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Recent Developments in Wind Erosion Research

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Abstract: Wind erosion has recently become a key focus of many different research disciplines, such as climate change, air quality, sustainable land use, etc. This short paper discusses the importance of wind erosion in these research fields. It is also attempted to provide an outline of recent progresses in wind erosion studies from the perspectives of wind erosion monitoring, field experiments and modeling.

Key words: wind erosion, wind erosion research, wind erosion modeling, climate change, dust cycle.

Wind erosion is a land surface process that takes place mainly in arid and semi-arid regions of the world. In some areas, wind erosion is accelerated due to the destruction of native vegetation and other human induced processes, such as over-grazing and farming. In recent years, the influences of wind erosion on atmospheric behavior (e.g., cloud formation and radiation transfer), air quality (e.g., concentration of PM_{10} and $PM_{2.5}$), land degradation (e.g., depletion of soil nutrients and desertification), global nutrient cycle and geomorphology, are increasingly realized. In particular, the need for better understanding of the global dust cycle, climate change, land use sustainability and air quality protection has significantly promoted the research on wind erosion. For the first time, wind erosion has become a focus of different research disciplines, attracting attention from scientists with diverse research interests and backgrounds. As a result, there is a rapid increase in observational data and a substantial progress in the development of wind erosion theories and modeling capabilities. In this paper, a brief description of the importance of wind erosion is given, followed by an outline of the recent developments in wind erosion research.

Significance of Wind Erosion Research

Climate

Wind erosion mainly occurs in areas where there is a lack of precipitation due to the effect of either global atmospheric circulation or surface topography. It is the main mechanism responsible for the emission of mineral dust, which constitutes a large proportion of aerosols. The total dust emission on the globe is believed to be about 3000 Mt per year and a large proportion of this dust is deposited in the ocean (Duce *et al*., 1991; Tegen and Fung, 1995). Particles suspended in the atmosphere play an important role in the climatic system, as they influence the atmospheric radiation balance directly, through scattering and absorbing various radiation components, and indirectly, through modifying the optical properties and lifetime of clouds. Aeolian dust particles are by far the most important aerosols in the atmosphere. The global total dust emission of 3000 Mt is more than twice the second-largest aerosol source, the sea salt (about 1300 Mt). The global mean column dust load is approximately 65 mg m^{-2}, more than 9 times of that of sea salt (about 7 mg m^{-2}). The Intergovernmental Panel on Climate Change (IPCC) 1995 and 1998 reports indicated that the radiative forcing of tropospheric aerosols on the atmosphere is still poorly understood. From the perspective of climate studies, an important research topic related to wind erosion is the global dust cycle, i.e., the emission, transport and deposition of mineral dust particles, and the atmospheric processes in which aerosol plays an important role, such as radiation, cloud formation and precipitation.

Air quality

Wind erosion causes air quality hazards in populated areas adjacent to major dust sources. In Beijing, for example, the measured near-surface dust concentration during severe dust storms has been reported to be as high as 5 mg m^{-3}. Near dust sources, the reported dust concentration can be as high as 20 mg m^{-3} (Yabuki *et al.*, 2002). The Northeast Asian dust storm that occurred between 18 and 24 March, 2002, caused severe disruptions of social activities in the northern part of China and Korea (e.g., closure of airports and schools). Many contaminants that pose significant risks to human health and the environment are found in or associated with dust, including metal, pesticides, dioxins and radionuclides. For these reasons, to determine areas and intensities of dust emission is important for air quality protection.

Land surface process

Wind erosion is the main mechanism responsible for the formation and evolution of sand seas in the world and the long-range transport of sediments from the continent to the ocean. Large quantities of minerals and organic matter are carried with dust particles and redistributed around the world. In recent history, human activities have created profound disturbances in the natural environment. Excessive clearance of native vegetation, over-grazing and inadequate agricultural practices have resulted in increased frequency and intensity of wind erosion in many parts of the world. In human-disturbed regions, the rate of wind erosion can be many times that over undisturbed natural surfaces. For example, during the 1930s decreased precipitation in the Great Plains of the United States, coupled with intensive agricultural activities caused a dramatic increase in wind erosion, which became known as the dust bowl of the USA. In the Sahel region, drought conditions combined with overpopulation also resulted in a considerable increase of wind-erosion events. The Mu Us region in North China has a mean annual precipitation of about 400 mm. Historical evidence indicates that this region was once a grassland, partially covered with forests. It is probably mainly due to over-grazing and agricultural activities that this region has changed to a desert. In Australia, many of the recent severe dust storms have originated in agricultural areas, where the native vegetation has been cleared in the past two hundred years.

Land degradation

Wind erosion in agricultural areas leads to land degradation in the long term. During an erosion event, fine soil particles rich in nutrient and organic matters, are carried away by wind over large distances, resulting in the loss of soil nutrients. According to Raupach *et al.* (1994), the February 1982 Melbourne dust storm generated a loss of 2 million tons of topsoil, including 3400 tons of nitrogen and 10 tons of phosphorus. The May 1994 dust storms in Australia caused a soil loss between 10 and 20 million tons. The preferential removal of fine particles by wind erosion leaves coarser and less fertile material behind. Consequently, eroded soils become less productive and have a small water-holding capacity.

Large Scale Experiments on Wind Erosion and Dust Storms

Several international collaborative projects have been carried out in the past few years, dedicated to the investigation of wind erosion, dust storms and dust cycle. The Asian Dust Experiment on Climate Change (ADEC) and the ACE-ASIA are two outstanding examples.

The Asian dust experiment

Chinese, Japanese and Korean scientists are carrying out a five-year project for studying the impact of mineral dust on climate change (Mikami *et al.*, 2002). The main purpose of the project is to measure and simulate the effects of dust particles on atmospheric radiative transfer. The project includes three major components:

(a) field observation of wind erosion process using automatic weather stations around the Tarim Basin and Dunhuang;

(b) observations of long-range dust transport using a network of Lidar, sky-radiometer and dust particle samplers; and

(c) using a general circulation model to simulate dust emission, dust deposition and dust concentration in the atmosphere as well as the associated radiative forcing. The numerical simulations will be directly verified using the field experiments and network observations.

Figure 1 illustrates the design of the ADEC experiment. As can be seen, a comprehensive set of sophisticated instruments, including satellite, a Lidar network and radio sounds for measuring dust concentration in the atmosphere, is employed for the experiment. In addition, a number of ground stations equipped with dust samplers are deployed at various locations of China, Korea and Japan. Intensive field campaigns are organized to measure wind erosion in the Tarim Basin. These intensive field campaigns offer a unique set of data for studying the mechanism of wind erosion.

Asia Pacific regional aerosol characterization experiment

In ACE-Asia, a series of experiments has been carried out which integrates *in-situ* measurements, satellite observations and models to reduce the uncertainty in calculations of the climate forcing due to aerosol particles. The main objectives of the project, as described in the Project Prospectus, are:

to "determine the physical, chemical and radiative properties of the major aerosol types in the Eastern Asia and Northwest Pacific region and investigate the relationships among these properties";

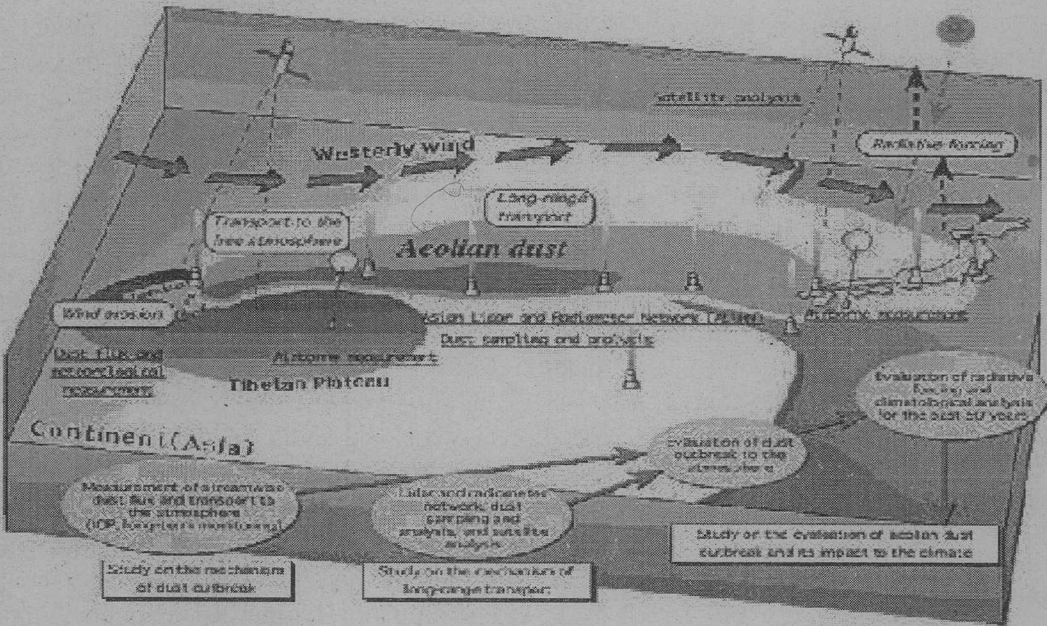

Fig. 1. Experimental design of the Asian Dust Experiment on Climate Change (Courtesy of Drs. M. Mikami and G.Y. Shi).

- to "quantify the interactions between aerosols and radiation in the Eastern Asia and Northwest Pacific region"; and
- to "quantify the physical and chemical processes controlling the evolution of the major aerosol types and in particular of their physical, chemical, and radiative properties"

The activities of the project included:

(a) *in-situ* and column integrated measurements at a network of ground stations to quantify the chemical, physical and radiative properties of aerosols in the Eastern Asia and Northwest Pacific region and assess their spatial and temporal (seasonal and inter-annual) variability;

(b) intensive field study to quantify the spatial and vertical distribution of aerosol properties, the processes controlling their formation, evolution and fate, and the column integrated. clear-sky radiative effect of the aerosol; and

(c) intensive investigation on the effect of clouds on aerosol properties and the effect of aerosols on cloud properties (indirect aerosol effect).

There are several other large-scale experiments, which provide excellent sources of observational data. For example, the Aerosol Robotic Network (AERONET) is a federation of ground-based remote sensing aerosol networks. AERONET assesses aerosol optical properties and validates satellite retrievals of aerosol optical properties. The data include globally distributed observations of spectral aerosol optical depths, inversion products and precipitable water. The network has been operating since 1993 and is now carrying out routine measurements around 150 stations distributed all over the world. The AERONET data are useful for validating numerical simulation of large-scale dust events.

Wind Erosion Monitoring and Modeling

Significant progress has been made in several aspects of wind erosion research. These are discussed below.

Laboratory and field wind-tunnel experiments and numerical simulation

In the past, the emphasis of laboratory and field wind-tunnel experiments was mostly on the estimation of threshold friction velocity for different particle sizes, sand drift intensity under various wind and surface conditions, dust-emission mechanism, the evolution of sand dunes and the impact of surface roughness and vegetation cover on wind erosion. These studies provided much of the core of our understanding on wind erosion. More recent wind tunnel studies have focused on the splash process of saltation (e.g., Rice *et al.*, 1995), saltation of multiple-sized particles, saltation under turbulent conditions and the mechanism of dust emission (e.g., Carvacho *et al.*, 2002; Leys *et al.*, 2002).

With the rapidly expanding computing power, advanced computational models are now used to simulate the processes of wind erosion. These models are powerful tools that complement, and to some degree replace, the conventional wind tunnel and field experiments. This approach enables certain types of investigations that were previously difficult to carry out. For instance, the evolution of sand dunes, the development and equilibration of saltation, splash entrainment, drag partitioning, etc., can all be examined in detail through advanced computational simulation. The main advantage of the computational approach lies in its efficiency and flexibility. An example of using a computational model to study drag partitioning is recently given by Li and Shao (2002), and an interesting study on sand dune evolution is given by Alhajraf (2002).

Field monitoring

Field monitoring and measurements of wind erosion have been carried out on different scales in many parts of the world. The intensity of sand drift has been measured using various saltation traps and the impact of land-surface parameters on wind erosion has been studied. The Owen's Lake experiment (Gillette *et al.*, 1997) provides an excellent example for field scale experiments. Measurements of wind and dust concentration profile have also been made using anemometers and dust samplers mounted on towers (e.g., Gill *et al.*, 2002). Apart from tower measurements, monitoring networks of high-volume air samplers for measuring dust concentration and deposition traps have also been setup in many parts of the world in recent years. Such networks are providing valuable information for dust movement in the entrainment phase (tower measurements), the transport phase (tower measurements and high volume air samplers) and at the deposition phase (deposition traps). Figure 2 shows an example of the research effort being made in measuring aeolian processes associated with sand dune evolution.

Fig. 2. A photo of an experimental site for studying wind erosion over a sand dune (courtesy of Drs. C. McKenna Newman, W. Nickling and N. Lancaster).

Wind-erosion assessment

Assessment of wind erosion on continental scales has been performed by considering wind erosivity and wind erodibility. For example, McTainsh *et al.* (1990) applied the model of Chepil and Woodruff to Australia and determined wind-erosion indices for the Australian continent. Studies of the long-term characteristics of wind erosion, mainly based on dust storms, have also been carried out by, for instance, D'Almeida (1986) and Littman (1991). Using meteorological records, D'Almeida identified the dust sources and revealed the characteristics of dust transport in the Sahara region. The study of Littman revealed the relationship between wind erosion and climate variations. In China, Zhou (2001) carried out a comprehensive assessment of dust storm pattern (frequency and intensity) using the original meteorological records of 681 weather stations over a period of 40 years (1959-1998). Zhou separated blowing sand events from dust storms and classified wind erosion regions into four categories according to the total number of dusty days. Zhou's study revealed two most active centers of wind erosion. The first one includes the Tarim Basin and adjacent areas and the second one includes the Alashan, the Ordos and the Hexi Corridor regions.

Wind-erosion equation

Empirical wind-erosion models have been under development for many years. For example, the Wind-erosion Equation (WEQ) is an empirical formulation that estimates wind erosion on the basis of soil type, vegetation, roughness, climate and field length. In the original WEQ, long (annual) averages of these descriptors were used to estimate annual average soil loss. The WEQ was modified by Bondy *et al.* (1980) and Cole *et al.* (1983) for estimates over shorter periods. More recently, the Revised Wind-erosion Equation (RWEQ) was developed, which includes input parameters such as planting date, tillage method and amount of residue from the previous crop. A weather generator is then used to predict future erosion (van Pelt and Zobeck, 2002). However, because of the empirical nature of the WEQ, its transferability from the Central Great Plains of the USA, for which it was originally developed, to other areas of the world is limited. Also, the complex interactions between the variables controlling wind erosion were not and could not be fully accounted for in the empirical WEQ. For this reason, a new, more process-oriented model called the Wind-erosion Prediction System (WEPS) has been under development in the USA. This model includes submodels for weather generation, crop growth, decomposition, soil, hydrology, tillage and erosion (Hagen, 1991). The USDA-Agricultural Research Services, in cooperation with the USDA-Natural Resources Conservation Service, the USDI-Bureau of Land Management, and the Environmental Protection Agency, has developed the latest version of WEPS. As reported recently by Wagner (2002), WEPS predicts average soil loss and deposition values for selected areas and periods of time. The system consists of seven sub-models, each based on the fundamental processes of wind erosion and produces estimates of dust suspension, saltation and creep. The system also has a user-friendly interface. The system serves as a useful tool for wind erosion extension work and land management practice. In several recent studies (e.g., Takarko and Wagner, 2002) the performance of WEPS has been examined.

Integrated wind erosion modeling system

Integrated numerical systems that comprehensively model all aspects of wind erosion and dust storms, from particle entrainment, transport to deposition, have been developed in recent years. The aim of such a modeling system is to provide quantitative assessment and prediction of wind erosion on scales from regional to global with a high spatial resolution (down to 1 km). To this end, the integrated system needs to be constructed with four basic components: an atmospheric-prediction model, a wind-erosion scheme, a land surface scheme and a geographic information database.

The atmospheric-prediction model provides the necessary spatial and temporal data required to drive the wind-erosion scheme, such as friction velocity, u_*, wind field for dust advection, turbulence intensity for dust diffusion and deposition and precipitation for wet deposition. In addition, the atmospheric model provides data, such as radiation required by the land surface scheme for modeling the environmental variables, in particular soil moisture and vegetation cover, which strongly influence wind erosion.

The wind erosion scheme should be physically based and have the capacity to model the entrainment through transport to deposition of soil particles of different sizes. For instance, as far as particle entrainment is concerned, the model should have the capacity to predict (1) the threshold friction velocity for wind erosion; (2) the total quantity of soil particles mobilized by wind (streamwise sand transport) and (3) the flux of fine dust particles emitted into the atmosphere (vertical dust flux).

Reliable land surface data is of critical importance to wind-erosion modeling. Land surface data are required, as the surface properties control three major processes of wind erosion: the erosion threshold friction velocity, the capability of soil to release dust particles and the partitioning of wind shear stress acting on non-erodible roughness elements and the erodible surface. Three categories of parameters can be distinguished. The first consists of parameters related to soil properties, including soil particle size distribution and parameters used to specify soil binding strength. The second comprises aerodynamic parameters related to surface roughness and drag partitioning, such as the overall roughness length of the surface, that of the erodible area of the surface and the erodible fraction of the surface. The third category consists of parameters used to specify the soil thermal and hydraulic properties. For the purpose of modeling wind erosion on regional to continental scales, these soil and land-surface parameters can be stored as layers in a geographic-information data base.

The first attempt to develop such an integrated system was probably made by Gillette and Hanson (1989), who used extensive atmospheric and land-surface data to determine the spatial and temporal variation of dust production in the United States. Gillette and Hanson did not employ an atmospheric prediction model and did not consider the aspects of dust transport and deposition. Similar frameworks have been developed by Westphal *et al.* (1988) and Tegen and Fung (1994, 1995) with an emphasis on the global dust cycle. In these studies, very simple wind erosion schemes were used and the effect of important properties such as soil moisture were not considered. Marticorena and Bergametti (1995), Shao *et al.* (1996) and Marticorena *et al.* (1997) developed physically-based wind-erosion models and have applied such models to improve the simulations of wind erosion. More recently, Shao and Leslie (1997), Shao (2001) and Shao *et al.* (2002) have developed a fully integrated wind-erosion modeling system, which couples a physically based wind erosion scheme with a high resolution atmospheric model, a land surface scheme and a geographic-information database. They have implemented the system for the prediction of dust-storm events in Australia as well as in Northeast Asia and obtained encouraging results.

In Spring 2002, Shao and colleagues from the China Meteorological Administration performed real-time 24, 48 and 72 h forecast of Northeast Asian dust storms using an integrated wind erosion modeling system. These numerical forecasts were very successful. As an example, Fig. 3 shows the simulated results for the severe Northeast Asian dust storm that occurred on 24-25 March, 2002. According to the China Meteorological Administration, this was a severe dust storm event, which affected large areas in ME Inner Mongolia, W Liaoning, W Jilin, as well as Heilongjiang and Hebei provinces. This event also caused air quality concerns in Korea and Japan. As is often the case, this dust storm was associated with a Mongolian Cyclone and cold air outbreak. The cyclone was located in the vicinity of

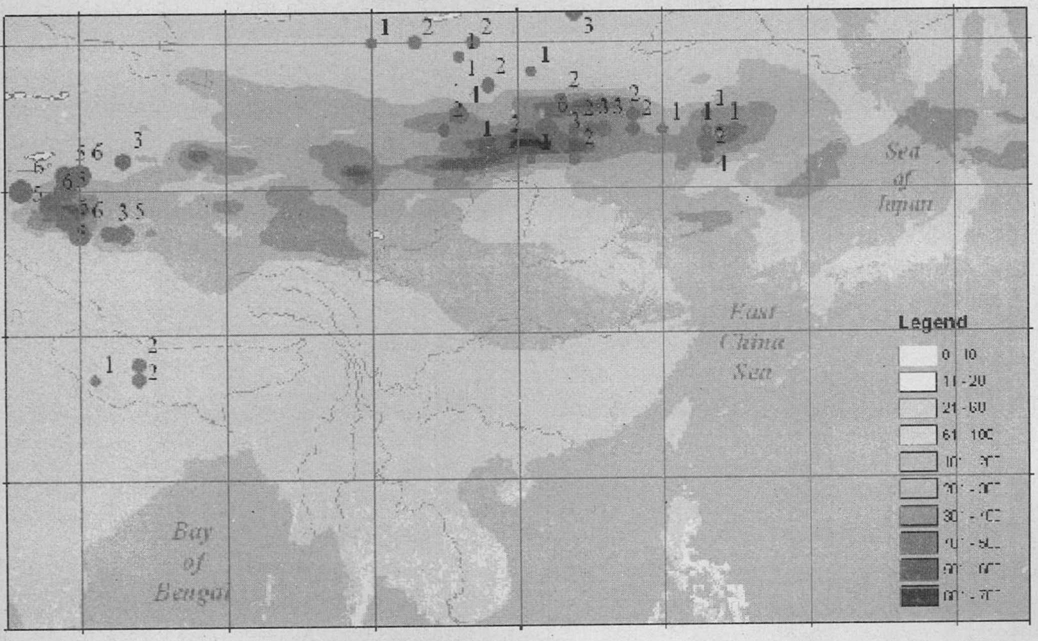

Fig. 3. Simulated dust load in mg m^{-2} for 24 March, 2002. According to surface meteorological observations, this event occurred on 24-25 March 2002, affecting large areas of South Mongolia and ME Inner Mongolia, W Liaoning, W Jilin, as well as Heilongjiang and Hebei of China. The red dots represent the locations where dust storm was observed on 24 March, 2002, and the sizes of the dots representing the number of reports made on that day.

115°E, 50°N, accompanied by very strong NW and WNW winds behind the cold front, reaching 14 m s^{-1}. As a consequence, wide spread dust storms occurred in Southwest Mongolia and Northeast China. The predicted dust load (in mg m^{-2}) is shown in Fig. 3 for 24 March, 2002. The prediction showed wide spread dust in a region between 30^{o}N and 50°N (probably partially attributed to the previous dust event occurred between 18 and 22 March, 2002) and particularly high dust load in South Mongolia, Northwest China and West China. The red dots represent the locations where dust storm was observed on 24 March, 2002, with the sizes of the dots representing the number of reports made on that day. As can be seen, the numerical prediction is generally in good agreement with the surface observations, demonstrating the capacity of the integrated modeling system. Bearing in mind that the Gobi Desert is not well covered by the meteorological network, it is likely that the predicted high dust load in the region was real but unobserved. It can be shown that the spatial and temporal evolutions of entire dust storm episode were well predicted. The results presented here are genuine predictions, because only the atmospheric model was forced using pre-specified boundary conditions. The integrated wind erosion modeling system has the capacity of predicting many other physical variables for the quantification of dust cycle, including dust emission, transport and deposition, apart from dust concentration and load.

In the scientific communities for atmospheric and aerosol studies, a number of models for dust storm predictions are rapidly emerging. Some of these models showed good capacities for modeling the dust cycle (e.g., Uno *et al.*, 2001 and Nickovic and Kallos, 2001). The Georgia Tech/Goddard Ozone Chemistry Aerosol Radiation Transport (GOCART) Model is an aerosol transport model that simulated the global distribution of dust, sulfate, carbonaceous and sea-salt aerosols (Chin *et al.*, 2000; Ginoux *et al.*, 2001; Chin *et al.*, 2002). The model simulates emission, transport and removal processes. The strength of this model is its usage of satellite data for identifying dust sources. Successful simulations of long-term dust variations have been reported.

The integrated modeling systems represent a new approach to the study of wind erosion. They take advantage of the recent rapid expansion in computing power, developments in atmospheric and land-surface modeling, and the increasing availability of quality land-surface data. Such a system has the capacity to predict spatial and temporal wind-erosion patterns as never before. However, integrated wind-erosion modeling is complicated, because nearly all processes involved in wind erosion are sensitive to parameters, which cannot be derived with great certainty. For example, threshold friction velocity is sensitive to soil moisture, especially if soil moisture is low, and it is sensitive to vegetation cover, especially if vegetation cover is small. Hence, it is almost impossible to predict wind erosion with great accuracy. Nevertheless, integrated wind erosion systems can produce results, which are comparable in magnitude with observed data, and the uncertainties embedded in the modeling system are comparable with the uncertainties of observations.

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