of the structure for improving the capacity and ability for long-term and short-term prediction and warning.

Sand-dust storms, particularly the black dust devil, possess unique optical characteristics. For instance, the black dust devil that occurred on May 5th 1993 in Northwest China, according to witness records of the meteorological station of Jinchang City of West Gansu province, was a 300-400 metres high sandstorm wall, observed when the black dust devil moved closer and its shape changed to that of a mushroom cloud similar to an atomic bomb explosion, manifested in revolving sand-dust masses. The upper part was coloured in yellow, the middle part was coloured in red and the lower part was coloured in black. Wang et al (1993) has explained this phenomenon from the point of view of optics. They pointed out that sunshine is composed of red, orange, yellow, green, blue, indigo and purple colours and its wavelength decreases progressively (0.75-0.4 μ). When sunshine passes the atmospheric stratum, the fine particles in the top stratum of the atmosphere can scatter some of the purple light of the sunshine. Consequently, the sky in the atmospheric stratum is purple coloured. Again, as the sunshine passes the middle and lower atmosphere, fine dust particles in these strata can scatter some blue light in the sunshine, because the diameter of fine dust particles is similar to the blue light waves. Therefore, the sky in this stratum is sky-blue coloured. In the sand-dust wall, the up-lifting force produced by the rising air current is powerful. The sand grains at the lower stratum of the sand-dust wall are coarse particles, the sand particles in the middle stratum are the next in size and those in the upper stratum are mainly suspension dusts. Because suspension dusts can scatter the yellow light in the sunshine, we can see the upper part of sand-dust wall is yellow coloured. When the sunshine passes through the middle stratum of the sand-dust wall, the fairly coarse particles can scatter the red light in the sunshine and thus we see the middle stratum of the sand-dust wall is red coloured. When sunshine passes the whole atmosphere and the upper and middle parts of the sand-dust wall, then all the seven lights of the sunshine have been completely scattered, refracted or blocked up and this is why we always see the bottom of the sand-dust wall as black coloured.

Qiu Jinheng et al (1994) conducted synthetic measurement of the three sand-dust storm weather processes in the Beijing region that occurred in April 1988 by using laser radar and photometer. His result shows that the optical thickness of aerosol of atmospheric column in Beijing varied between 0.11 and 0.25 and average value was 0.18 before the occurrence of sand-dust storms. But when the sand-dust storm occurred, the average value of the optical thickness was as high as 5.27 and the latter was twenty times as high as the former. The sand-dust storm was very serious during 8:00-11:00 on April 11th 1988: the sky was fully yellow coloured and the optical thickness of aerosol of atmospheric column varied between 8-15. Mainly high-altitude inputs and great quantity of sand particles and dusts blown up from land surface caused this characteristic. An experiment on the interrelationship between land surface and air current in the Heihe River region was carried out and field measurements of aerosol of sand-dust were conducted. The experiment concluded that the scattering light coefficient of aerosol or optical thickness of sand-dust in April is much high than that in October. The sand particle and dust of 0.1-1.0 μ are the main grains to block the light.

1.5. Physical chemistry and radiation characteristics of aerosol of sand-dust

During sand-dust storm weather process, the concentration of various elements of sand particles and dust are quite different. Yang Dongzheng, et al (1995) measured the various elements of sand-dust particles of the sandstorm that occurred on April 9th-12th 1988 in the Beijing region. The analysis results show that the element concentration exceeding >500 ppm contains Al, Fe, K, Mg, S, P, Ti, Na. The element concentration exceeding 100-500 ppm contains Mn, Ba, and V. The element concentration exceeded 1-100 ppm includes Zn, Ni, Pb, Cr, Co, and Cd. They also conducted measurements of element concentrations of sand-dust particles in two sandstorms that occurred in April 1990 and analysis results show that the majority of elements in aerosol of sand-dust are the elements from the crust of the earth and are mainly found in big-sized grains (d>2.1 mm). Some artificial pollutant elements are mainly found in the small-sized particles (d<2.1 mm). As a consequence, the elements in aerosol of sand-dust originated from natural sources. The characteristics of rich concentration and physical chemical nature of sand-dust elements are closely related to the sources of sand-dust. According to the measurement of sand-dust elements of the sandstorm that occurred in April 1988, the value of rich elements factors (mean value) possesses the following characteristics: 1) EF (Ti) is higher than EF (Fe) in the same element; 2) only one element S has its EF value exceeding 10. The EF (Ti) and EF (Fe) of sand-dust are 39.45 and 15.52 respectively; 3) the EF value of the rest of the elements are less than 10 and mostly close to 1.

Legrand, et al (1988) studied the characteristics of the radiation of sand-dust in the Sahara Desert and their research shows that dust haze, through the impact of radiation process, cuts down the heating effect on land surface during the daytime and slows down the cooling effect near ground surface during the nighttime.

Shen Shaohua and Chen Shoujun (1993) studied, by using numerical value modes, the compelling effect of the effective radiation on the peak system while sand-dust storm are occurring and developing. Their research shows that radiation heating of sand-dust storms causes occurrences of peaks at low atmospheric strata during the daytime, and that radiation cooling of sand-dust storm causes disappearance of the peak at low atmospheric strata during the nighttime. This fact coincides with results of ground measurements and observations. They pointed out that, when they analyzed the occurring process of the peak under the radiation of sand-dust storms, the peak occurrence during daytime was mainly caused by a combination of non-heat insulation heating and horizontal speed transfiguration field. The perpendicular speed field causes an inferior effect on the occurrence of the peak and it accelerates the disappearance of the peak. At nighttime, the key factor accelerating the disappearance of the peak at low atmospheric strata is the non-heat insulation heating process. The level-flow at horizontal temperature gradient does not cause any effects on the occurrence or disappearance of the peak. When the sand-dust accumulation takes place, the peak front intensity and gradient under the radiation compelling will be correspondingly deducted.

Wen Jun (1995) conducted measurements and observations on the aerosol of sand-dust which affects the input and output of radiation on land surface. His research and analysis show that the weakening effect of aerosol of sand-dust on solar radiation takes place at a low atmospheric stratum below 3000 metres. Under the background condition, the weakening effect can be achieved up 25.0-58.0 W/m^2 and the weakening effect will be more significant while the sand-dust storm is breaking out. The aerosol of sand-dust plays a significant radiation-heating role for the low atmospheric stratum below 3000 metres. The maximum heating rate at low atmospheres in October and April are 1.12 k/d and 2.27 k/d respectively. According to mode calculation, under the condition of sand-dust weather, the maximum heating rates of aerosol of sand-dust are 2.59 k/d, 5.12 k/d and 11.30 k/d when the optical thicknesses are at 0.49, 1.42 and 2.12, in 540.5-m positions.

Ackerman and Hyosang Chung (1992) conducted studies on the effect of accumulating dust to radiation effectiveness of local energy input and output. Their research shows that, in the sky above the ocean, the existence of dust increases short-wave radiation volume at the top atmospheric stratum up to 40-90 $w.m^{-2}$ while the sky was clear. On contrary, long-wave radiation on the top atmospheric stratum will be decreased by 5-20 $w.m^{-2}$. Sand-dust will cause certain impacts on the heating rate of the atmosphere and the input and output of radiation energy on the surface of the earth and, as one of the aerosol in desert region, it is an important local climatic variation. Wei Li, et al (1998) carried out analysis of the data of ten times AVHRR passing the testing areas in the Heihe region in March-May 1991 and interpretation of the data of turbidity of the atmosphere at the same period. Their efforts show that the sand-dust in the atmosphere can cause increases of the backward scattering of the ground-atmosphere system, namely increase the refraction rate of the planet. The impact on the long-wave radiation that shoots from the ground-atmosphere system can be indicated mainly through the impact on surface temperature.

1.6. Calamity of sand-dust storms and their impacts on the environment

Sand-dust storms, especially serious-strong sand or dust storms are hazardous weather with extreme calamity. When it occurs, sand-dust storms can move forward like an overwhelming tide and strong winds take along drifting sands to bury farmlands, denude steppe, attack human settlements, reduce the temperature, pollute the atmosphere, blow out top soil, hurt animals and destroy mining and communication facilities. These hazards bring about frost freeze to crops and result in a loss of production. They accelerate the process of land desertification and cause serious environment pollution and huge destruction to ecology and living environment. The hazardous consequences severely threaten the safety of transportation and electricity supplies and contributes unforeseen casualty to people's life and property.[4]

It was estimated that the direct economic loss caused by the serious-strong sand-dust storm that occurred on May 5th 1993 was 560 million RMB Yuan and 1.1 million sq. km of territory, occupying 11.5% of the total land area of China, was threatened by this sand-dust storm. About 12 million people of 72 counties of 18 prefectures and cities of the four Northwest provinces were affected. According to the statistics, 85 people were killed, 31 people were lost and 264 people were wounded, with the majority of the death and missed people being children. Hundred of thousands of animals were killed and lost during this serious sand-dust storm. Hundred of thousands of ha of arable land, fruit plantations and seedlings were un-vegetated. Hundreds of greenhouses and plastic sheds for cash crops were destroyed. Steppe and grazing lands were seriously denuded. Infrastructure facilities, highway, railway and electricity supplies were seriously ruined. In addition, this sand-dust storm, through denudation, erosion, blow out, sand transport and accumulation, has brought about critical destruction of desert plants and ecological environment in Northwest China, promoting the desertification process in the affected areas, and its indirect economic loss is hard to assess (Wang Shigong, et al, 1995).

[4] In the Sahelian region at the south edge of the Sahara desert in Africa, from the early 1970s to the middle of 1980s, due to prolong drought, rangeland and savanna were degraded, agricultural lands were desertified, sand-dust storms occurred, desertification processes accelerated, and wind and sand disasters intensified. It was estimated that hundreds of thousands of African villagers and farmers became destitute and homeless, and that their livelihood was pathetic. China is also one of the countries suffering from sand-dust storms, particularly Northwest China faces strong or serious-strong sand-dust storm attack almost every year.

During the recent decade, the frequency of sand-dust storms has increased year by year and the situation of overloading land resources cannot be improved in a short period of time. Along with global warming, constraints of shortage of water resources become as intense as ever. As consequence, sand-dust storms will bring about more harmful calamities to human beings.

The process of sand-dust storm weather is a huge mobile source of pollution and it can increase silt pollutants in the atmosphere significantly, where sandstorms or dust devils blow up. Yang Dongzheng, et al (1991) made measurements of physical and chemical characteristics of sand-dust of the sandstorm that occurred in the Beijing region on April 9-12th 1988. The analysis results show that the mean value of the total suspension particles (TSP) was 5.118 mg/m^3 and it was 15.7 times higher than that under normal weather conditions. Scientists of the Changsha Institute of Labour Protection have done measurements of sand and dust of the sandstorm that took place on May 5th 1993 in Jinchang City of Gansu Province. Their analysis shows that the TSP was 1016 mg/m^3 outside a room and 80 mg/m^3 inside a room, which exceeded by more than 40 times the criteria that stipulate and result in severe air pollution.

In addition, sand transports will produce positive effects. According to Swap et al (1992), it is indicated that each sand-dust storm in the Sahara Desert can blow up 480,000 tonnes of sand and dust into the Northeast part of the Amazon Valley. The annual sand transport is approximately 13 million tonnes, meaning sand-dust storms have brought about an accumulation of 190 kg of sand and dust particles per ha every year in the region. It was estimated that, along with the accumulation of sand-dust, 1-4 kg of phosphate has been transported and accumulated per ha per year. It can be assumed that the rate of production of the rain forest in the Amazon depends on the phosphorous and other elements transported along with sand-dust storms from the Sahara. The output, increase and decrease of the area of rain forest in the Amazon are directly related to the enlargement and cut down of the area of the Sahara Desert and the sand transport capacity.

Furthermore, sand-dust is partially alkali itself and can restrain certain harm from acid rain during its transportation in the affected area. Japanese scientists' research indicated that yellow sands and dust from Northwest China are the major component of coagulation tubercles cooling clouds in the sky of Japan and play an important role in precipitation in Japan. At the same time, ice crystals of yellow sand are alkali and play an active role in the neutralization of emerging of acid rain in Japan (Qu Zhang et al, 1994).

2. ANALYSIS ON THE ROOT CAUSES OF SAND-DUST STORMS

2.1. Macroscopic condition

Research (Xia Xuncheng, et al, 1996; Qian Zheng, et al, 1997) shows that the formation of sand-dust storms is determined by the following three basic conditions:

1) Wind is the motive power of the formation of sand-dust storms.
2) Sand composition on land surface is the material foundation. For instance the excessive opening-up of rangeland in the Western part of the USA has accelerated the desertification process, opened more sand sources and caused frequent occurrences of sand-dust storms. The same disaster phenomenon took place in Kazakhstan and former USSR Siberia in the 1950s: a large amount of wasteland was blindly opened up and

vast sandy land areas were exposed to strong wind erosion and serious sand-dust storms frequently occurred causing hazardous impacts.

3) Unstable atmospheric condition is the local heating power condition. Most sand-dust storms took place during the period from afternoon to evening. This fact shows the importance of the unstable atmospheric status.

Wang Shigong, et al (1995) carried out systematic analysis on the macroscopic weather and climatic conditions causing sand-dust storms and the condition of the underlying surface. He concluded that sand-dust storms occurred and developed mainly in spring and early summer seasons because of the following five reasons:

1) Underlying surface and unusual topographic conditions of abundant sand source.
2) Long time aridity and freezing weather in winter months and loose topsoil after defrosting weather in spring season.
3) Position of rapid stream axis in high altitude in spring is an important reason causing strong wind in northern regions.
4) The instability of atmospheric stratification in spring is increased and convections easily emerge in afternoon and this condition is advantageous to the under-blow of atmospheric dynamic power.
5) Spring is the season with frequent cold fronts in the northern region and strong winds behind cold fronts is one of the most important elements causing sand-dust storms.

2.2. Main circulation trends and affected systems

Sand-dust storms are a consequence of various factors. Particularly, the occurrence and development of serious-strong sand-dust storms are related to the matching reaction of advantageous circulation conditions and weather systems under the circumstance of macroscopic climate and underlying surface conditions.

An analysis of various weather conditions of sand-dust storms in Arizona, USA during the period 1965-80 concluded that the following systems could easily cause the occurrence of sand-dust storms: 1) frontal systems; 2) thunder storm and convection; 3) torrid turbulence; and 4) cut-off of low pressure at top stratum.

Swap, et al (1992) indicated that sand-dust originating from the Sahara Desert passes through torrid Atlantic Ocean to the Amazon Basin over large-scale circulation. In the central Amazon basin, matching the main precipitation system in the rainy season, the low-pressure centre of the precipitation system produces motive power and vertically blows up sand-dust to the sky causing suddenly paroxysmal sand-dust storms. Precipitation is generally composed of thunderstorms, which are formed in several kilometres long horizontal scale and several days' time scale. Along with these main precipitation systems, sand-dust storms are intermittently transported to the Amazon Basin. As a consequence, development of thunderstorms can provide energy to sand-dust storms. Although not all precipitation processes are associated with cases of sand-dust storms in the Amazon Basin, the phenomenon of all sand-dust storms associated with precipitation was observed in the mentioned basin.

Pauley, et al (1996) studied one sandstorm event along the California Valley and it was concluded that sandstorms are closely related to torrents in high skies, secondary circulation of peak fronts and the boundary stratum process. Dynamic power is transported downward with great quantity at the upper convection stratum to form the peak. Then the dynamic power accumulates at the low altitude of convection, the development of the boundary stratum process is promoted, and wind force on land surface is reinforced. High wind velocity on ground plays an important role in the occurrence of sand-dust storms.

Jiang Jixi, et al (1997) studied and observed seven serious-strong sand-dust storms and concluded that the occurrence of serious-strong sand-dust storms can be divided into three types:

1) Serious-strong sand-dust storms caused by prefrontal squall lines. This is one of the most important parts of strong sand-dust storms in Northwest China and the north of Northern China.
2) Sand-dust storms caused by strong convection clouds at tail peak. This kind of sand-dust storm is particularly strong in intensity, but its threatening scope is limited.
3) Strong sand-dust storms caused by strong convection clouds at the frontal peak. The frequency of occurrence of this kind of sand-dust storm is fairly rare, but its threatening scope is very vast. Hu Yingqiao and Yasushi Mitsuta (1996) conducted research on the relationship between developments of squall lines or squall lines at the strong cold front and the breakout of the black dust devil. It was concluded that when a strong cold front passes through the sky, the squall line at the cold front is transported to the ground surface, heated by strong solar radiation, and with the area atmospheric condition being unstable, the squall line is further developed and results in a black dust devil.

We conclude, through integrated analysis of domestic and international, particularly the large-scale serious and strong sand-dust storms in the Northwest China, that main circulation conditions and weather systems easily cause sand-dust storms containing:

2.2.1. Adjustment of longitude and latitude circulation

The occurrence and development of large-scale sand-dust storms in Northwest China is always followed by a one-time large-scale circulation adjustment, namely, when the longitude circulation is adjusted to latitude circulation, cold air from Siberia moves rapidly from northwest to southeast in China. If it is just in the spring season with scarce rainfall and prolonged drought, the lower stratum of the convection stratum is fiercely unstable, and sand-dust storm weather on a large scale is then the result.

2.2.2. Cold front activity

Spring is the season when cold front activity is most frequent in the Northwest China. A very strong pressure gradient is brought about after the transit of each strong cold front, and twinkles at wind velocity of 20-30 m/s will consequently take place. Sand-dust storms will often be brought about in the region where the twinkle wind prevails. Sand-dust storms that occurred in the northeast part of Peninsular Arabia, namely in Iraq and Kuwait, were concentrated and took place during the daytime in the summer season. The cold front transit was accompanied by strong wind and sand-dust storms resulted. In the Peninsular region, wind speed is usually accelerated in daytime and weakened in nighttime (Wolfson, N. and Matson, 1986).

2.2.3. East wind torrents at lower altitudes

During the early days before the appearance of sand-dust storms, large degrees of temperature raising often took place at lower altitudes in the east part of the Qinghai-Tibet Plateau. This fact urged the development of low eddy in the northeast of the Plateau. If development of high pressure took place at the same time in the southeastern part of the Mongolian Plateau, the eastern wind torrent would possibly be formed in the lower sky along the Hexi Corridor in the North of the Plateau and this is the important condition causing large-scale sand-dust storms in the Baidan Jilin Desert, the Tengger Desert, the Hexi corridor of West Gansu and the western part of Great Bay of the Yellow River.

2.2.4. Meso-scale system

By analyzing several serious sand-dust storms that occurred in Northwest China since the 1980s and the early 1990s, the central areas of serious-strong sand-dust storms were always interrelated to the meso-scale lower pressure and the meso-scale squall line. This fact shows that the meso-scale system plays an important role in the occurrence and development of strong and serious-strong sand-dust storms. In addition, Qu Zhang, et al (1994) concluded from their research that although sand-dust storms were associated with strong wind at force 7, some winds, without transport of sand-dust particles, were even stronger than those prevailing under sand-dust impacts were. Moreover, the fact is that mean annual sand-dust days are less than windy days and the fierce instability of convections at the lower convection stratum is the most important condition to *"blow up sand to cause dust storms."*

Joseph et al (1980) studied convection sand-dust storms (termed *Andhi* in the northwest part of India) that occurred in the season before the monsoon season and his research shows that the majority of local sand-dust storms are also related to the meso-scale system. For instance, on May 13th 1973, the observed sand-dust storm around New Delhi Airport was related to the meso-scale squall line system at wind speeds of 84 km/hr. On May 20th 1976, a similar sand-dust storm was caused by strong a windstorm system at wind speeds of 73-80 km/hr. Sand-dust storms that occur in Gulf of Arabia region are usually the result of meso-scale thunder storm systems (McNaughton, 1987). Therefore, although the topography, underlying surface, large-scale circulation background and weather system are essential conditions favoring sand-dust storms, under the above-mentioned conditions, the meso-scale system plays an extremely direct role in the occurrence of sand-dust storms. In addition, the sand-dust storms that appear in the Persian Gulf and the Gulf of Arabia regions are usually related to thunder storm activities (McNaughton, 1987).

2.3. Remote correlation between sand-dust storms in the Hexi Corridor of West Gansu Province and sea temperature of the Central and East Pacific Ocean

Shang Kezheng, et al (1998) studied the tele-connections between sand-dust storms in the Hexi Corridor of West Gansu and ocean temperatures in the middle of the Equator and the Eastern Pacific Ocean, and their analysis shows:

1) The number of sand-dust storms in the Hexi Corridor in spring season correlates to the negative correlation of ocean temperature factors in the autumn and winter seasons of previous two years. Time factors too long ago or recent are fairly weak in correlation. This means that when the ocean temperatures in the middle and eastern parts of the Pacific Ocean in spring and autumn in certain years are higher (lower), the number of sand-dust storms threatening the Hexi Corridor will be partially fewer (frequent) in the spring two years later. The number of sand-dust storms in the Hexi Corridor in summer season correlates to ocean temperature factors in spring and summer seasons two years before. Namely, when the ocean temperature of the east Pacific Ocean in spring and summer in a certain year is higher (lower), the number of sand-dust storms in the Hexi Corridor will be partially fewer (frequent) in the summer season two years later.

2) In terms of each month during the spring season, the correlation between the number of sand-dust storms in the Hexi Corridor and the years' early ocean temperature factors in March is approximately identical. In April, it is rather well correlated to the negative correlation of ocean temperature factors two years' before. In May, it intervenes among spring and summer seasons.

3) By using the anomaly of ocean surface temperatures in the middle of the Equator and the eastern Pacific Ocean in early years and the given correlated prediction, the number of sand-dust storms in the Hexi Corridor in spring can be well forecasted.

In general, the occurrence and development of sand-dust storms is a consequence of joint functions under circumstances of specific topography, sand-dust sources and various scale weather conditions.

3. NUMERICAL VALUE OF SAND-DUST STORMS AND STUDIES ON SAND TRANSPORT

Sand-dust storms, particularly serious-strong sand-dust storms, are a consequence of interactions of macro-scale, meso-scale and micro-scale weather conditions, unusual topography and underlying surface conditions. In order to study physical mechanism of the formation of sand-dust storm, the numerical value simulation should be adopted as one of the important measures.

By using the meso-scale mode, Cautenet et al (1992) conducted numerical value simulation observations on impacts of heating power of sand-dust storms that originated from the Sahara Desert in Niamay, the capital of Niger. His result is satisfactory and the sand-dust contents and radiation characteristics in the atmosphere are the most significant parameters.

Slobldan (1996) has conducted a three-dimension space numerical value simulation on the distance transport of sand-dust that took place in July 1985 in the Western Mediterranean Sea. He is the first researcher that divided the sand-dust transport process into two phases, namely the shifting phase of sand-dust on land surface and the lifting-up phase of sand-dust by rapid current. In his observation, severe vertical mixture, flank diffusion, horizontal and perpendicular movement and the accumulation process of sand-dust in the atmosphere have been simulated and the result of sand-dust transport simulation is extraordinarily similar to satellite observation.

Shen Shaohua and Chen Shoujun (1993) studied, by utilizing two-dimension and three-dimension numerical value simulation respectively, the front-genesis process reinforced by sand-dust radiation and the impacts of isolated sand-dust radiation effectiveness on front circulation while sand-dust storms spread and develop. His research shows that the impact of sand-dust radiation on weather systems is very important. During the daytime, sand-dust radiation heating causes front-genesis at lower atmospheric strata and produces powerful a lifting-up movement. Due to the continuous heating of sand-dust, an instability consequently appears in the middle stratum of the atmosphere and the first rate entropy mixture layer is finally formed in the middle stratum of the atmosphere. The horizontal speed following the front movement direction is characterized by significant convergence (divergence). The high altitude torrent vertical to the front direction is weakened and the low altitude torrent is accelerated. During the nighttime, radiation cooling of sand-dust storms results in the disappearance of the front at low atmospheric strata. The vertical speed field is mainly a sinking movement and the horizontal speed field also takes place to corresponding changes.

Isolated radiation heating (cooling) of sand-dust storms forces a significant perpendicular circle along the large-scale prevailing wind direction at an approximated height of 1,000 metres. In daytime, this perpendicular circulation circle is very thick and the lifting-up branch is comparatively strong while the sinking branch is fairly weak. In nighttime, the perpendicular circulation circle reverses and thins. There is obviously an existence of horizontal shearing change around the sand-dust spreading area and it accelerates horizontal change and convergence of rapid currents. The response of horizontal wind fields to sand-dust radiation is different at different heights. Cheng Lingsheng and Ma Yan (1996) conducted a meso-scale numerical value simulation on the root causes and sand transport of the black sandstorm that occurred on May 5th 1993 in Northwest China. Their research shows that the two-dimension numerical value mode simulated the lifting-up blowout and horizontal transport. The three-dimension numerical value mode simulated the horizontal and vertical distributions of sand-dust and the simulation result on low pressure and high pressure ridges ahead and behind the cold front is better.

Cheng Lingsheng and Ma Yan (1996), by improved MM4 and high resolution Planet Boundary Layer (PBL) parameters and a 40 km fine net control experiment, basically simulated the structure and variation of the Black sandstorm on May 5th 1993. Simulation results show that the black sandstorm is concomitant to the strong vortex of the meso-scale inside the PBL at its beginning stage of development. It is concomitant to vertical eddy-pillar inside the convection stratum. The lower (upper) part of the eddy-pillar extending to the convection top stratum is a vortex eddy pillar (reverse vortex) that is concomitant to the strong convergence (divergence) inside (outside) flow at lower (high) altitudes.

Song Zhenxing and Cheng Linsheng (1997), by using meso-scale numerical simulation data of the Black Sandstorm on May 5th 1993, have conducted numerical diagnosis and analysis on the contribution of effective potential energy and wet stir energy in the process of the Black Sandstorm on May 5th 1993 on the basis of wet stir energy formulation of moist barocline atmosphere. The analysis shows that the huge amount of released effective potential energy of agitating wet energy inside the planet boundary layer (PBL) is the main source of energy brought about by rapid occurrence and development of the sand-dust storm on May 5th 1993. The emergence of the mentioned energy is not only related to the powerful vertical slash of the wind in the wet inclined atmosphere, but also related to the powerful heating and strong convection instability of the underlying surface inside the PBL. The agitating wet energy source decreases rapidly above the PBL and the agitating energy in the black sandstorm area is basically negative; namely it is the energy convergence.

Zhang Xiaoling, et al (1997) conducted diagnosis and analysis of the vortex origin causing the occurrence and development of the meso-scale whirlpool during the black sandstorm weather on May 5th 1993 by utilizing MM4 high-resolution data. The results of the diagnosis and analysis indicate that the development of the black sandstorm on May 5th 1993 was directly related to the occurrence and development of the meso-scale air vortex eddy. The occurrence, development and formation and variation of the vertical pillar structure coincide with the vertical structure and variation of the meso-scale vortex formation. It was concluded that the dynamic mechanism of such rapid development of the meso-scale vortex is determined by total vortex origin. The classification of total vortex sources of the atmosphere shows that the agitating vortex that is related to powerful wave agitating air current makes the biggest contribution to the total vortex sources. The contribution of the non-linear interacted vortex between large-scale and meso-scale systems is second biggest. The contribution of the time average vortex related to topographic compelling is the minimum.

Chen Weimin, et al (1996) simulated, by utilizing the improved PSU/NCAR meso-scale numerical value mode (MM4 Standard edition), the variation and distribution of sea-plane air pressure during processes of large-scale suspension floating dust and sandstorm weather that occurred from 5^{th} to 11^{th} April 1994 in Northwest China. Normal observation data was applied at the initial stage. Special attention was paid to the meso-scale low pressure in Zhangye and Dunhuang of the Hexi Corridor in Western Gansu and the Qaidam Basin in Qinghai. At the same time, the strong eastern wind in the Hexi Corridor of Western Gansu prevails among the Zhangye middle-low pressure, and the Mongolian cold high pressure has also been simulated. The result of the sensitive experiment shows that dry physical processes of the atmosphere mainly restrict the formation and development of middle-low pressure of sand-dust storms. Yet the heating power, dynamic process and compelling outside source of unusual topography play important roles.

Genthon (1992) studied the characteristics of desert sandstorms and aerosol of the ocean salt of Antarctica by using the atmospheric circulation mode. His research indicates that the quotation of parameterization programmes of simple aerosol into climatic forecast modes gained solution from the observation value of desert sandstorms and ocean salt of the Antarctic, reflecting the interaction between climate and aerosol in the past and at present. The most interesting result is that the vertical structure of aerosol distribution is a very important parameter of the numerical value simulation and the stability of the planet boundary layer greatly affects the vertical distribution of closer-ground aerosol.

The aerosol of sand-dust storms that emerged during the process of sand-dust storm weather can be transported to remote regions through atmospheric circulation and bring about impacts on the weather and climate there. Iwasaka, et al (1979) carried out research on the process of sandstorms that occurred on April 14-15^{th} 1979 in Northwest China. Their results indicated that the horizontal scope of sand-dust clouds was approximately 1.36×10^6 km^2 and the total quantity of sand-dust particles was at least $1.63x10^6$ tonnes. Results of radar observations showed that the sand-dust clouds were composed of two layers, with the upper layer of the cloud being 6 km and bottom layer being 2 km. Analysis of locus of sand-dust clouds demonstrated that the upper layer of the sand-dust cloud originated from the Taklimakan Sand Desert of China and the bottom layer sand-dust cloud originated from the Gobi Desert and the Yellow River valley in Northwest China. These facts show that sand-dust weather processes in Northwest China have an important impact on the weather and climate in Japan.

The Sahara Desert and its adjacent arid zones are the one of the four sand-dust areas in the world. Sand-dust storms that originated from the Sahara and its neighbouring arid areas can be transported to the American Continent via the Atlantic Ocean by tropical eastern wind air currents. According to Swap's (1992) research, the sand-dust of the Sahara Desert was transported to the Amazon Plain of Brazil and approximately 4.8×10^5 tonnes of dust particles was brought to the northeastern part of the Amazon Plain during a one time sand-dust storm that occurred in the Sahara Desert. The annual transport and accumulation was 1.3×10^7 tonnes, namely 190 kg of dust particles accumulated annually on one ha of land. Through analysis of aluminum in 4 μ aerosol in Barbados in Latin America, Ellis Jr. et al (1995) concluded that 55% of aluminum particle samples originated from North Africa. Franzen, et al (1995) made analyzed sand-dust storm processes that occurred in central and southern Europe and the north of Scandinavia in March 1991, which originated from the Sahara Desert, and they concluded that the sand-dust of the Sahara Desert was transported and accumulated in the northern region of Germany. The affected area of the sand-dust storm process of this sand-dust storm in March 1991 was at least 3.2×105 km^2 and dust accumulation in the above-mentioned region was estimated to be as much as 5.0×10^4.

4. STUDY OF STRATEGIES AND PROJECT ARRANGEMENTS FOR PREVENTING AND REDUCING SAND-DUST STORM DISASTERS

Sand-dust storms, particularly when developed into black sandstorms, are hazardous weather events with serious calamity and bring about critical harm to local people's life, property and agricultural and industrial productions. Sandstorms accelerate the desertification process in affected regions. Although the occurrence and development of sand-dust storms cannot be completely controlled through human ability at the moment, as long as further studies and efforts are conducted to explore objective regularity of the occurrence and development of sand-dust storms, the casualty and economic loss caused by sand-dust storms, particularly the black sandstorms, can be reduced to a minimum extent, by utilizing appropriate modern science and technology and by popularizing valuable experience and know-how to fight against desertification and sand-dust storms, through researchers and people working in the field combating the issues. In recent years, relevant research has been carried out in China (Xia Xuncheng, et al, 1996), as follows (*see also Chapter 14*).

4.1. Study on emergency protection measures of human life property

Sand-dust storms particularly black sandstorms, move violently along with strong roaring winds and suffocating dust-laden blasts. Black sandstorms darken the sky and conceal the sun while yellow sand blows and devil winds sweep across the area. Sandstorms are a terrible disaster easily causing injuries, deaths and property loss. Relevant studies have raised some effective measures for preventing children from dropping into water bodies, avoiding broken walls and collapsed cliff, safeguarding domestic fowl and animals, cutting off electricity supplies and controlling fires.

4.2. Withdrawing crop cultivation for revegetation and other eco-environment improvement projects

In light of the implementation of the China Western Region Development Strategy and Acceleration of Central-Western Region Progress, the central government of China, from 2000, is going to facilitate Ten New National Projects in the China Western Region. Among the total, the National Project for Withdrawing Dry Farming for Revegetating Forest and Grasses and Ecology Restoration in the Central-Western Region is one of the ten initiative arrangements. It is planned that, from 2000, demonstrations and pilot interventions for withdrawing dry farming to restore forest and grasses are arranged in the Yunnan and Sichuan provinces at the upper reach of the Yangtze River and Shaanxi, Gansu and more than 10 other provinces in the middle and upper reaches of the Yellow River. The target of the plan is to withdraw 343,000 ha of dry farming land and to plant 432,000 ha of forest and grasses through artificial means. This initiative will play an important role in controlling the occurrence, the development and calamity of sand-dust storms on a large scale.

4.3. Study on the establishment of protective oasis shelterbelts

According to the actuality of the situation in Northern (especially in Northwest China), the following protective networks and green tree belts have been implemented.

1) Sandbreaks and grass-shrub kulun for preventing natural psammophyte from destruction at the oasis fringes, for instance the *"Three North Regions Shelterbelts Construction Project"* since the late 1970s.

2) Enclosure of degraded land and protection of natural desert forests to control the occurrence and development of sand-dust storms.
3) Establishment of windbreaks and sandbreaks around oasis to control and reduce shifting sand disasters and threats of black sandstorms.
4) Adoption of engineering approaches to stabilize shifting sands and revegetate mobile dunes at the oasis fringe.
5) Plantation of protective farmland shelterbelts at the marginal areas and oasis edges to avoid soil erosion of sandy land surface and preventing farmland from blowing-out sand-dust storms. Such plantations can partly improve the microclimate of the protected farmland.
6) Popularization of optimum agricultural cultivation skills to prevent or reduce the extent of wind erosion and sand accumulation. For instance, adoption of soil transformation, reinforcement of the roughness of land surfaces to reduce denudation and optimum introduction of varieties and inter-cropping systems.

4.4. Wind-sand control in arid and semi-arid zones in the north part of the Loess Plateau

The arid and semi-arid zones in the northern part of the Loess Plateau are characterized by extremely abundant material sources for causing sand-dust storms. Furthermore, most land surface is exposed to frequent prevailing winds and human disruption in the long winter months. The sand-dust storm calamity is critical and wind-sand impacts are serious in the mentioned loess plateau. In respect to these severe conditions, the following measures have been taken in recent years.

1) Measures for controlling wind erosion were adopted in the dry-farming areas where excessive reclamation of wasteland and mismanagement of drylands have been practiced during the 1950s to the 1970s. For instance, crop residues were kept on the land surface after harvest to reduce soil erosion and bush-shrub seedlings were re-planted to decrease wind blowout and denudation. An effective measure has been formulated to withdraw dry farming and revegetate degraded lands in dryland areas.

2) Rejection of wasteland opening-up and rotation cropping were encouraged while practicing enclosure and protection of fodder-farm/steppe/rangeland and rational grazing systems or optimum carrying capacity. Promotion of rangeland management, animal husbandry development and rotation fence installation constituted a series of effective measures improving natural steppe vegetation. Vegetative cover in the mentioned loess plateau has increased and the potential dynamics to control wind and sand disasters has been strengthened.

4.5. Preventive approach for stabilizing shifting sands by plantation in inter-dune areas

In the inter-dune or lower-lying areas, artificial plantation of seedling trees and shrubs was done directly on mobile dunes. Man-made vertical wheat straw barriers were planted on shifting sands and then as a second step, psammophyte was transplanted on the straw checkerboards and air seeding was initiated to sow sand-holding varieties. This approach has effectively reduced the acceleration of desertification and turned mobile dunes into fixed sand mounds.

4.6. Control of sand disasters along traffic lines and adjacent industry and mining facilities

In Northwest China, mining fields, communication and transportation facilities, newly emerging rural and urban towns, water resources and hydro-stations, electric power, petroleum and gas exploitation are impacted by hazards and threats of sand-dust storms, particularly the damages caused by the serious sand-dust storms or black sandstorms. In recent decades, some successful research and technical engineering efforts have been conducted in many sections along railway lines in Northwest China and these efforts have not only guaranteed unblocked operation of the railway, but have also limited the occurrence and development of local sandstorms. Both economic and eco-environmental benefits are satisfied.

5. CONCLUSION

Research efforts on sand-dust storms over the last five decades, done on many aspects and in various countries, have gained a series of valuable results. These results have served decision-makers and governmental agencies as important scientific evidence for formulating policies and determining measures to control the issues of sand-dust storms and land desertification. These results set a substantial foundation for further studies on the issues in the future. However, along with the continuous rapid growth of human population and the intensification of global change, the contradiction between limited resources (especially water resources) and environmental conditions and the fast increase of human requirements becomes outstanding day by day. The natural eco-environmental situation in certain regions will gradually worsen if more effective efforts and approaches are not adopted as soon as possible. It is estimated that the occurrence and development of sand-dust storms will be more frequent than in previous decades in the world's dryland regions. As a consequence, the possibility of intense sand-dust storms will be crucial, the threatening scale will be widened and issues that need to be studied will be more complicated. The research on sand-dust storms is yet facing challenges and long-term efforts are needed for future strategy.

6. REFERENCES

Ackerman, Steven A. and Hyosang Chung. 1992, Radiative Effects of Airborne Dust on Regional Energy Budgets at the Top of the Atmosphere. *J. Appl. Meteor.*, 223-233.

Cautenet, G., et al. 1992, Thermal Impact of Saharan Dust over Land. Part I: Simulation. *J. Appl. Meteor.*, 166-180.

Chen Min-lian, Guo Qing-tai, Xu Jian-fen, et al. 1993, Research and Discussion on the Black Storm. *Journal of Gansu Meteorology*, 11 (3): 16-27.

Chen Wei-min, Wang Qiang, Niu Zhi-min, et al. 1996, The Numerical Simulation of Meso-scale Lower Pressure of "4.5" Dust Storm in Northwest China. *Journal of Desert Research*, 16 (2): 140-144.

Cheng Lin-sheng, Ma Yan. 1996 Numerical Experiments of Developing Construction and Different Model's Resolution on the "93.5" Black Storm. *Quarterly Journal of Applied Meteorology*, 7 (4): 386-395.

Ellis JR, W.G. and J. T. Merrill. 1995, Trajectories for Saharan Dust Transported to Barbados Using Stokes' Law to Describe Gravitational Settling. *Journal of Applied Meteorology*, 34: 1,716-1,726.

Franzen, L. G. et al. 1995, The Saharan dust episode of South and Central Europe, and northern Scandinavia March. 1991. *Weather*, 50 (9): 313-318.

Fu You-zhi, Liu Kun-xun, Ding Rong, et al. 1994, The Causative Factors and Forecasting of the Black Storm in Hexi Corridor. *Journal of Meteorology*, 20 (12): 50-53.

Genthon, C. 1992, Simulations of desert dust and sea-salt aerosols in Antarctica with a general circulation model of the atmosphere. *Tellus*, 44B, 4: 371-389.

He Hui-xia, Qian Zheng-an, Qu Zhang. 1993, Example Registers of Partly Strong Sand-dust Storms in Northwest China. *Journal of Atmospheric Information*, 30 (4): 14-18.

Hu Yin-qiao, Yasushi Mitsuta. 1996, Development of the Strong Dust Storm and Dry Squall Line – A Mechanism Analysis on Generating Black Storm. *Plateau Meteorology*, 15 (2): 178-185.

Iwasaka, Y. et al. 1983, The transport and spatial scale of Asian dust storm Clouds: a case study of the dust-storm event of April 1979. *Tellus*, 35B, 3: 189-196.

Jauregui E. 1989, *The dust storms of Mexico City*. Inter. J. Climatol, 9 (2): 169-180.

Jiang Ji-xi, Xiang Xu-kang, et al. 1997, *A Study on the Short-range forecasting Method for Strong Sandstorm Taking Satellite Cloudness Imagery Data as the Dominant Factor.* Studies on Sand-dust Storms in China. Press of Meteorology.

Jiang Ji-xi. 1995, A Study of Formation for "Black Storm" Using GMS-4 Imagery. *Quarterly Journal of Applied Meteorology*, 6 (2): 177-184.

Joseph, P.V., Raipal, D.K. and Deka, S.N. 1980, "Andhi," the convective dust storms of Northwest India. *Mausam*, 31, 431-442.

Legrand, M. et al. 1988, Satellite Detection of Saharan Dust: Optimized Imaging during Nighttime. *Journal of Climate*, 1 (3): 256-264.

Liu Jing-tao, Zheng Ming-qian. 1998, The Climatic Characteristics of Black Storm in the Northern Part of North China. *Journal of Meteorology*, 24 (2): 39-44.

McNaughton, D. L. 1987, Possible connection between anomalous anticyclones and sandstorms. *Weather*, 42 (1): 8-13.

Pauley, Patricia M., Baker, Nancy L. and Barker, Edward H. 1996, *An Observational Study of the "Interstate 5" Dust Storm Case*; Bulletin of the American Meteorological Society, 77 (4), 693-720.

Qian Zheng-an, He Hui-xia, Qu Zhang, et al. 1997, Classified Standard, Example Registers and Statistical Characteristics of Sand-dust Storms in Northwest China. *Studies on Sand-dust Storms in China*. Press of Meteorology.

Qiu Jin-heng, Sun Jin-hui. 1994, Optically Remote Sensing of the Dust Storm and Result Analysis. *Scientia Atmospherica Sinica*, 18 (1): 1-10.

Qu Zhang, Xu Bao-yu, He Hui-xia. 1994, Some Enlightenment from A Sandstorm Occurred in Northwest China. *Arid land geography*, 17 (1): 63-67.

Shang Ke-zheng, Sun Li-hui, Wang Shi-gong, et al. 1998, The Tele-connections of Sand-dust Storms over Hexi Corridor in Gansu Province and Sea Surface Temperature in Area of Middle and Eastern Pacific Ocean near Equator. *Journal of Desert Research*, 18 (3): 239-243.

Shen Shao-hua, Chen Shou-jun. 1993, The Analysis of Fronto-genesis Process Forced by Dust Radiative Heating. *Acta Meteorologica Sinica*, 51 (4): 425-433.

Shen Shao-hua, Chen Shou-jun. 1993, The Numerical Simulation of Fronto-genesis Process Forced by Dust Radiative Heating. *Acta Meteorologica Sinica*, 51 (3): 283-294.

Slobldan N., Srdjan. 1996, A Model for Long-Range Transport of Desert Dust. *Monthly Weather Review*, 2,537-2,544.

Song Zhen-xin, Cheng Lin-sheng. 1997, Diagnostic Analysis of the Perturbation Sources on the "93.5" Black Storm. *Journal of Lanzhou University*, 33 (4): 116-122.

Swap, R. et al. 1992, Saharan dust in the Amazon Basin. *Tellus*, 44B, 2: 133-149.

Tanaka, Toyoaki. 1974, Ice-crystallization process of cloud, Ice crystal core, *Journal of Meteorology*, (122): 689-737.

Wang Shi-gong, Dong Guang-rong, Yang De-bao, et al. 1996, A Study on Sandstorms over the Desert Region in North China. *Journal of Natural Disasters*, 5 (2): 86-94.

Wang Shi-gong, Yang De-bao, Jin Jiong et al. 1995, Study on the Formative Causes and Countermeasures of the Catastrophic Sandstorm Occurred in Northwest China. *Journal of Desert Research*, 15 (1): 19-30.

Wang Shi-gong, Yang De-bao, Jin Jiong, et al. 1995, Analyses of Time-space Distribution and Formative causes of Sandstorms Occurred in Northwest China. The Proceeding of the Second Academic Conference of Young Scientists of Chinese Association for Science and Technology. *Press of Sciences and Technology of China*, 364-370.

Wang Shi-gong, Yang De-bao, Meng Mei-zhi, et al. 1993, Analyses of Structure Characteristics and Formative Causes of the "5.5" Black Storm. *Journal of Gansu Me*teorology, 11(3): 28-31.

Wang Shi-gong, Yang De-bao, Zhou Yu-su, et al. 1995, Analysis on the Formative Causes of Sand-dust Storms in the Northwest China during 3-12 April 1994. *Journal of Desert Research*, 15 (4): 332-338.

Wei Li, Wen June, Shen Zhi-bao. 1998, The Radiative Characteristics of Atmospheric Dust Observed from Satellite. *Plateau Meteorology*, 17 (4): 347-355.

Wolfson, N. and Matson, M. 1986, Satellite observations of a phantom in the desert. *Weather*, 41 (2): 57-60.

Xia Xun-cheng, Yang Gen-sheng, et al. 1996, Disasters of Sand-dust Storms and Their Prevention and Control in Northwest China. *Press of Environmental Sciences of China, Beijing*.

Xu Guo-chang, et al. 1979, Analysis of the "4.22" Much Stronger Sand-dust Storm in Gansu Province. *Acta Meteorologica Sinica*, 37 (4): 26-35.

Xu Xi-hui. 1997, Analysis and Study on Cloudiness Feature of Sandstorms over Talimu Basin. Studies on Sand-dust Storms in China. *Press of Meteorology*.

Yan Hong. 1993, A Nationwide Meeting Summary of Discussing Sand-dust Storm Weathers Occurred in China. *Journal of Gansu Meteorology*, 11 (3): 6-11.

Yang Dongzhen et al. 1991, A case study on Sandstorm. *Acta Meteorologica Sinica*, 5 (2): 150-155.

Yang Dong-zhen, Wang Chao, Wen Yu-pu, et al. 1995, An Analysis of Two Sandstorms in Spring 1990. *Quarterly Journal of Applied Meteorology*, 6 (1): 18-26.

Zhang Xiao-ling, Cheng Lin-sheng. 1997, Diagnosis of Vorticity Source for the Genesis and Development of Meso-scale Vortex during "93.5" Black Storm. *Journal of Lanzhou University*, 33 (4): 123-131.

Zhao Xing-liang. 1993, Damages and Countermeasures of Catastrophic Sandstorm Occurred in Gansu Province. *Journal of Desert Research*, 13 (3): 1-7.

Zheng Xin-jiang, Liu Cheng, Cui Xiao-ping, et al. 1995, Cloudiness Features of Two Kinds of Dust Devil weather in China. *Journal of Met*eorology, 21 (2): 27-31.

Chapter Three

BLACK WINDSTORM IN NORTHWEST CHINA: A CASE STUDY OF THE STRONG SAND-DUST STORM ON MAY 5TH 1993

Yang Gengsheng, Xiao Honglang and Tuo Wanquan *Translated by Yang Youlin*
Cold and Arid Regions Environmental and Engineering Research Institute
Chinese Academy of Sciences

Key words: Black sandstorm, Beaufort scale, wind, atmospheric pressure, weather patterns, monsoon, drought, climate change, hazards, root causes, wind tunnel, geomorphology, convection, erosion

SYNOPSIS

China is one of the countries where calamitous sand-dust storms are on the increase. The link between widespread desertification and the increase in the frequency and severity of dust storms has prompted more study of the causes and mechanics of such wind-related events. Of necessity it requires an inter-disciplinary approach because meteorologists, geomorphologists, ecologists and soil scientists need to work together.

A major sand-dust storm on May 5th 1993 caused serious economic loss and was as hazardous as a disaster caused by an earthquake. According to ground observation and investigation made by the expert group of the Ministry of Forestry, a total of 85 people died, 31 people were lost and 264 people were injured (most of these victims were children). Agriculture and animal husbandry were mostly severely hurt. In total 373,000 ha of crops were destroyed. 16,300 ha of fruit trees were damaged. Thousands of greenhouses and plastic mulching sheds were broken. 120,000 heads of animals died or were irrecoverably lost. The fundamental agricultural installations and grassland service facilities were ruined. More than 1,000 km of irrigation channels was buried by sand accumulation. Many water resource back-up facilities, such as reservoirs, dams, catchments, underground canals and flood control installations were filled up with sand silts. About 6,021 communication poles and electricity grids were pushed down and electricity transports and communication services in some regions were stopped for several days. Some sections of railway and highway were interrupted due to deflation and sand accumulation.

This chapter describes in detail 1) the time, location and characteristics of the sand-dust storm on May 5th 1993 (hereafter called the 5.5 Sand-dust storm); 2) evaluation of hazards and economic loss caused by the 5.5 sand-dust storm; 3) analysis of the root causes of sand-dust storms and its processes; 4) and the present situation in the affected regions.

KEY POINTS

1. *China, especially northwest China, is one of world's regions most susceptible to widespread and disastrous sand-dust storms. There are reasons for this, many of them due to the natural conditions (climate, topography, soils and vegetation) but there are also strong influences from human activities.*
2. *Analysis of the sand-dust storm on May 5th 1993 tells us a lot about the mechanics and dynamics of such a wind-related event and of the consequences for human life and property as well as for the ecosystem.*
3. *The root causes are complex and involve an interaction between natural factors, weather, climate, geomorphology, edaphics and vegetation and the impacts of human use under high population pressure and unbridled economic development in an era when potential environmental consequences were disregarded in favour of economic advancement.*

1. FACTS ABOUT THE 5.5 SAND-DUST STORM

On May 5th 1993 (hereinafter referred to as the 5.5. storm), a strong sand-dust storm of an intensity seldom seen in history occurred in Northwest China. This sand-dust storm (of a type called *"Black windstorm"*) brought about violent terror and extreme destruction and caused disastrous loss to people's life and property. All walks of life in China paid great attention to this calamity.

1.1. Space-time characteristics

The 5.5 sand-dust storm originated from the northern part of Xinjiang and gradually died out in the eastern part of Ningxia. It swept across Urumqi, Turpan, Hami of Xinjiang Uygur Autonomous Region, Jiuquan, Zhangye, Jinchang, Wuwei, Gulang, Jingtai in Gansu Province, Ejina, Alxa Youqi, Baiyanhot, Dengkou, Jailantai, Wuhai of Inner Mongolia, and Zhongwei, Qingtongxia, Huinong, Taole, Yinchuan in Ningxia Hui Autonomous Region. In total, 72 counties and cities in 4 provinces and autonomous regions were engulfed. About 1.1 million km² of land was directly affected which covers 11.5% of the total land territory of China and 12 million people were threatened.

The 5.5 sand-dust storm started at 20:00 hrs on May 3rd 1993 along with the southward cold air from Siberia. At 20:00 hrs on May 4th, strong winds of 20 m/s prevailed in the north of Xinjiang and a sand-dust storm was initiated at the periphery of the Gurban Tonggut Desert, in the northwest part of Urumqi. The weather charts of sky and ground at 08:00 hrs on May 5th indicated that the ground peak of the sand-dust storm moved eastward to Dunhuang, the western part of Jiuquan and, at the same time, just behind the storm peak, a 20-24 m/s wind weather appeared and developed in nearby Hami of eastern Xinjiang and along the Mazongshan Mountain of western Gansu, that moved southeastward. At 13:52 hrs on May 5th, strong winds had swept across Gaotai of western Gansu with a maximum velocity of 25 m/s and yellow winds prevailed and the sky became dark and visibility worsened. At 14:16 hrs on May 5th, the yellow storm had moved to Lingze and arrived in Zhangye at 14:19 and caused great damage in Minle at 14:25 where a serious sand-dust storm occurred.

At 15:42 hrs on May 5th, a strong sand-dust storm formed with maximum wind velocity of 34 m/s at force 12 (Beaufort scale). In a very short period of time, yellow sands blocked up the sky and the entire world was hazy. Heavy thunder exploded in air and dust cloud peaks rose to the atmosphere. Daylight was dim. Cloud colour varied from grey to red to black and visibility at ground level was near zero. The dust clouds moved quickly and overwhelmed everything in their path. By 16:40 hrs on May 5th, a strong sand-dust storm had reached Wuwei, Gulang by 17:00 hrs and swept across Jintai by 17:50 hrs. At 19:26 hrs, the storm landed in Zhongwei, in Ningxia and arrived in Taole (eastern Ningxia) at 20:02 hrs. Altogether, the strong storm travelled for 4 hours and 57 minutes from Gaotai in Western Gansu to Zhongwei in Ningxia. It finally died out in Taole and Huinong of Ningxia at 3:12 hrs and 9:37 hrs respectively on May 6th.

1.2. Characteristics of the form of the storm

Before the sand-dust storm passed through the territory, a grey-dark sand-dust wall appeared on the horizon; it came over quickly (*Photo 1*). On the flank side, it can be seen that the heavy and cold air inserted under the light and warm air in the shape of a wedge. The front peak of the cold air pillar with thick sand-dust near the ground surface was thin and the rear peak was deep and thick (*Figure 1a*). When it moved forward, due to the friction function of the ground surface, the front edge of the cold air wedge did not connect directly to the ground as false line AM' N' shows. Instead, it turns over to pull behind in a *"Nose"* BAMN form. It is called a cold air nose. The nose bottom (A) was at least 40 metres from the ground surface. It can be seen from the obverse side (*Figure 1b*) that the visible part that can be seen is the CD part of the cold air nose. It is just a small part of the forward-moving arc of cold air at the nose. From E and F points at the left and right sides, up to the G and H points, down to M and N points, a dense rim of sand-dust storm and its interior tumble becomes gradually unclear. For instance, the dark and light uneven layers of G and H above B can be identified, but the interior sand-dust tumbles (particularly point H) cannot be recognized. This unclear part is the part of the cold air nose that slopes backward in a far distance and corresponds respectively to points G and H in *map 1a*. Similarly, the alphabet letters in *map 1a* and *map 1b* correspond to each other.

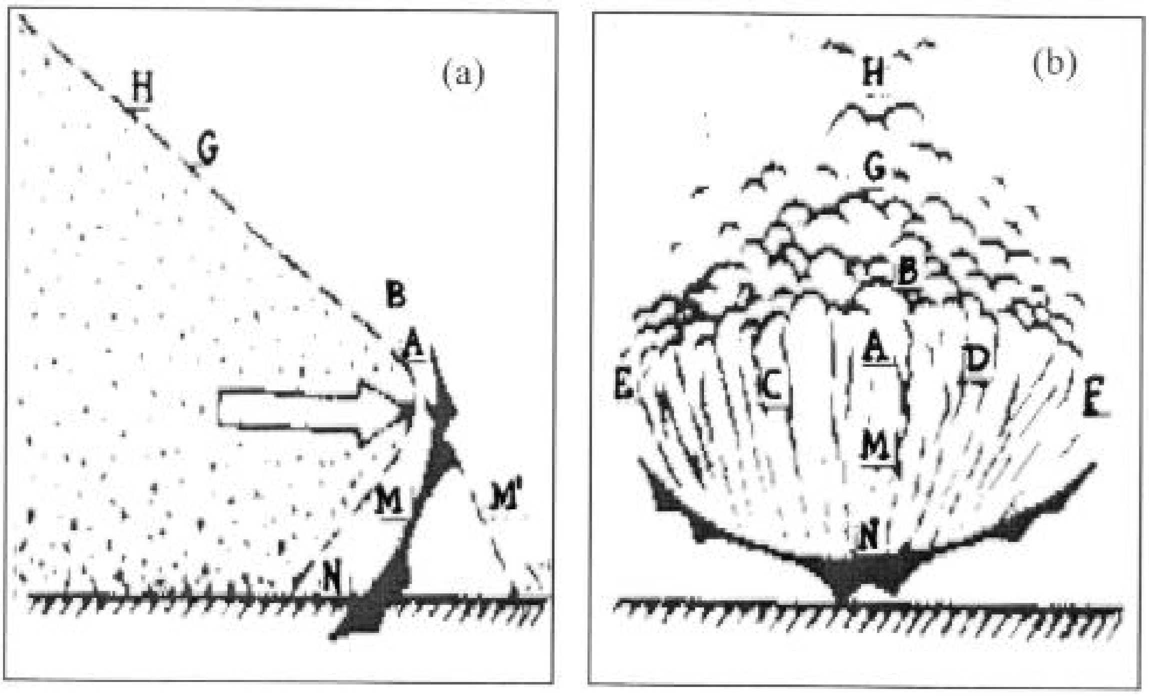


Figure 1: Sketch from a video capture of the side vision (a) and front-vision of sandstorm peak (b)

1.3. Characteristics of convection

The sand-dust wall was clearly 300 metres high and, in fact, the thick sand-dust peak was much higher. According to the analysis of dust accumulation on the long-standing snow on Wushaoling Mountain, it is estimated that the thick sand-dust peak was 700 metres. However, this sand-dust was already reduced when it crept to the Wushaoling Mountain. It was roughly estimated that the height of the peak in the serious section of Jinchang was more than 1,000 metres. In fact, it was calculated that, according to the brightness temperature of the thick peak on satellite images, the height was about 2,200 metres.

Before the arrival of the sand-dust storm, the near-ground air was unstable and sand-dust clouds inside the sand-dust wall rolled and turned over in waves. Along with the occurrence of this sand-dust storm, strong winds and thunder were observed in many regions and this indicates that, like hail and thunderstorms, the sand-dust storm belongs to convection weather.

1.4. Characteristics of optical phenomena

A sand-dust wall is composed of three strata. The upper stratum was yellowish and reddish, the bottom stratum was black in colour and the middle stratum was grey-black in colour. It was bright sometimes and dark at other times and metamorphosed in an unpredictable way. This is a normal optical phenomenon of sudden attenuation of sunshine as it cuts through uneven thick sand-dust walls (*see Chapter 2*).

When sun light goes straight through the atmospheric stratum, a series of changes of light reflection, absorption and scattering will occur as sunlight passes across cloud layers, and encounters suspended water drops and dust particles. As a consequence, disseminating direction of sunlight will be changed and sunlight intensity will be reduced. When the weather is clear without clouds, the sky is blue. When the weather is dusty, the sunlight will not only be significantly reduced because of absorption of dust particles and the colour of the sky becomes dark, but there is also more red and orange light. Light will be scattered as sunlight cuts through the thick dust peak and the colour of the sky becomes red. The time-space distribution of the thick dust peak is uneven and as a consequence, the thinness and thickness and density of the dust peak determine the distinct brightness and change of colour of the sky.

2. HAZARDS OF THE 5.5 SAND-DUST STORM

2.1. Forms of hazards

The 5.5 sand-dust storm was a highly destructive disaster. Everywhere it swept across, traffic lines and communication were blocked, water and electricity facilities were paralyzed, settlements and houses collapsed, grazing lands and farmlands were invaded with sand accumulation. It even led to death and loss of personnel. In addition, it resulted in atmospheric pollution and caused impacts to the ecological environment outside China's borders (including the Pacific Ocean near Hawaii).

2.1.1. Sand accumulation

Under the driving force of strong winds, sand particles under the lower stratum of the sand-dust peak roll forward. When the wind force became weaker or sand materials collided with an obstruction, a great amount of sand accumulated on the surface and buried farmland, attacked villages, mining sites, railways and highways, and water supplies. This form of disaster appeared especially at the periphery of oases and gobi[5] areas. It also happened in sandy desert or in the newly cultivated area at the desert periphery, or in the sand and gravel gobi area where human disturbance associated with resources development is frequent and severe.

2.1.2. Wind erosion: deflation and abrasion

Wind erosion does not only blow away fine clay minerals and organic matter in the soil, but also brings about sand accumulation on topsoil and on abandoned cropland and thus enlarges the area of desertification.

During the process of soil erosion, blown sands cut seedlings of cereal crops or may even destroy whole crops. This disaster mostly takes place in open fields with widely spaced tree networks and on farms without shelterbelts. Particularly, on newly cultivated farmland outside shelterbelts, sandy surface soil is more easily eroded under strong wind conditions.

2.2. Strong wind attack

When sand-dust storm enters into artificial oases, particularly the tree-networked area, sand-dust is manifested in the form of suspended dust because sand movement on the ground surface has been arrested. Under this circumstance, sand-dust storm is in fact caused by strong wind attacks. Strong wind pulls out trees with their root system, pushes down walls, ruins houses, turns over moving trains, breaks communication facilities and destroys agricultural installations.

2.2.1. Atmospheric pollution

The 5.5 sand-dust storm not only brought about harm to local people, but its dust particles also caused serious impacts to adjacent regions. The 5.5 sand-dust storm that prevailed in the Hexi Corridor brought suspension dust to Lanzhou (hundreds of kms further east) where atmospheric air quality was severely polluted and all factory workshops and office buildings had to turn on their lights during the day. Air inside rooms was full of mud smell and irritated the nose. Whitewash dusts floated everywhere. Respiratory diseases were spread. Particularly, the tailings dust exhausted from the metallurgy industry caused heavy metal pollution as these particles were entrained and tranported.

[5] The term gobi refers to a stone-covered desert surface. The so-called Gobi desert in China is a vast expanse of such stoney desert but smaller areas of similar landform occur in scattered patches throughout NW China.

3. ECONOMIC LOSS

The 5.5 sand-dust storm caused serious economic loss that was as hazardous as a disaster caused by an earthquake. According to ground observation and investigation made by the expert group of the Ministry of Forestry, a total of 85 people died, 31 people were lost and 264 people were injured (most of these victims were children). Agriculture and animal husbandry were most severely hurt. In total 373,000 ha of crops were destroyed. 16,300 ha of fruit trees were damaged. Thousands of greenhouses and plastic mulching sheds were broken. 120,000 heads of animals were killed and lost. The fundamental agricultural installations and grassland service facilities were ruined. More than 1,000 km of irrigation channels was buried by sand accumulation. Many water resource back-up facilities, such as reserviors, dams, catchments, underground canals and flood control installations were filled up with sand silts. About 6,021 communication poles and electricity grids were pushed down and electricity distribution grids and communication services in some regions were stopped for several days. Some sections of railway and highway were interrupted due to deflation and sand accumulation.

The Lanzhou-Xinjiang Railway line was interrupted for 31 hours and the Wuhai-Jilantai Special Railway Line in Inner Mongolia was stopped for 4 days. About 37 freight trains were stopped or delayed. Approximately 28,000 tons of industry-use salt and nitre was blown away in Inner Mongolia, 4,412 houses were buried and numerous sheds and stalls for breeding animals collapsed. It is estimated that 560 million RMB Yuan (about USD $70 million) was lost. In addition, the sand-dust storm brought about a serious environmental crisis. In many regions, 10-30 cm of topsoil was deflated and soil fertility was reduced. At the desert periphery, sand dunes moved 1-8 metres forward and invaded into arable lands and grazing fields. The transport and movement of dust and sand during the storm increased the contents of dust in the air and polluted the atmosphere. For instance, in Jinchang in Gansu Province, the dust content in the air was as high as 1,016 mg/m^3, the dust content indoor was 86.7 mg/m^3, dust accumulation was 161-266 tons/ km^2 and these suspension dusts caused serious impacts to human health.

3.1. Calamity to traffic

The sand-dust storm brought about poor visibility and sand accumulation. It caused cessation of transport and even train derailments. For instance, the Lanzhou-Xinjiang Railway was interrupted for more than 30 hours. Similar disasters were caused to highways. Road bases were denuded and road surfaces were corroded and such damage weakened the performance of roads and the life of vehicles. The sand–dust storm produced severe threats to the aviation service, airports were closed and many air flights were delayed or cancelled due to its impact.

3.2. Disasters to agriculture and animal husbandry

In the areas adjacent to deserts, sandy land, gobi or in the oases[6] of deserts, because of the attack of the sand-dust storm, the land surface was violently destroyed. Near to the surface, strong wind erosion and sand movement occurred and crops were damaged and buried. Strong wind raised sand grains and dust particles, flower buds were blown off and melon and vegetable gardens were damaged. The 5.5 sand-dust storm, according to the statistics of Jinchang, Wuwei, Gulang, Jintai in Gansu provicne and Zhongwei in Ningxia Hui

[6] Oasis is a term used to describe irrigated agriculture on desert fringes. Sometimes these oases are an expanded version of a natural oasis but more commonly in China they were created in the last 50 years by diverting rivers and installing irrigation schemes.

Autonomous Region, destroyed 64,400 ha of farmland. The depth of erosion (soil loss) was about 10 cm and the maximum was 50 cm. The average loss of arable land due to wind erosion was 2,100 $metres^3$ per ha. Sand accumulation averaged 20 cm.

In the 5 counties mentioned above, about 750 power poles were pushed down and 22 km of electricity supply wires were cut, 89 sets of transformers and generators were damaged. Accumulated sands affected around 55 km of irrigation canals. About 20,000 ha of plastic mulching of cropping fields was blown away and 90,000 individual trees were pushed down during the 5.5 sand-dust storm.

3.3. Threats to industry production

The 5.5 sand-dust storm also damaged two electricity supply systems with a capacity of 35 kv and 6 kv of the Jinchuan Company of Jinchang. The main production assembly and some assisting networks were forced to stop production and the estimated direct economic loss was 83 million RMB Yuan (USD $10 million).

3.4. Loss of settlement

The 5.5 sand-dust storm flattened 4,412 houses and settlements in Jinchang, Wuwei, Gulang, Jintai in Gansu Province and Zhongwei in Ningxia Hui Autonomous Region.

3.5. Calamity to people's life and property

According to the statistics, 85 people were killed, 264 were injured and 31 lost during the 5.5 sand-dust storm. About 120,000 heads of animals died and were lost and 730,000 heads of animals were threatened by the sand-dust calamity.

4. PRESENT SITUATION IN THE AFFECTED REGIONS

After the 5.5 sand-dust storm, the Government of China attached great importance to the affected areas of the Hexi Corridor of Western Gansu and the sand-dust source area of Alxa of Western Inner Mongolia and a serious approach was adopted to reduce the severity of the calamity. Detailed efforts were made to study the mechanism of the formation of sand-dust storms and prediction and forecasting of such disasters (*see Part VI*). More attention was given to biological and engineering approaches. Policy and legal measures were adopted to control the expansion of land desertification. But because of the impact of La Nina events, strong cold flow and strong winds frequently occur in Northern China. Air temperature has obviously heightened, precipitation has declined, water resources became deficient and the ecology has further worsened. Since the late 1990s, the tendency of re-activation of sand-dust storm is increasing and particularly in 2000, the frequency of sand-dust storms has doubled up to the maximum record during the last five decades. From December 31st 2000 to January-April 2001, 9 sand-dust storms took place in the above mentioned regions. On 4 occasions there were threats to central northern China and the downstream regions of the Yangtze River. Sand-dust storms occur earlier in the spring and are more frequent than in any decade before and the whole nation now attaches great importance to the issue. The following are fundamental sources of sand-dust storms.

- **There are abundant sand-dust sources**. In Western Gansu and Western Inner Mongolia where sand-dust storms are frequent, there are more than 300,000 km^2 of sand deserts and gobi areas, more than 6,000 km^2 of dried up lacustrine basins, more than 500 km^2 of dried lakes and catchment, more than 1,000 km^2 of deflation, abrasion and denudation. All these landforms are the essential sources of sand-dust storms. In sand deserts, the silt content in sand material is generally 2-6% and the maximum is 10%. The silt content in gravel deserts or gobi desert is 16-35% and that in sandy loess is 20%. The dust-silt content in eroded land is as high as 80%. The silt content in dried up lacustrine sediments is more than 70% and fine particles in newly cultivated fields are more than 70%. Besides the natural landforms, artificial sediments, such as the tailing sands and dust coals are also a potential source of sand-dust storms.

- **Existing topography and landforms are conducive to sand-dust storms**. There are vast areas of gorges, inter-mountain corridors and plain landforms that are advantageous surface conditions to the sweep of strong cold air from the north.

- **Vegetative coverage is sparse and wind erosion is serious.** All the lakes in the mentioned regions are dried up, wetlands have declined and underground water tables have dropped. As a consequence, large areas of vegetation were degraded and/or withered and died and the land surface was exposed to serious deflation. The transitional zone at the desert periphery was interrupted and sand shifting and dune movement became active.

- **Water resources are mis-managed or irrationally used**. The deficiency of water reources downstream in inland rivers, the break of flow, the drying-up of lakes and the decline of underground water are the root causes of ecological deterioration.

Because of the above-mentioned causes, new sand-dust sources were enlarged in the affected regions and this is one of the reasons that frequency of sand-dust storms has increased. Since 1999, effective measures were adopted to slow down the frequency of sand-dust storms. For instance, a water-distributing plan of inland rivers was developed and water-saving techniques were extended to the upstream and middle reaches of inland rivers and a certain amount of inland-river water flow reached the downstream areas. But the water-use conflict downstream was only partially resolved. National and provincial nature preservations were established downstream to prevent the wetlands, lakes and desert plant communities along river course from degrading and withering. In some seriously degraded areas, ecological immigrants were appropriately moved out of the affected regions to allow revegetating the deteriorated lands. National projects to combat desertification and withdraw dryland farming for ecological restoration were financed and incorporated into the National Social and Economic Development Plan. Now the shed-feed breeding of livestock is actively encouraged to relieve pressure on the rangelands. It is planned that ecological deterioration will be controlled in near future.

5. ROOT CAUSES AND PROCESSES OF THE 5.5 SAND-DUST STORM

Sand-dust storms are a result of an interaction between the weather process and the land surface reactivation process. The weather processes include mainly the wind dynamic process and the thermal dynamic process. The surface reactivation and exposure process of sand material is composed climatically of drought and deficient rainfall and anthropologically of irrational activities, namely the mismanagement of water resources, over-cultivation, over-grazing and human-induced accumulation of wastes and tailings. The above-mentioned interactions caused the occurrence and development of the sand-dust storm.

5.1. Weather process

Wind and thermal dynamics are factors of the weather process favouring the formation of sand-dust storms. These two factors are the dynamic conditions to form sand-dust storms. Without these dynamic powers, sand-dust materials on land surfaces cannot be blown up into sky (entrained and transported, see Chapters 1 & 2).

5.2. Dynamic process of wind

Sand-dust cannot be blown up without wind: sand particles can move only under the condition of a certain wind force (*see Chapter 1*). When the wind reaches a threshold velocity, the sand-dust particles can break away and enter into movement. The threshold velocity is called sand-blowing wind. According to observations, when the wind velocity reaches 30 m/s, sand particles with a diameter of 0.5-1 mm can be blown up for several tens of cm high; sand particles of 0.125-0.25 mm can rise up to 20 cm high; fine sand dust of 0.05-0.005 mm can be blown up to 1.5 km; and very fine sand dust less than 0.005 mm can be lifted up to a height of 12 km.

The occurrence of sand-dust storms and serious wind denudation cause sand transport. Sand particles move in the form of creeping and saltation over a short distance. At the same time, fine dust materials can be lifted up into the atmosphere by vertical thermal convection and be transported for a long distance in a suspended form. Some samples of different locations have been tested in wind tunnels and sand-blowing rates under different wind velocities are listed in *Tables 1 – 3* below.

Table 1: Wind tunnel experiment of sand blowing rate on alluvial gobi desert in Jiuquan of Gansu Province

Wind velocity(m/s)	10	15	20	25	30.8
Sand blowing rate ($kg\cdot m^{-1}\cdot min^{-1}$)	0.0021	0.0388	0.0504	0.0866	0.1357

Table 2: Wind tunnel of sand blowing rate on alluvial-deluvial gobi in eastern Dunhuang of Gansu Province

Wind velocity (m/s)	7	15	20	25	32.15
Sand blowing rate ($kg\cdot m^{-1}\cdot min^{-1}$)	0.0020	0.0039	0.0113	0.0426	0.1124

Table 3: Wind tunnel experiment of blowing sand and suspension dust

Wind velocity (m/s)	7	15	20	25	32.15
Sand blowing rate ($kg\cdot m^{-1}\cdot min^{-1}$)	3,406.9740	13,534.8834	49,127.9070	112,558.139 4	178,708.444
Sand blowing rate ($kg\cdot m^{-1}\cdot a^{-1}$)	88.6382	519.7386	2,976.7963	4,896.6110	6,235.7202

Gales or strong winds cause sand-dust storms: the formation of strong winds or gales needs proper atmospheric circulation conditions. Meteorological studies show that there are two major types of atmospheric circulation conditions.

5.2.1 Invasive strong cold air

The half a year of winter season is the most active season of cold air mass in the Northern Hemisphere (polar region) and cold air enters into China from different regions in the southern parts of Xinjiang almost every 5-7 days (see below). Northwest China is the gateway of cold air entering into China. The cold air in the Northern Hemisphere often land on Northwest China through different paths from Iceland and the New World islands of the Arctic Ocean. On the upper air weather chart, strong cold air moves southward at a height of 5,500 metres and cold low troughs with minimum air temperatures of 30-40^0 in the sky above Xinjiang are deepened. Behind the trough, a strong northern wind with a velocity of 30-40 m/s forces the air southward.

On the surface chart, a central air pressure with a strong high pressure of 1,050 hpa can be seen in Siberia, or Central Asia, and East Europe. In its front, a northeast-southwest oriented cold front enters into the northern part of Xinjiang from the north-northwest and crosses over the Tianshan Mts and sweeps across eastward into the western part of Inner Mongolia and the Hexi Corridor and is funneled straight to Ningxia and the north of Shaanxi. This cold front moves rapidly with a speed of 70-80 km per hour and sometimes even reaches 100 km per hour. When the cold air sweeps across all exposed surfaces sandy surface materials will be deflated and blown up forming sand-dust storm. Beside the southward movement of cold air from the north, another path of cold air comes from central Asia and crosses over the Pamir Plateau and enters southern Xinjiang. Under these circumstances sand-dust storm weather will be formed along Karshi, Hetian, Ruoqiang and the Hexi Corridor of Gansu.

Sand-dust weather with strong cold air does not always occur after the cold front; it sometimes occurs before the cold front. Meteorologists found, through analysis and studies of the 5.5 sand-dust storm in the Hexi Corridor, that the unstable warm air was lifted up and developed into a series of juxtaposed belt-shaped rainy-clouds, because of the fast advance of strong cold air. When it is powerfully developed, strong sinking air currents behind the belt-shaped rainy clouds will bring the cold air at high altitudes down to the land surface and form dense cold air mass with high pressure under the rainy clouds. It is meteorologically called thunderstorm high pressure. A squall line of medium scale weather system from several kilometres to 100-200 km at the horizon level can occur at the joining point of thunderstorms and front warm air. Where it passes over, wind direction will turn over suddenly, wind force will increase, air pressure will rapidly heighten, temperature will decrease and sand-dust storms will appear as a companion of the thunderstorm. For instance, when the squall line passed through Jinchang on the afternoon of May 5th 1993, air pressure was raised by 3.1 hpa in ten minutes, temperature dropped down for 6.6^0 in two minutes and wind velocity accelerated to 22.7 m/s. The sand-dust storm in Jinchang first occurred under the impact of a squall line before the strong cold front and second occurrence and enhancement took place after the disappearence of the cold front.

5.2.2. Thermal surface depression before the cold front

In spring and early summer, thermal processes in the Southern Xinjiang basin heat land surfaces before the cold front arrives. Warm air rises in cyclonic convergence inside the basin and forms a thermal depression. The rising convergence air current can stretch to the mesosphere at 3,000 metres. At high altitudes, the upper air is full of divergence air current. When the horizontal divergence air current of the upper air exceeds the horizontal convergence air current of lower air, compensation function of air current will be promoted and this promotes the continuous development of a thermal depression at the ground surface.

When the thermal depression is developed in the Tarim Basin, west-oriented strong wind weather, or east oriented strong wind first and then the west oriented strong wind later, will prevail in Hetian that is just behind the thermal depression and in south part of Bayan Gol, Mongolia Autonomous Prefecture of Xinjiang, that is just in front of the thermal depression. When the thermal depression moves eastward close to the western part of the Hexi Corridor of Gansu, sandstorms will possibly occur in Jiuquan Prefecture of Gansu. Wind strength of the thermal depression is determined by the intensity of pressure gradients between the Mongolian High Pressure and the Tarim Thermal Depression. Wind in the centre of thermal depressions is strongest. The duration of a sand-dust storm is determined by the duration of the thermal depression and the transporting speed.

5.3. Thermal dynamic process

5.3.1. Stability of air is the decisive element in the occurrence of sand-dust storm

If the air in the lower stratum is stable, drifting sand-dust cannot be entrained and blown up too high. If the air at the low stratum is unstable, drifting sand-dust will be entrained and blown up high in the air stratum. The thermal dynamic process of weather systems is the element causing instability in air and up-down vertical movement of air. It entrains and blows up sand-dust materials on land surfaces into high altitude forming sand-dust storm weather and fine dust transport in the atmosphere.

In arid zones in Northwest China, strong winds prevail almost every winter and spring seasons, but the occurrence of sand-dust storms does not develop along with each wind. Statistics show that strong wind weather is more frequent than sand-dust storm weather in some regions and sand-dust storm weather is more frequent than strong wind weather in other regions (*Table 4*). It is apparent that the frequency of strong wind weather and sand-dust storm weather is related to thermal conditions or surface soil composition, or to both of the two elements. It can be seen from *Table 4* that sand-dust storm weather in Hetian, Zhangye, Minqin, Yulin and Yan'an is more frequent than strong wind weather, which is related to the abundance of sand materials in the aforementioned regions. In Kuche, Jiuquan, Wuwei and Yanchi regions, the number of days with strong wind is equal to that of sand-dust storms and this is related to both the ground sand materials and thermal conditions. In the other regions, frequency of strong wind is higher than sand-dust storm weather and is related to sand materials in the regions.

Table 4: Mean days of wind and sandstorm in March-June over the years in the Northwest China

Location	March		April		May		June		Total in Mar-Jun	
	Wind	S-storm	Wind	S-storm	Wind	S-sanc	Wind	S-storm	Wind	S-storm
Kwlamiyi	4.4	0.1	8.4	0.1	11.5	0.2	12.1	0.1	36.4	1.4
Turpan	1.1	0.8	4.2	3.2	6.3	1.8	9.1	0.7	20.7	6.5
Kuche	0.6	1.1	3.4	3.6	3.3	2.7	4.0	3.0	11.3	10.4
Karshi	1.0	1.1	3.5	2.1	5.0	3.2	5.8	2.6	15.3	9.0
Hetian	0.8	4.4	1.5	6.1	1.8	6.9	2.1	3.2	6.2	23.6
Ruoqiang	3.6	3.3	6.2	3.4	7.2	3.4	5.7	1.9	22.7	12.0
An'xi	8.7	3.3	9.7	1.6	9.0	1.3	6.7	0.9	34.1	7.1
Dingxin	4.0	2.3	5.5	3.2	5.1	2.4	4.9	2.5	19.5	10.4
Jiuquan	2.3	3.0	4.1	3.7	2.5	1.9	2.4	1.4	11.3	10.0
Zhangye	1.6	3.1	2.8	3.8	2.5	2.7	1.9	2.1	8.8	11.7
Minqin	2.8	4.1	4.5	5.9	3.6	4.2	3.7	4.3	14.6	18.5
Wuwei	1.9	1.9	3.3	2.6	2.9	1.9	2.1	1.3	10.1	7.4
Lenghu	3.1	0.6	4.0	0.5	3.1	0.5	3.3	0.4	13.5	2.0
Xining	1.8	2.0	6.8	1.4	4.9	0.5	3.6	0.8	17.1	4.7
Maduo	9.6	1.6	6.7	1.3	5.1	1.2	1.6	0.1	23.0	4.2
Shizuishan	6.9	2.0	8.0	3.3	7.3	2.4	6.2	1.7	28.4	9.4
Yanchi	3.2	3.2	5.3	8.2	3.1	2.9	2.7	0.9	14.3	12.2
Yulin	0.9	2.6	2.1	3.3	1.7	2.0	1.8	1.8	6.5	9.7
Suide	8.6	1.3	10.8	1.9	10.8	1.9	10.2	1.1	12.4	6.2
Yan'an	0.2	0.7	0.2	1.1	0.2	0.3	0.3	0.2	0.9	2.3

5.3.2. Unstable air (high-pressure gradient force) is the thermal condition causing local sand-dust storms

The main origin of unstable energy during the 5.5 sand-dust storm weather process was the occurrence and development of low air depression (700 hpa) in the eastern Qinghai-Tibet Plateau that promoted the easterly air current in the eastern part and central part of the Hexi Corridor. At 08:00 hrs on May 5th, strong cold high pressure had entered into the northern part of Xinjiang and pressure difference between Urumqi and Yumen in Gansu Province was 21 hpa and the pressure gradient was 3-hpa/100 km. When the pressure gradient increased, the cold front moved forward with a speed of 50-60 km/h. At 14:00 hrs on that very day, the cold front moved into Jiuquan of Gansu and the difference value of the allobaric centre, in a duration of 3 hours before or after the cold front, was 9 hpa and the difference value of allobaric centre was 44 hpa in a duration of 24 hours before or after the cold front. At 17:00 hrs on that day, the temperature in Zhangye was 25^0 before the arrival of the cold front and the temperature in Dingxin (adjacent to Zhangye) was 7^0 after the cold front; the temperature gradient in this duration was 12^0/100 km. Such strong geostrophic deviating wind caused by pressure gradients played a decisive role to form the sand-dust storm. In addition, from 20:00 hrs on the 4th to 08:00 hrs on the 5th May, rapid currents of western wind at high altitudes accelerated and the dynamic subsidence brought about impoirtant impacts to the occurrence of sand-dust storm.

5.3.3. Rapid increase of air temperature and acceleration of cold-heat convection in regions where the sandstorm occurred

The 5.5 sand-dust storm: mean temperature, extreme average and extreme maximum temperature from January to May in 1993 in Jinchang of Gansu rapidly increased (*Table 5*). Similarly, in the sand-dust storm on December 31st 2000: mean temperature in December in 2000 in Minqin and other regions was 4^{0} higher than mean temperature in the same period of time in history.

Table 5: Air temperature of Jinchang, Gansu from January to May

Air temperature (^{0} C)	Jan.	Feb.	March	April	May
Mean temperature	-8.6	-0.6	5.2	11.2	15.8
Extreme average	-1.7	6.1	11.6	17.8	22.2
Extreme maximum air temperature	7.8	15.9	18.5	28.1	29.6

5.4. Processes of reactivation and exposure of sandy topsoil

The process of reactivation and exposure of surface materials is a consequence of desertification and is one of the important processes contributing to sand-dust storms. Sand-dust storm frequency is an important criterion to assess the process, spread and reversal of desertification in the affected regions. Namely, the frequency and intensity of desertification in the affected region relates directly to the severity of desertification (*see Chapter 1*). On the contrary, the severity of desertification in the affected region reveals the intensity and frequency in the occurrence and development of sand-dust storms. The process of land desertification is closely related to factors of natural conditions and human initiatives.

5.4.1. Natural elements contributing to dust storms

Climatic regime, material sources, topographic conditions and underground water status are the main (closely correlated) factors of the natural environment and the formation of land desertification. Climatic factors include precipitation, precipitation variation, air temperature, wind regime, etc. A series of specific features, such as low biomass, sparse vegetative coverage and high intensity of exposed land in ecosystem characterize arid climatic environments. In such arid areas, frequent winds may cause soil erosion. For this reason, weather conditions, aridity and prevailing winds are the basic natural conditions that cause occurrence and development of land desertification. Material source is an environmental factor contributing to desertification, but human factors play an important part. In some regions where climate is not arid, but sand-dust sources are abundant, sand movement and sand-dust storms occur as well. In arid and semi-arid zones with similar climatic conditions, sand material sources are the most important impact factor.

The impacts of geomorphological conditions on the occurrence and development of land desertification are characterized by the following four aspects: a) the geomorphological position determines the distribution of land surface materials; b) the geomorphological condition affects the change of local wind force and contrast of erosive accumulation; c) the geomorphological position determines land-use patterns; d) and the geomorphological condition affects the distribution and storage of underground water. In the areas with abundant sand material, better underground water conditions is one of the effective elements that limits the occurrence and development of land desertification. Underground water regimes indicate water conditions in a region and water-holding capacities of soil. When the water-holding capacity of soil is 4% the sand-dust blowing up and sand transport will be negative.

Table 6: Composition of sand grains in sand desert in the Northwest China (%)

Desert	Items*	Very fine sand	Course sand	Medium Sand	Fine sand	Fine dust sand	Dust sand	No. of samples
Taklimakan	A.value	□	0.02	4.54	34.15	41.97	19.32	
	M.value	□	0.40	43.1	77.9	67.70	49.10	63
	Mi.value	□	□	□	4.9	5.9	3.3	
Gurban Tunggut	A.value	□	□	8.70	68.2	19.1	4.0	
	Ma.value	□	□	50.8	92.3	58.9	12.9	21
	Mi.value	□	□	0.1	27.8	7.0	0.4	
Baidan Jilin	A.value	□	3.40	23.4	61.4	9.82	1.98	
	Ma.value	□	34.0	58.4	98.7	66.0	32.0	17
	Mi.value	□	□	0.70	23.0	□	□	
Tengger	Me.value	0.01	1.60	6.61	86.88	4.90	□	
	Ma.value	0.02	33.30	36.20	99.38	19.78	□	33
	Mi.value	□	□	□	41.84	0.50	□	
Ulan Buh	Me.value	0.01	0.78	17.31	72.11	9.52	0.27	
	Ma.value	0.02	7.00	58.7	97.50	42.9	5.59	28
	Mi.value	□	□	□	32.10	0.40	□	
Kubqi	Me.value	□	1.10	1.90	85.3	11.70	□	
	Ma.value	□	5.6	9.60	98.0	69.60	□	11
	Mi.value	□	□	□	29.60	1.00	□	
Sandland east of the Y.River, Ningxia	Me.value	□	0.13	17.99	75.05	60.16	0.67	
	Ma.value	□	3.00	69.99	93.00	37.48	6.00	44
	Mi.value	□	□	0.5	30.00	0.10	□	
Mu Us Sandy Land	Me.value	□	3.2	41.20	47.3	8.3	□	
	Ma.value	□	17.00	67.10	89.85	36.56	□	15
	Mi.value	□	□	0.60	21.98	3.02	□	

*Average value, Maximum value and Minimum value (10 point)

5.4.2. Climatic factors

5.4.2.1. Drought, sparse rainfall and unstable precipitation

Northwest China is located inland of the Eurasian continent far from oceans and blocked by high mountain ranges and plateaus. In particular the up-lift area of the Qinghai-Tibet Plateau is the barricade of the summer monsoon. The warm moist vapour cannot reach Northwest China and, as a consequence, the region is dry. Precipitation decreases progressively from east to west. In the eastern part of the Helan Mountain, annual precipitation varies from 200-400 mm and that in the west of the Helan Mountain is less than 200 mm.

Precipitation in the central and eastern parts of the Taklimakan Desert, eastern Xinjiang, the western Qaidan Basin and the Baidan Jilin Desert, annual rainfall is less than 50 mm and even below 25 mm.

Precipitation is sparse and unevenly distributed. The annual variation of rainfall is 30-40% in the eastern regions and more than 40% or even as high as 50% in the western regions. The rainy season is also uneven and is mostly concentrated in the period of June-August. Most rainfall is concentrated in several days and this makes for prolonged drought periods (210-300 days). Spring drought is especially serious. The evaporation is severe and varies generally from 2,000-3,000 mm and even as high as 4,000 mm in some regions. In consideration of aridity, it is 2.5-4.0 in the eastern region and exceeds 4.0 in the western region. Among them, aridity in the eastern Xinjiang and Taklimakan Desert is as high as 16 or even reaches 60.

5.4.2.2. Strong wind force and prevailing frequency

Northwest China is under the influence of northwest and southeast winds and follows the seasons. In winter, impacted by Mongolian High pressure, NNE-SSW oriented divergence air currents are formed near the 96°E longititude and cause the formation of NNE wind regimes in the eastern part of the Tarim Basin in Xinjiang and in the western part of the Hexi Corridor, Gansu. The eastern divergence air current passes over the Ningxia Plain and the Ordos Plateau in northwest wind along the north edge of the Alxa Plateau. In summer, secondary torrid air is moved northward and the westerly wind is blocked by the Pamir Plateau and turned over. One air current crosses over the Pamir Plateau Outlet and enters into the western part of the Tarim Basin, and another air current enters into the North of Xinjiang through the western inlet of the Jungger Basin. Therefore, NW wind is the prevailing wind in the north of Xinjiang, the Hexi Corridor, and the Ningxia Plain. Impacted by the southeast monsoon, SE wind is the prevailing wind in the eastern part of the Helan Mts.

Mean annual wind velocity is 3.3-3.5 m/s and mean wind velocity in spring seasson is 4.0-6.0 m/s. There are approximately 200-300 days where the wind exceeds the threshold wind velocity. There are 20-80 days when the wind force is at or above 8 on the Beaufort scale. Strong wind appears along the China-Russia and China-Mongolia border. Particularly in the gorges, valleys and outlets of mountains, like the Alashankou Gorge, Dabanchen and Qijiaojin, wind force is normally at force 12. The seasonal change of wind velocity is significant and almost all wind at force 8 is concentrated in the spring season, accounting for 40-70% of the total frequency of wind.

5.4.2.3. Reduction of water resources

Because of global warming, prolonged drought on a large scale is causing severe impacts to various water resources (glaciers, lakes and runoff).

Glaciers retreat: In Northwest China, water resources originate from high mountain glaciers. Because of global warming and drought, the glaciers retreat. For instance, the Altay Mts., the Tianshan Mts., the Pamir, and Qilian Mts. and 73% of the 227 registered glaciers are under retreat. According to ground measurements, the glacier areas of the Urumqi River of the Tianshan Mts. and the Shuiying River of the Qilian Mts. have retreated for 43% and 46% respectively since the Small Glacial epoch. The average retreat speed of glaciers in Northwest China is 10-20 metres per year.

Drying up of lakes: There are many inland lakes without outlets in Northwest China that are impacted seriously by climate variations and human activities. Lakes on the plain are mainly affected by human activities. For instance, the Lop Nor was a well-known inland lake and it covered an area of 3,000-km² one century ago because of the discharge of the Tarim River. Because of artificial embankments and reservoir catchments, the water flowing into the lake became less and less and the size of the lake contracted 2006 km² in total in the 1950s. It was completely dried up in 1972. Sogo Nor in western Inner Mongolia was named a natural oasis in history and it is dried up nowadays. The Qinghai Lake is an upland lake and water discharge of the lake is decreasing because of the arid climate and the development of 55,000 ha of irrigated agriculture near the lake. From 1956-86, the water level had declined to 3.35 metres. In recent years, because of water consumption exceeding supply, average perennial water deficiency is 456 million m^3/a, lake water level declines at an average rate of 10.57 m^3/a and water surface contracts at an average area of 9.43 km^2/a thus forming an exposed shore around the lake. In recent decades, the average annual decline rate is 13 cm. At the same time, due to the deterioration of the ecological environment, the land desertification process is accelerating and sand content in streams linking the lake is increasing. It is estimated that the total annual sand transport is 607,500 tons.

Change of runoff: The shrinking of lakes indicates the decrease of runoff. With regard to average runoff of rivers on Xinjiang's mountains in the past three decades, river flow comes from rainfall in Northern Xinjiang and is seriously being decreased and the proportion of river flow that comes from melting water of glaciers in southern Xinjiang is being increased. Along with the retreat of glaciers on a large scale, the rate and total runoff of melting water of glaciers in river flow are being decreased.

5.4.2.4. Abundant sand materials

Northwest China is an important source of inland sand-dust storms in Asia: the type of sand-dust is diversified and the area threatened is vast. It contains not only sand-dust storms caused by natural factors, but also the ones caused by human factors. Along with changes in natural conditions and human interruption factors, the system of sand-dust sources is unstable and is a major supplier of material for sand-dust storms. Desert, gobi, desertified land and loess supply sufficient sources of sand-dust materials for storm events. The area of desert in Northwest China is 503,000 km² and Gobi covers an area of 381,500 km². Desertified lands are approximately 184,400 km² and loess plateaus cover an area of 225,200 km². In total, the four types of affected lands occupy 1,2941 million km² of the land representing 42.52% of the total land territory of Northwest China. Sand and dust materials from the above-mentioned lands have all made a certain contribution to the occurrence and development of sand-dust storms.

Table 7: Microelements in aeolian sands in Hexi, Gansu (mg/kg)

Elemen	Ba	Mn	P	Sr	Zr	Cr	Rb	V	Zn	Ni	Cu	Y	Pb	Co	N	As
Conten	637 3	436.	318. 8	218.2	141.8	63.5	66.3	58.5	34.1	20.9	13.8	14.8	11.9	9.5	8.	6.2

Table 8: Composition of sand grains on gobi desert

Type of Gobi	Sampling site	Depth (cm)	Grain size (mm) and composition (%)							
			Grave l	Very coarse sand	Coarse sand	Medium Sand	Fine sand	Very fine sand	Dust sand	Clay particles
			72.0	2-1.0	1-0.5	0.5-0.25	0.25-0.125	0.125-0.063	0.063-0.002	<0.002
Alluvial gobi	40 km east Dunhuang	0-3	28.3	5.77	6.37	7.64	7.2	12.84	31.93	
		Less 3	23.2	7.07	8.5	9.64	11.84	19.57	20.18	
	Yumen Pass	0-2	18.04	2.34	4.41	8.46	13.4	28.8	24.56	
		Less 2	15.87	2.43	4.33	12.30	17.73	27.56	19.78	
Deluvial gobi	50 km east An’xi	0-2	28.21	2.96	5.26	9.76	10.26	19.53	24.02	
		Less 2	12.33	8.47	9.12	15.31	12.61	13.63	28.53	
	Yumen Town	0-5	43.07	3.76	3.39	6.53	7.93	18.46	16.86	
		Less 5	31.5	5.0	4.87	9.7	12.33	19.10	17.50	

Table 9: Composition of Loess particles

Soil	Sampling site	Depth (cm)	Grain size (mm) and Composition (%)				
			mid size sand	Fine sand	Very fine sand	Dust sand	Clay
			0.5-0.25	0.25-0.125	0.125-0.063	0.063-0.002	<0.002
Loess	Shenmu County, Shaanxi			0.27	51.03	47.83	0.96
Sandy loess	Chuanbei, Yulin				78.48	20.32	1.20

5.4.2.5. Advantageous geomorphologic conditions causing sand-dust storms

Landform and geomorphological features play significant roles in the distribution of sand-dust sources for sand-dust storms, running paths, blocking air currents, friction, diffusion, narrow-pipe (funneling) effects and local thermal functions. It is clear that landform and geomorphological features have a positive influence on the occurrence, development, acceleration and destructive force of sand-dust storms. It can be summarized in the following manifestations.

A. Geomorphological structure and sand-dust materials

The large geomorphological skeleton in Northwest China is inter-mountain basin or inter-distribution of upland plain and lowland. In Xinjiang, the Jungger Basin is located amongst the Altay Mts. and Tianshan Mts. the Tarim Basin is situated between the Tianshan Mts. and Kunlun Mts. In Gansu, the Qilian Mts. in the south and the Longshou Mts. in the north bound the Hexi Corridor. The Dahuang Mts. and Yumu Mts. divide the Hexi Corridor Basin into three small basins: namely the Wuwei Basin, Zhangye Basin and Jiuquan Basin. In Inner

Mongolia, broken basins and mountains surround the Ordos Plateau. The Yellow River plain is located in the north and the Ushen Lowland is situated in the south of the Ordos Plateau. In Qinghai, the Qaidan Basin is seated amongst the Altay Mts. and Kunlun Mts.

Figure 2: Travelling paths of sandstorm in Northern China

In the above mentioned basins and plains, huge accumulations of loose sediments are deposited in deserts, sandy lands, gobi, loess, dried-up river beds, denuded hills, alluvial-deluvial plains and lacustrine plains. These geomorphological types are typical of the Quaternary sediments.

B. Geomorphological structure and sweeping path of strong sand-dust storms

The spacial distribution of geomorphological features plays an obvious limiting function of the running path of strong sand-dust storms. First, the influence of topography cannot be ignored as to its influence on the entry of cold air. Outlets of high mountains, gorges or plain terrains serve the entry of strong cold air. The running paths of strong sand-dust storms in China are divided into three directions, namely the western path, northwest path and north path.

The running path of strong sand-dust storms is restricted either by upper-level air pressure fields, or the geomorphological structure. It can be seen from *Figure 2* that the eastward movements of strong sand-dust storms from the western and the northwestern path are mainly influenced by the latitudinal oriented mountain systems of the Qingling Mts. and Yingshan Mts. The underlying surface along the path of sandstroms is mainly gobi and sandy desert. Because of the increase of turbulence thermal exchange volumes, strong thermal convection was brought about, movement energy of sand-dust storm was heightened and intensity of sand-dust storm was intensified. However, due to the block barricades of the Qingling Mts. and Da Xinganling-Taihang Mountain systems, strong sand-dust storms do not cross over these two topographic limits. Along the northern path, strong sand-dust storms can move explosively southward because of the smooth terrains of Inner Mongolia Upland that helps the cold air from Lake Baikal drive straight downward and form strong sand-dust storms on the Inner Mongolia Upland and Ordos Plateau.

Sand-dust storms from the northern path normally cause a few calamities in the eastern parts of the Da Xinganling Mts. and Taihang Mts.

C. Geomorphological structure composition and its impacts on wind force

Air currents enter mountain valleys from open piedmont hills and air density at the inlet of the valleys is increased, wind velocity is strengthened and wind force is accelerated under the function of revolving flow of the two-side hills. It is estimated that wind velocity will be increased 17% inside the valley than that in the open piedmont. When the air current enters into the valley, due to the influence of two-side slopes, the friction will be increased and wind speed will be gradually decreased. In comparison with the wind velocity in open piedmonts, wind velocity will be decreased 35% at the outlet of valleys. The air current will be diffused when it moves out of the valley and the narrow-pipe function of the valley will disappear, and flow speed will be slow under the influence of the barricade function of a mountain. At a reasonable distance from the outlets of valleys, due to weakness of the barricade function of mountains at two sides of the valley, flow speed will once again be gradually increased and wind velocity will be restored to the same as that in the open piedmont (*Table 10, Figure 3*).

Table 10: Wind velocity observation in gullies of 2 metres deep

Sites	Distance to gully (m)	Wind velocity (m/s)	Wind velocity rate in comparison with velocity outside gully	Rate of increase and decrease (%)	Remark
1	0	10.8	100	0	Length of gully is 1,143 metres; Width of gully is 30 metres.
2	113	12.6	117	+17	
3	773	11.1	103	+3	
4	998	9.2	85	-15	
5	1068	8.7	81	-19	
6	1143	7.1	66	-34	
7	1248	6.1	57	-43	
8	1298	6.6	61	-39	
9	1398	6.7	62	-38	

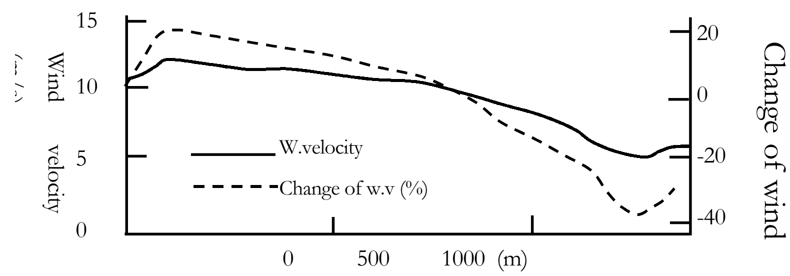


Figure 3: Wind velocity at horizontal level under narrow gully function

On the windward slopes (natural slope exceeds 70 degrees) of steep mountains and hills, because of the block and hinderance of the mountain barricade, some of the air current is lifted up and the speed of the air current close to the ground is obviously reduced in a certain scope. The intensity of air current reduction fields is related to the height of mountains and hills. When the mountain is higher, the scope of air current reduction fields is wide (it is normally four times the height of mountains.) The closer to foothills, the higher the intensity of wind speed reduction. Wind velocity in front of foothills, in comparison with wind velocity in remote plain terrains, is decreased by 67.4% (*Table 11, Figure 4*).

Table 11: Change of horizontal wind velocity at height of 2 metres on the windward slope

Sites	Distance to foothill (m)	Wind velocity (m/s)	% of site 8th	% decline in wind velocity	Times of distance to Mt.	Remark
1	Hillside 0	6.55	32.6	67.4	0	Relative height of Mt. is 75 metres
2	34	10.45	52.1	47.9	0.45	
3	64	13.82	69.0	31.0	0.85	
4	94	15.07	75.2	24.8	1.25	
5	124	17.33	64.4	13.6	1.65	
6	179	18.02	90.0	10.0	2.49	
7	282	19.02	95.2	4.8	3.76	
8	382	20.06	100.0	0	5.09	

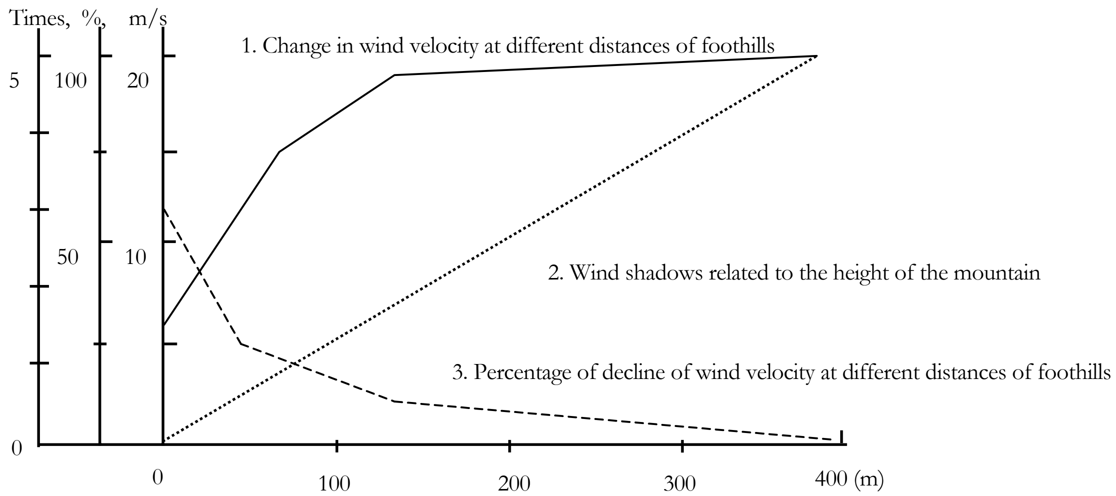


Figure 4: Wind velocity change on windward side of steep slope

On the leeward slope of steep mountains, because of the barricade function of mountains and the revolving flows on the top of mountains and on two sides, strong eddy currents are formed behind the mountain. There is a wind shadow that occurs on the leeward slope and its size is related to the height of the mountain. The higher the mountain is, the bigger the wind shadow is (it is normally twelve times as big as the mountain body.) Wind velocity at the foot of hill or mountain is low. In comparison with wind velocity at the piedmont terrain, wind velocity at foothills is lowered 61.4% (*Table 12, Figure 5*).

On gentle hills and mountains (natural slope degree is 7-5°). Air current at windward slopes is impacted by hills. The reductive scope of wind speed is related to the height and slope of hills. The higher and more gentler the hill and slope is, the bigger the impact scope, but the smaller the reduction of wind velocity. The lower the hill and the steeper the slope, the smaller the impact scope is and the higher reduction of wind velocity. Reduction rate of wind velocity at foothills is maximum and can be 22.6% (*Table 13, Figure 6*).

Under the barricade function of mountains, the air current on the leeward slope of gentle mountains varies at great rates. According to observation, the impact scope is fourteen times the height of the mountain. The reduction of wind velocity at a distance of two times the height of a mountain is maximum and can be 40% (*Table 14, Figure 7*).

Table 12: Wind velocity on leeward side at a height of 2 metres under barricades

Sites	Distance to hillside (m)	Wind velocity (m/s)	% of wind velocity of sites and base point	% decline wind velocity	% of distance to hill height	Remark
Base point	No mt. Impact	17.8	100	0		Relative height of hill 165 metres
1	0	6.7	38.6	61.4	0	
2	150	11.2	63.0	37.0	0.91	
3	300	14.1	79.2	22.8	1.82	
4	400	15.2	85.4	14.6	2.41	
5	700	15.6	87.6	12.4	4.24	
6	1,400	16.1	90.5	9.5	8.49	
7	1,700	17.2	96.0	3.4	10.39	

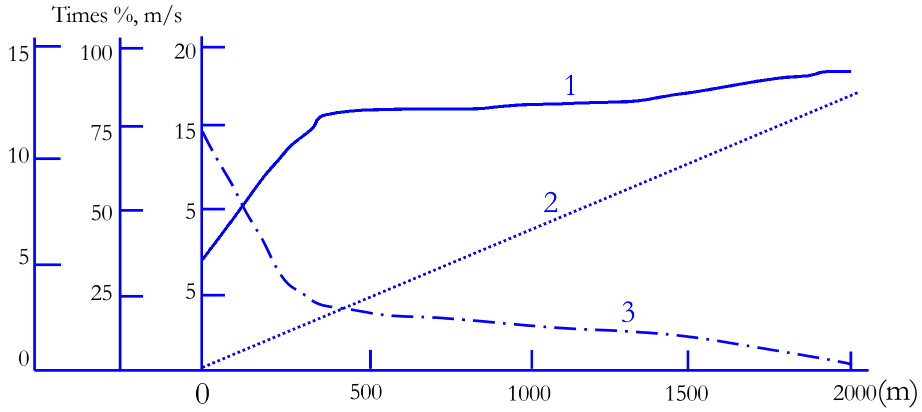


Figure 5: Wind velocity change at leeward-side of steep slope

Table 13: Wind velocity at horizontal height of 2 metres on gentle slope

Site	Distance to hillside (m)	Wind velocity (m/s)	Rate of wind velocity of sites in comparison of site 6 (%)	% decline wind velocity (%)	Times of distance to hill	Remark
1	0	12.7	77.4	22.6	0	Relative height of hill is 81 metres
2	51	13.2	80.5	19.5	0.63	
3	105	14.6	89.1	10.9	1.24	
4	178	15.4	94.9	5.1	2.14	
5	378	15.8	96.2	3.8	4.67	
6	578	16.4	100	0	7.14	

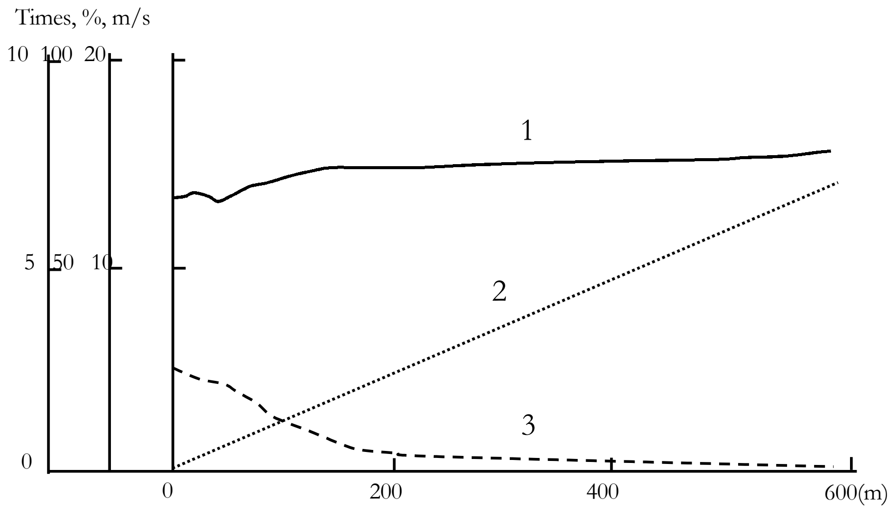


Figure 6: Wind velocity change on gentle windward slope

Table 14: Wind velocity under barricades on leeward slope

Sites	Distance (m)	Wind velocity* (m/s)	% of site to base	% Decline of w.v. on base point	Ratio of distance to hill height	Remark
Base Point		20.1	100			Relative height of hill is 73 metres
1	60	12.7	62.9	37.1	0.82	
2	113	12.1	60.3	39.7	1.55	
3	168	11.9	59.2	40.8	2.30	
4	258	13.9	69.2	30.8	3.54	
5	433	14.2	70.7	29.3	5.94	
6	643	15.8	78.7	21.3	8.81	
7	875	17.9	89.1	10.9	11.99	
8	1031	18.7	92.1	6.9	14.0	

* Wind velocity = w.v.

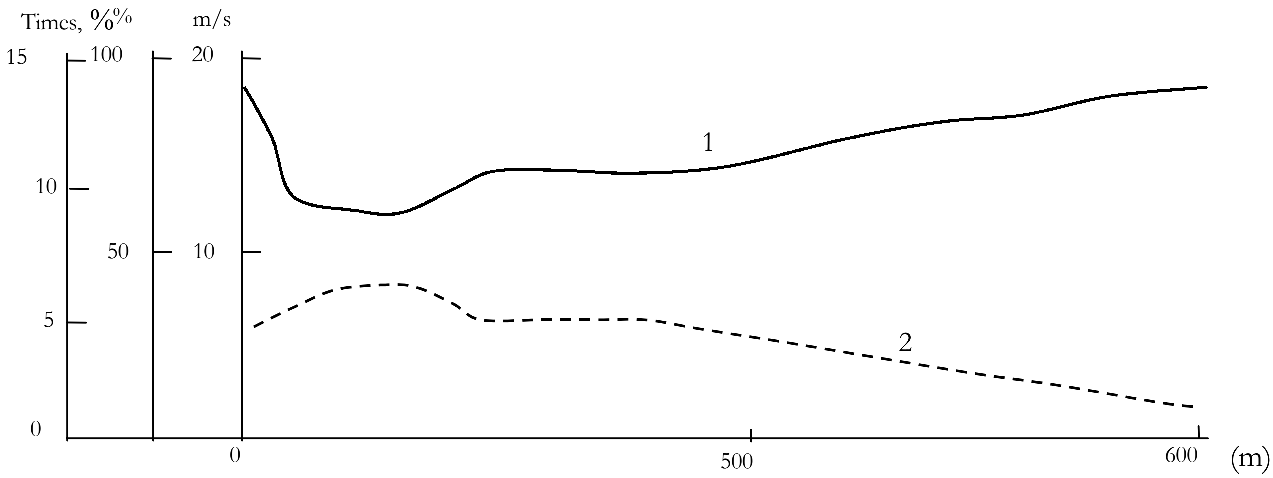


Figure 7: Wind velocity on gentle leeward slope

Because of the differences in geomorphological structure in southern and northern Xinjiang, dynamic wind conditions of sand-dust storms are different. The Southern Xinjiang basin is located at the western and southwest parts of Mongolian High Pressure zones; cold air in the winter season flows backward to the eastern open gorge of the basin and then eastern wind and northeastern wind are formed in the eastern part of the basin. The western part of the basin, under the impact of invasion of western cold air, western wind and northwestern wind prevails. Xinjiang is located on the northern side of thermal low pressure; climate in the summer season is under the influence of local topographic circulation, where eastern wind prevails in eastern Xinjiang and western wind is the dominant wind in western Xinjiang. In the Tarim Basin, there are two perennial wind systems namely, the western wind that prevails in the vast area of the western region of the Niya River and the eastern wind that prevails in the vast area of the eastern region of the Niya River. The Niya River and its adjacent area is a convergence zone of the eastern wind system. Furthermore, in northern Xinjiang, there are approximately 5 sand-dust storm days and in southern Xinjiang, average annual frequency of sand-dust storms is 20-30 days.

The Hexi Corridor, a long and narrow belt lined by Qilian Mts. in the south and Longshou Mts. in the north, Gansu Province is characterized by its narrow-pipe function. The Hexi Corridor is divided into two parts: east corridor and west corridor centred from the boundary line of Jinta-Jiuquan. The western corridor covers a wide *"narrow-pipe"* amongst the Qilian Mts, Mazong Mts. and Ser Ula Mts. The eastern corridor covers a tight *"narrow pipe"* amongst the Qilian Mts., Longshou Mts., and Heli Mts. When air currents flow over these two narrow pipes respectively, wind velocity will be heightened and wind force will be strengthened. Wind regimes of Dunhuang, Anxi and Yumen in the two narrow pipes is cited in *Table 15*.

It can be seen from *Table 15* that the western corridor can heighten mean annual wind velocity by 91% and wind velocity in sand-dust storm seasons in spring by 74%. Wind regimes of several counties in the central part of the narrow pipe are cited in *Table 16*. It clear from *Table 16* that, from the western entrance to the eastern outlet of the Hexi Corridor, mean annual wind velocity is increased by 40% and up to 60% in spring season. The maximum wind velocity of the 5.5 sand-dust storm in various counties along the Hexi Corridor proved the above conclusion. Record of maximum wind velocity from the western to the eastern corridor was: Gaotai 21 m/s; Lingze 21 m/s; Minle 23 m/s; Yongchang 28 m/s; and Gulang 25 m/s. The regular gradual increase of wind velocity in the Hexi Corridor is the manifestation of the narrow-pipe function of the corridor.

Table 15: Wind velocity in different seasons in Hexi Corridor, Gansu province

Site	Met. Station	Average wind velocity (m/s)					>force 8 wind (days)
		Annnual mean	Winter	Spring	Summer	Autumn	
West Hexi County	Dunhuang	2.2	2.1	2.7	2.2	1.8	15.4
	An'xi	3.7	3.4	4.4	3.5	3.3	68.5
	Yumen	4.2	4.7	4.7	3.6	3.9	42.0

Source: Soil and Water Resources in Hexi of Gansu and Their Rational Development and Utilization, 1980.

Table 16: Wind velocity in east Hexi Corridor, Gansu

Site	Met Station	Average wind velocity (m/s)					>force 8 wind (days)
		Annual mean	Winter	Spring	Summer	Autumn	
East Hexi County	Gaotai	2.5	2.2	3.1	2.6	2.1	9.1
	Lingze	2.5	2.8	3.4	3.2	2.5	21.7
	Minle	3.4	3.4	3.7	3.4	3.1	11.2
	Yongchang	3.2	3.0	3.7	3.0	3.0	18.3
	Gulang	3.5	3.7	3.3	3.7	3.5	4.5

6. CONCLUSIONS

Sand-dust storms are both a symptom and a consequence of desertification. They are an environmental disaster in China. Regrettably, the frequency and severity is increasing.

There are five principal ingredients to such wind-related calamities. There must be:

1. A source of material, such as fine sediments that can be entrained and transported.
2. Wind power at a velocity and in a direction that will raise and carry the sediments.
3. Weather conditions that favour the developmnent of convection cells that can generate enough energy.
4. Landforms and geomorphological features that favour wind funneling.
5. Soil surfaces that are susceptible to erosion by wind – usually devoid of vegetation or other protection.

Northwest China has all five prerequisites. The situation has gotten worse because the situations described in points 1 & 5 above have increased as a result of poor land management over the past decades. This has been brought about by faulty policies and by uninformed human actions.

Since the early 1990s the government at all levels is paying close attention to the problem and measures to mitigate the effects of sand-dust storms are being put in place.

An analysis of the root causes shows the vital role that environmental management plays and the significance of involving the local land users in the control of desertification and sand-dust storms.

7. FURTHER READING

Chen Longheng, 1993, *Damage of Strong Sandstorm in Ningxia and Alxa of Inner Mongolia and Control Strategy*, Journal of Desert Research, (3), 9.

Chen Mingjian, 1993, *Study and Discussion on Black Windstorm, Gansu Meteorology*, 11 (3).

Cheng Daoyuan, 1994, *Atmospheric Dust Source and Duststorm*, World Desert Research, (1) 5.

Dept. of Geosciences, Chinese Academy of Sciences, 2000, Root Causes of Sand-Dust Weather in Northern China and Controlling Strategy, Impact of Science on Society, 4.

Fu Youzhi, et al, 1993, *Root Causes and Prediction of Black Windstorm in Hexi of Gansu*, Gansu Meteorology, 11 (3).

Jiang Fengqi, et al, 1993, *Investigation Report of Strong Sandstorm in Ningxia*, Applied Ecology, 4 (4).

Qian Zheng'an, 1993, *Investigation Report on 5.5 Strong Sand-Dust Storm in Gansu and Ningxia*, Atmospheric Information, (4) 3.

Su Yucheng, 1993, *Analysis of Sandstorm on May 5th 1993 in Hexi Corridor*, Gansu Meteorology, 11 (3).

Wang Jiaying, 1963, *China Geological History*, Science Press, p. 110.

Wang Jixi, 1993, *Analysis on Causes of Black Windstorm on May 5th 1993 in Gansu*, Gansu Meteorology, 11 (3).

Yang Gengsheng, 1996, *Black Windstorm in Northwest China and Calamity Reduction Approaches*, Journal of Desert Research, 16 (2).

Yang Gengsheng, 1993, *Developmental Process of 5.5 Black Windstorm and Controlling Strategy*, Journal of Desert Research, 13 (3).

Yang Gengsheng, 1993, *Disasterous Status and Strategy against Black Windstorm on May 5th 1993 in Northwest China*, Gansu Meteorology, 11 (3).

Zhao Xingliang, 1993, *Damage of Strong Sand-Dust Storm in Gansu and Countermeasures*, Journal of Desert Research, 13 (3).

Zhu Zhengwen, 199, 3*Report on Black Windstorm on May 5th 1993 in Gansu*, Gansu Meteorology, 11 (3).