The effect of turbulence and gust on sand erosion and dust entrainment during sand storm

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1.Large Scale Dust Storm and Sand Blowing Events Spring in East Asia

2. Characteristics of turbulent eddies and wind gust disturbances in the lower part of atmospheric boundary layers

3.The numerical simulation of dust entrainment

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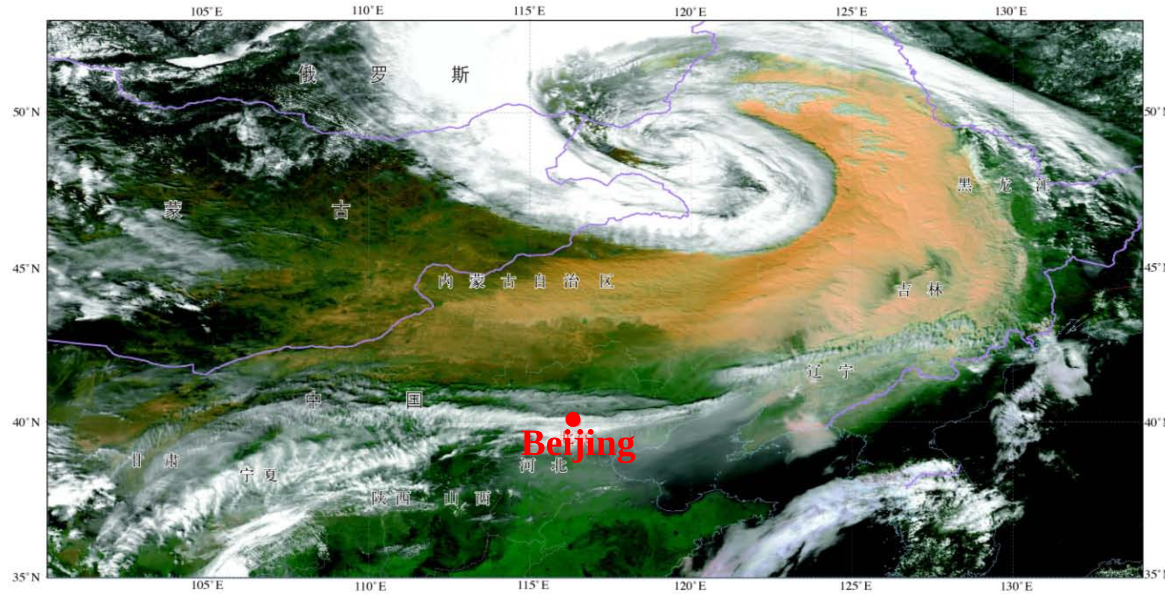
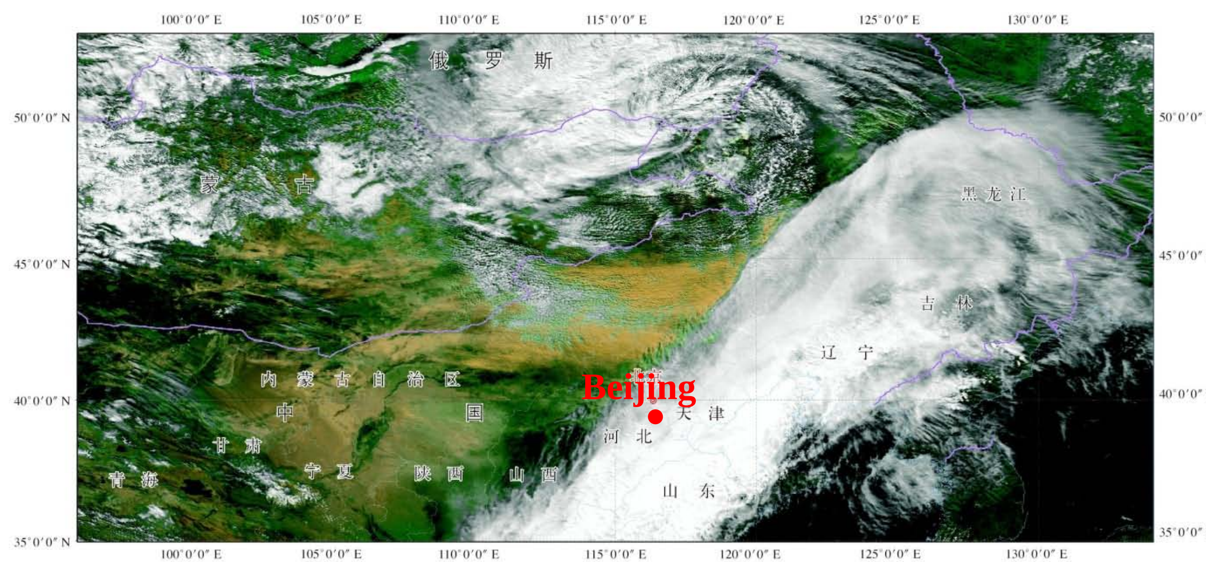
- In China, the spring dust storms are common. Usually a large low pressure system brings a lot of dust from middle Asia, Mogolia and northwest China to spread over the whole northern China, and even further.



Dust storm in 7 April, 2001, by polar-orbiting weather satellite.

- Why the dust particles can fly up to the top layer and propagate far away?



Dust storm in 20 March, 2002, by polar-orbiting weather satellite.

- The data from the tower in the dust storm and sand blowing weather are studied.
- The data include
  - ✓ Average data: wind speed, temperature, humidity whose sampling frequency is once every 20 seconds.
  - ✓ Turbulence data: sampled by ultrasonic anemometers (10Hz).

The internet station of sand storm investigation of China Meteorological Administration

Beijing 325m synthetical meteorology tower

The data of dust storm and sand blowing in North China from 2000 to 2004

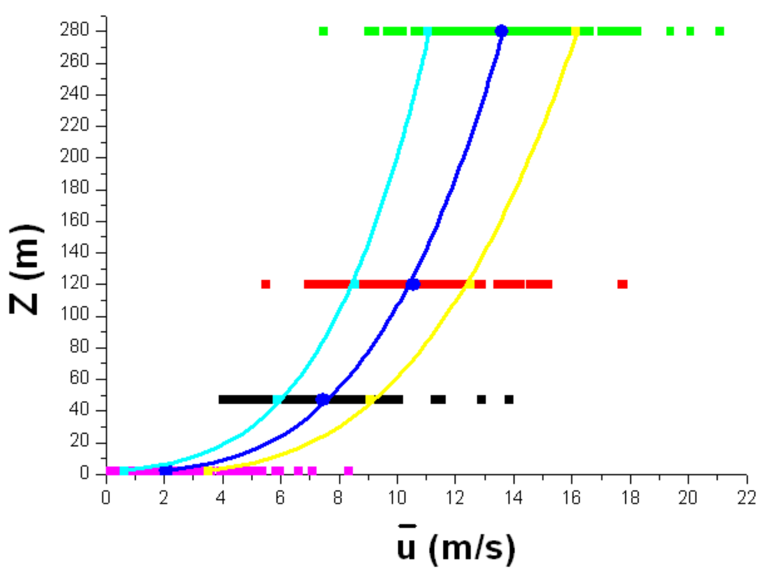
Year	2000	2001	2002	2003	2004
N_1	14	16	11	3	4
N_2	6	6	5	0	3

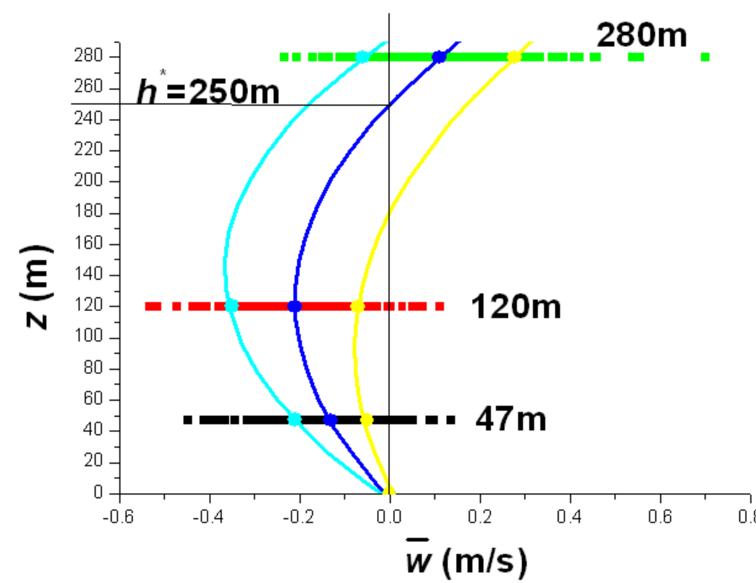
N_1—— the number of events in Mongolia and North China

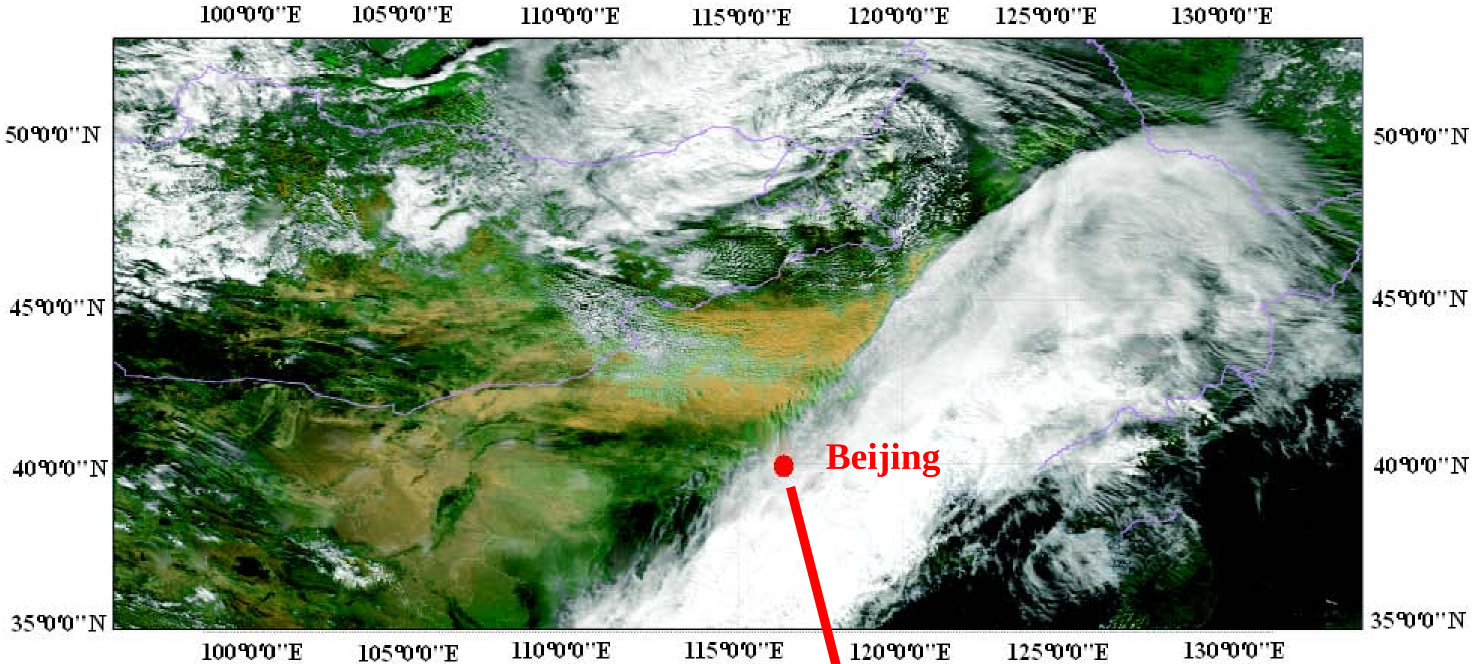
N_2—— the number of N_1 events covering Beijing

There were **48** weather processes with dust storm or sand blowing covering Mongolia and North China. Among them, **20** events consisted of **133 h data** that covered Beijing and its vicinity were analyzed.

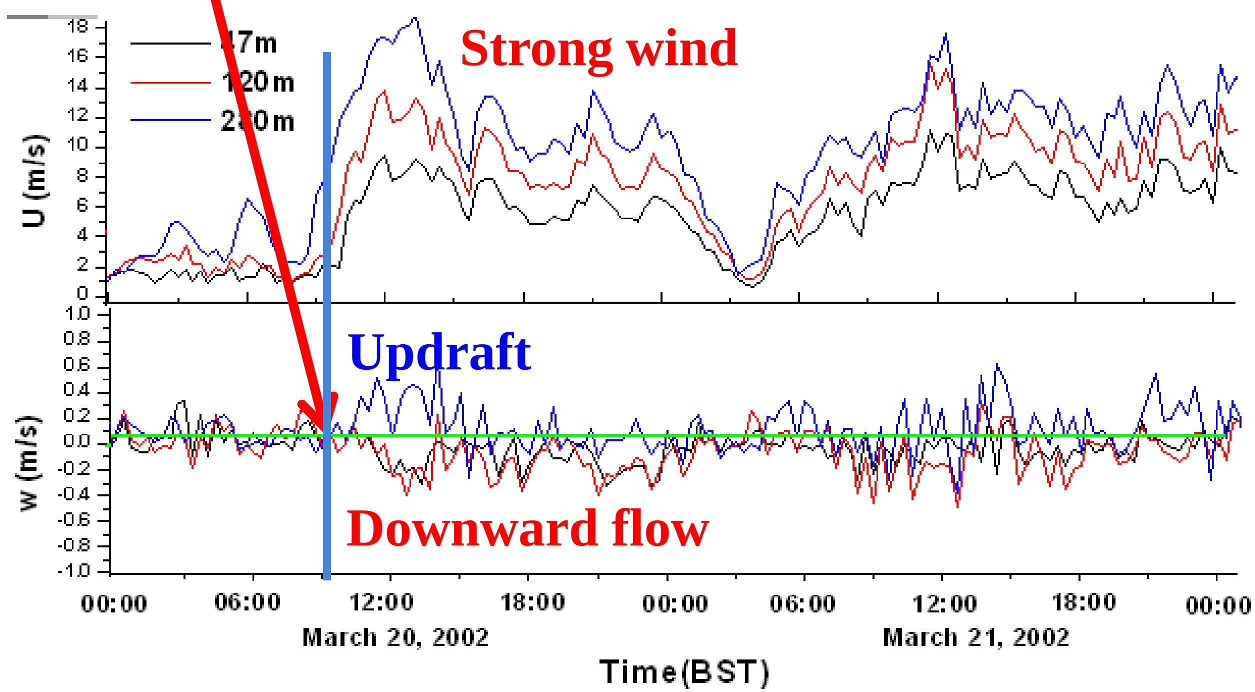
Vertical profiles of velocities

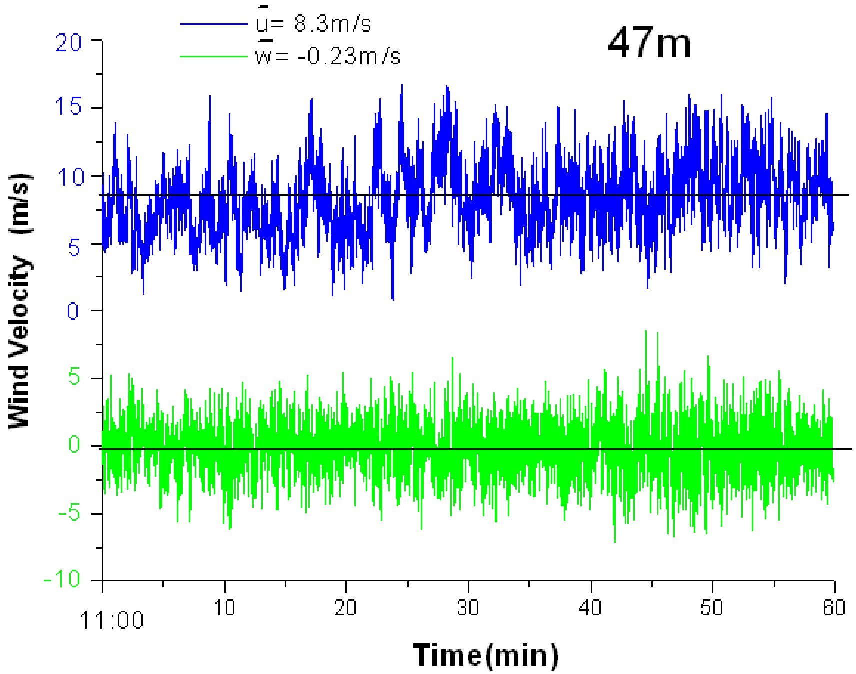




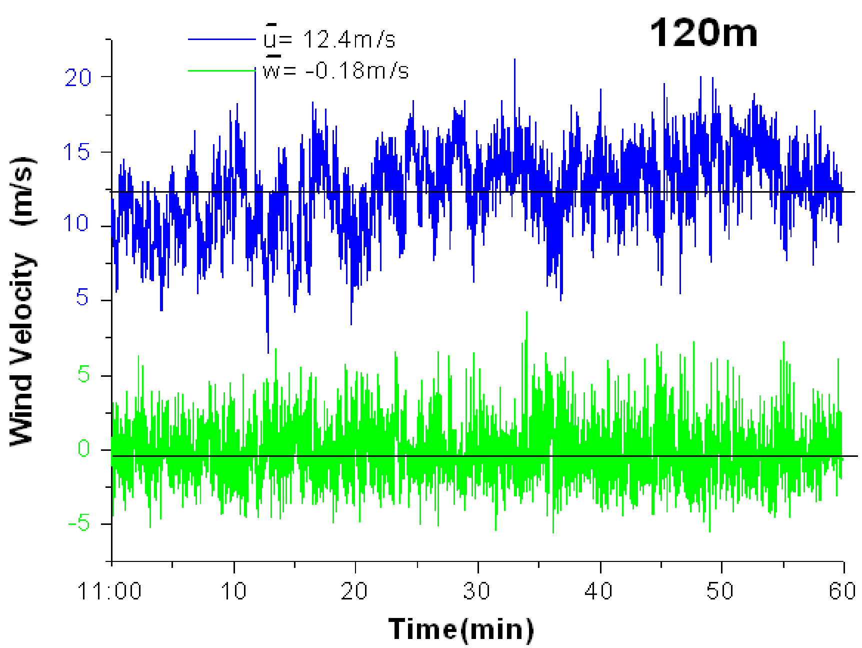


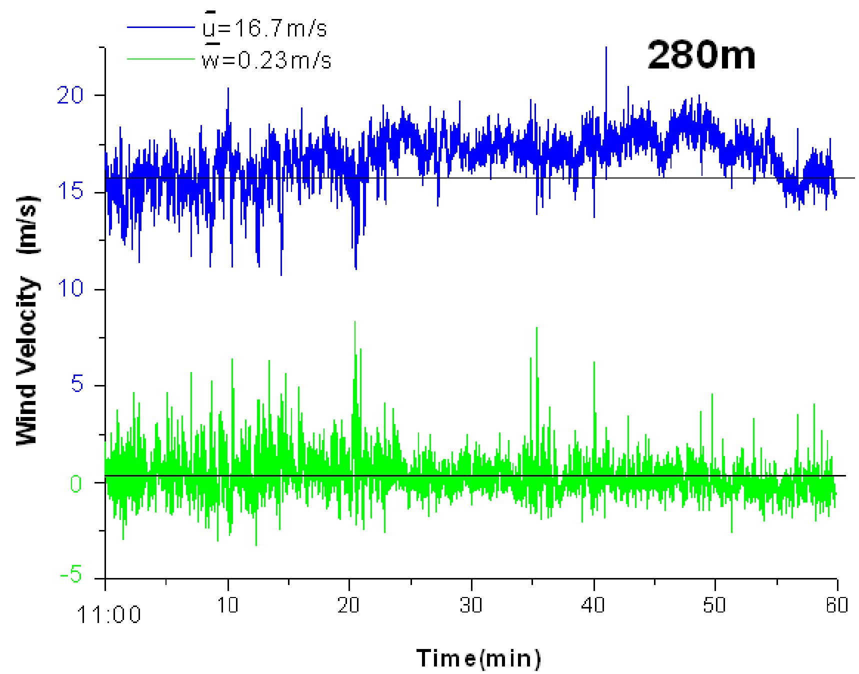
- During the sand storm in 2002, there is a cyclone development in Mongolia with spiral cloud systems and dust area. A cold frontal cloud belt before the dust area passed Beijing.





- Fluctuations in 2002.3.20 11:00
  - Turbulent eddies
  - Wind gust disturbances





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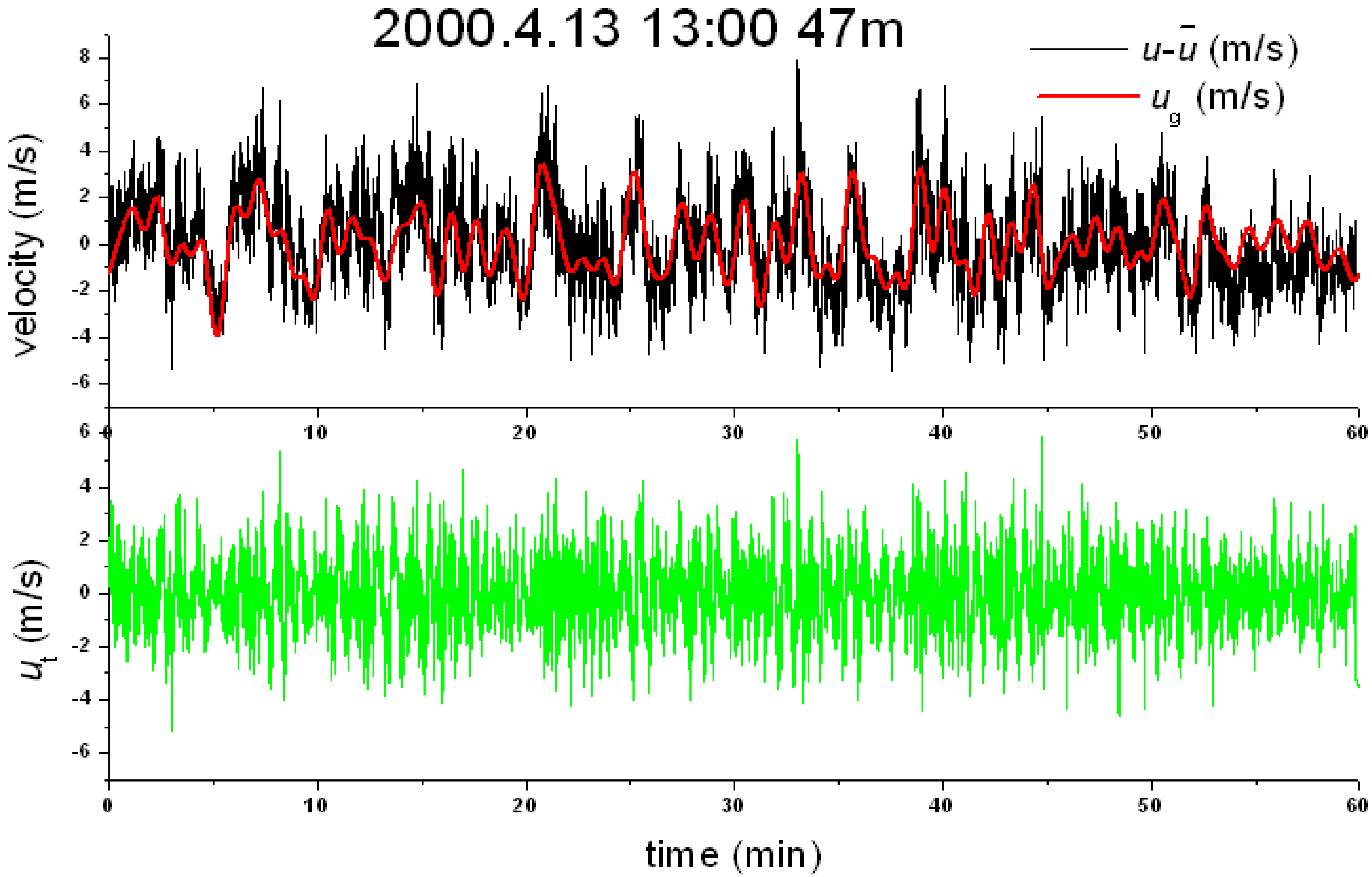
Division of the motions



- **10min:** **basic flow**
- **1~10min:** **wind gust** (anisotropic, coherent structure, u_g, v_g, w_g)
- **0~ 1min:** **turbulence** (quasi isotropic, near random or stochastic, u_t, v_t, w_t)

The essential difference between turbulence and gust

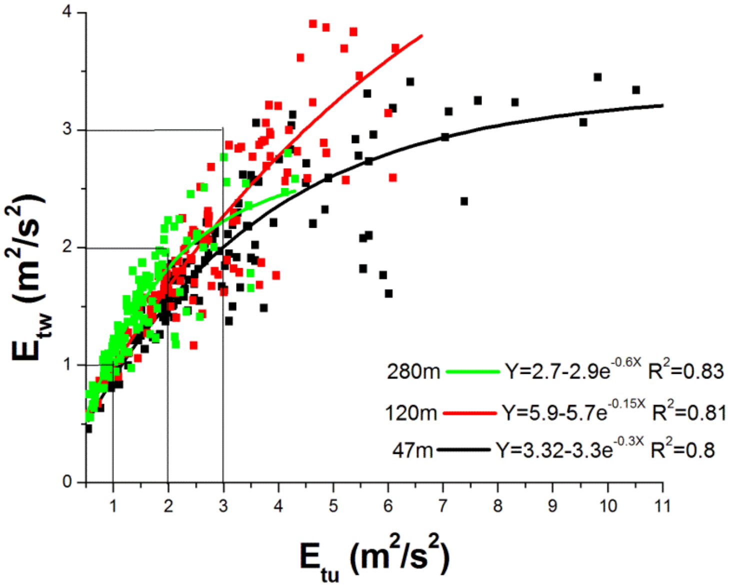
(1) Energy distribution in horizontal and vertical direction.

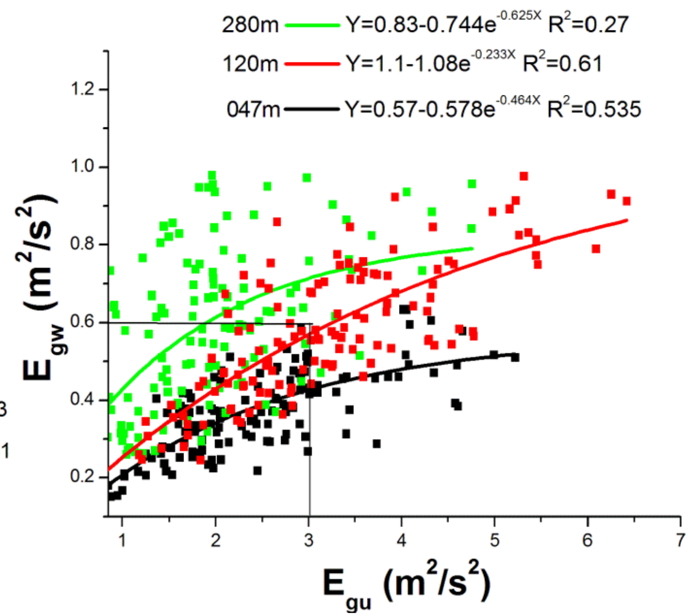
Turbulence —— quasi isotropic:

$E_{tu} \approx E_{tw}$

Gust—— ansiotropic:

$E_{tu} > E_{tw}$





(2) Index of correlation between horizontal and vertical components ($0 \geq r \geq 1$).

$$\left.\begin{aligned} r_t &= \frac{< u_{wt}^2 >}{\left(< \bar{v}_{ht}^2 > < w_t^2 >\right)^{1/2}} \\ r_g &= \frac{< u_{wg}^2 >}{\left(< \bar{v}_{hg}^2 > < w_g^2 >\right)^{1/2}} \end{aligned}\right\}$$

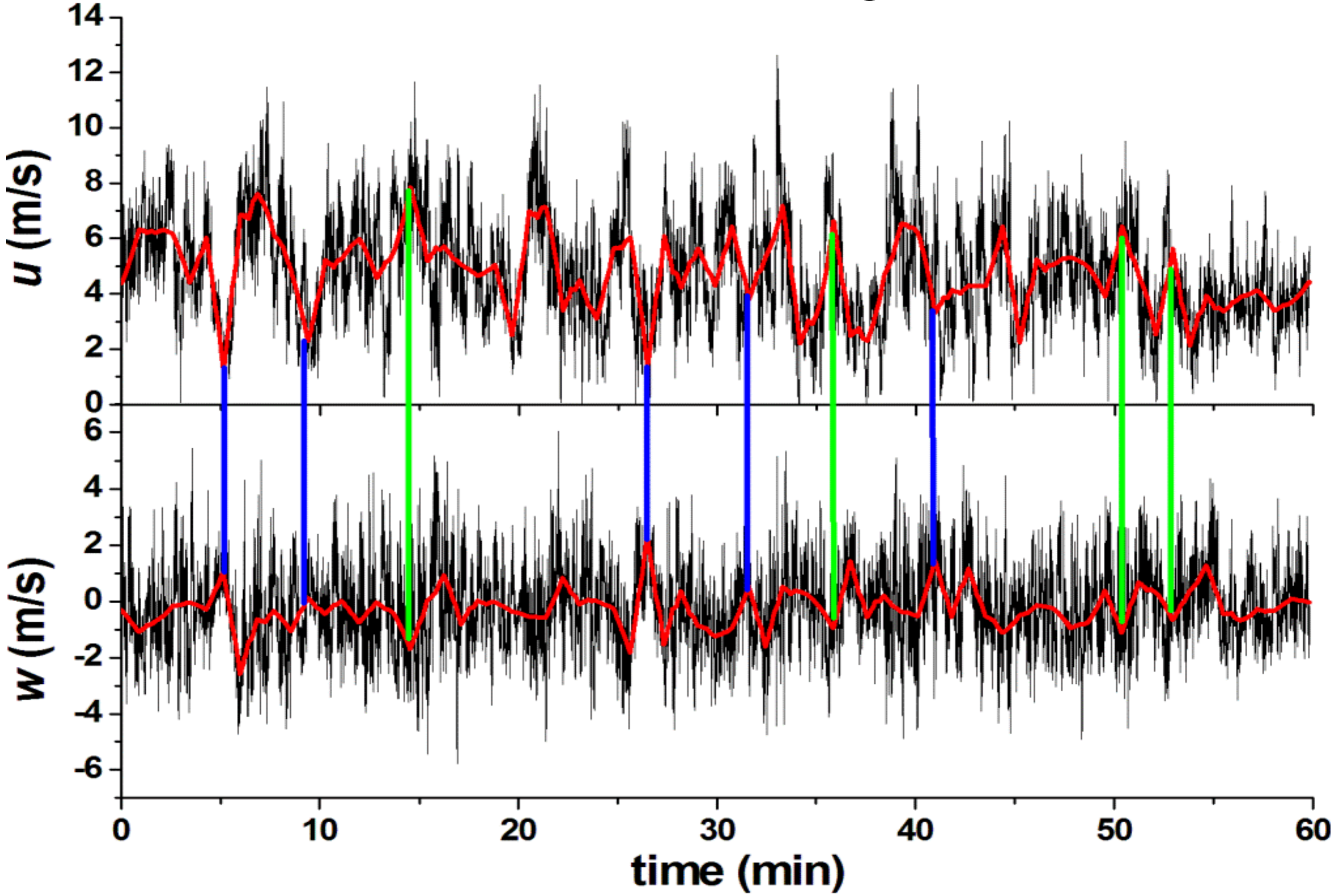
Turbulence —— near random (stochastic):

$r_t \approx 0.08 \sim 0.29$

Gust —— nearly coherent structure:

$r_g \approx 0.4 \sim 0.8$

The coherent structure of wind gust



- The vertical velocity is downward, horizontal velocity is on the peak, this strengthens soil erosion.
- Air is upward, horizontal velocity is on the valley, and the upward speed is greater than the basic sinking speed, this make dust particles entrained.

Parameterization of the wind gust characteristics

The major characteristics of the wind gust

- **mean amplitude of horizontal component A_{gh}**

$$A_{gh}^2 = U_g^2 + V_g^2$$

U_g —— **along basic wind ($\overline{u}$) direction**

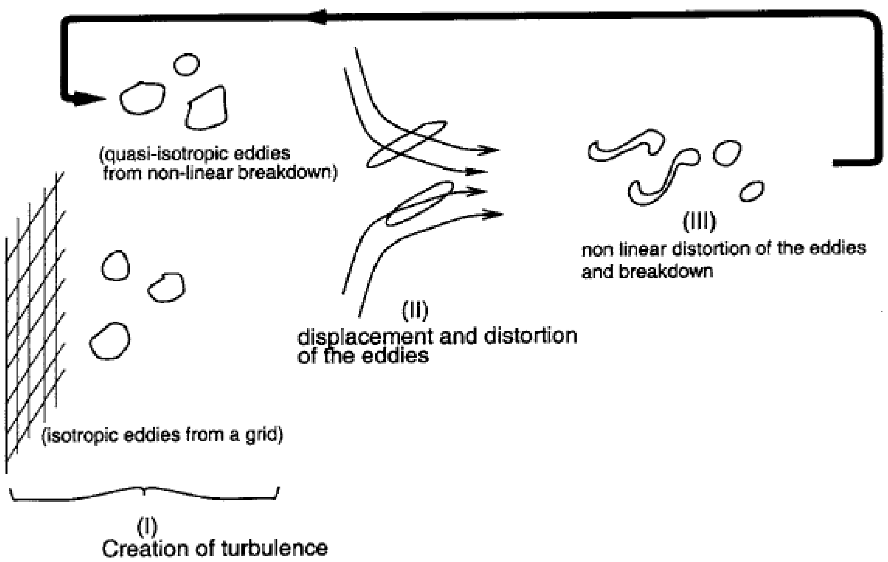
V_g —— **across $\overline{u}$ direction**

- **mean amplitude of vertical component A_{gw}**
- **friction velocity u_{g*}**

The major factors determining the wind gust characteristics

(a) neutral or weak unstable stratification

(b) the linear and nonlinear distortion



- Based on the linearised rapid distortion theory (Hunt and Carlotti, 2001), in shear flows, the eddies are advected and distorted on a time scale short enough that the dominant dynamics is linear.
- And during strong wind period, the shear is mainly due to the downward flow which brings energy to the low level of boundary layer.

(c) the parameter

$$G = \frac{\partial \overline{u}}{\partial z} h^{*} u_{t*}$$

h^{*} is the thickness of the shear layer (downward flow).

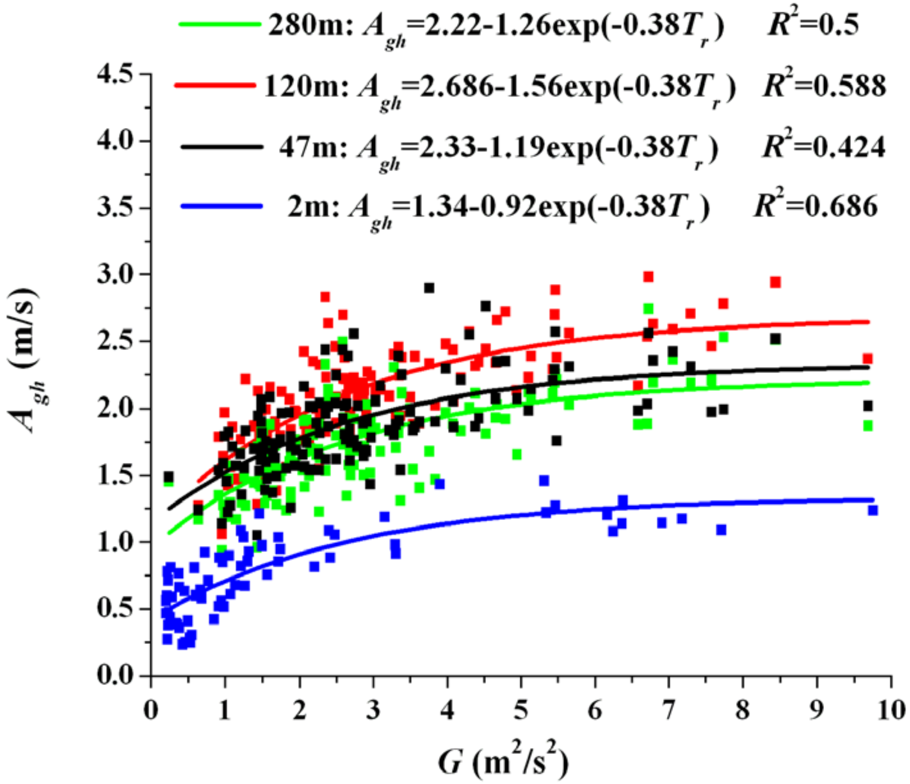
u_{t*} is the characteristic turbulence friction velocity which can be express as the function of *S*.

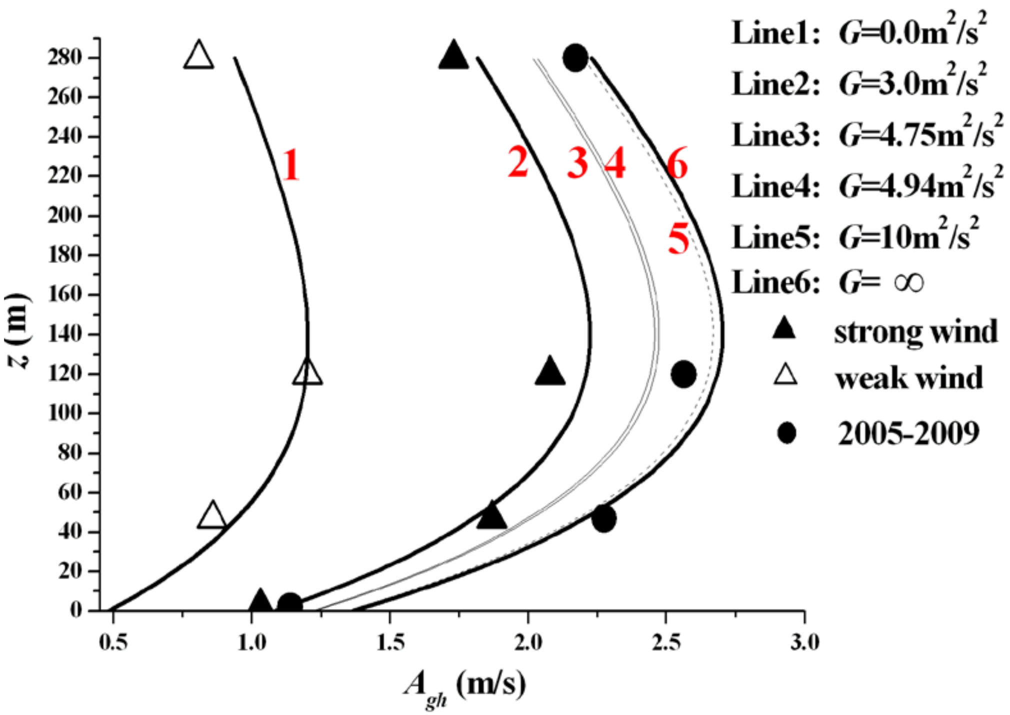
parameterization formula for mean amplitude of horizontal component

$$A_{gh}(\xi,G)=c_0(\xi)-c_1(\xi)e^{-\delta_0 G}$$

$$c_0(\xi)=\left(1.72+\frac{\xi}{25}\right)e^{-0.136\left(1.72+\frac{\xi}{25}\right)}$$

$$c_1(\xi)=\left(1.17+\frac{\xi}{50}\right)e^{-0.245\left(1.17+\frac{\xi}{50}\right)}$$



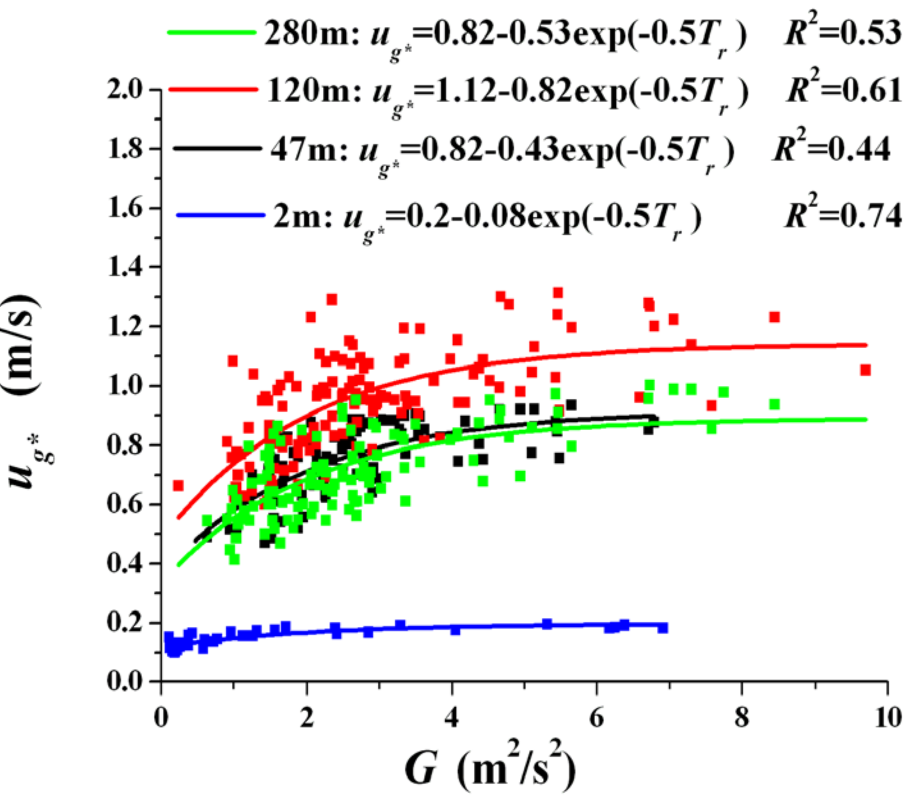


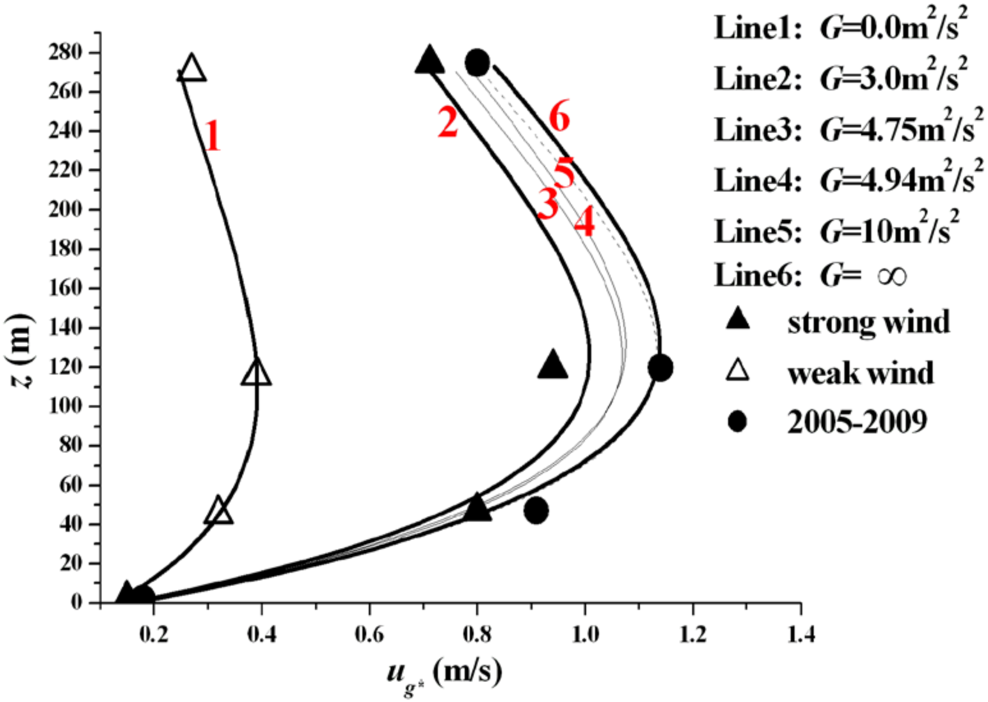
parameterization formula for gust friction velocity

$$u_{g*}(\xi, G) = f_0(\xi) - f_1(\xi)e^{-\lambda G}$$

$$f_0(\xi) = \left(0.168 + \frac{\xi}{45}\right)e^{-0.323\left(0.168+\frac{\xi}{45}\right)}$$

$$f_1(\xi) = \left(0.03 + \frac{\xi}{70}\right)e^{-0.488\left(0.03+\frac{\xi}{70}\right)}$$





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The equation governing the motion of a particle—— BBO equation

The equation governing the motion of a particle in a stationary fluid is generally attributed to Basset (1888), Boussinesq (1903) and Oseen (1927). It is called the BBO equation.

$$m_p \frac{dV_i}{dt} = (m_p - m_f) g_i + \cancel{m_f \frac{Du_i}{Dt}\Big|_{\vec{Y}(t)}}$$

$$\cancel{-\frac{1}{2} m_f \frac{d}{dt}\left\{V_i(t) - u_i\left[\bar{Y}(t),t\right] - \frac{1}{10} a^2 \nabla^2 u_i\Big|_{\vec{Y}(t)}\right\}} - 6\pi\mu a\left\{V_i(t - u_i\left[\bar{Y}(t),t\right] - \frac{1}{6} a^2 \nabla^2 u_i\Big|_{\vec{Y}(t)}\right\}$$

$$\cancel{- 6\pi\mu a^2 \int_0^t \left(\frac{d/d\tau\left\{V_i(\tau) - u_i\left[\bar{Y}(\tau),\tau\right] - \frac{1}{6} a^2 \nabla^2 u_i\Big|_{\vec{Y}(t)}\right\}}{\left[\pi\nu(t-\tau)\right]^{1/2}} \right) d\tau}$$

<u>1st term</u>: gravity – buoyancy force

<u>2nd term</u>: pressure gradient acceleration due to the acceleration of the surrounding fluid

<u>3rd term</u>: add mass term caused by the surrounding fluid being deflected around the particle.

<u>4th term</u>: force due to quasi – steady Stokes drag

<u>5th term</u>: Basset history term, arising from the diffusion of vorticity.

In a typical gas – particle flow, pressure gradient term, added mass term and Basset term are small. The particle motion is governed by Stokes drag and gravity.

$$\frac{dV_i(t)}{dt} = \frac{\left[u_i^p(\bar{y}(t),t) - V_i(t)\right]}{\tau_p} f - g\delta_{i3}$$

V_i is the particle velocity, u is the fluid velocity.

τ_p is the particle relaxation time. f is the Stokes drag coefficient.

Equation of fluid around the particle —— Langivan equation

- The movement of fluid around the particle $(\vec{x},\vec{u})$ is a markovian process
- The evolution of $(\vec{x},\vec{u})$ can be described by the Langivan equations

$$\begin{cases} dx_i = u_i dt \\ du_i = a_i(\vec{x},\vec{u},t)dt + b_{ij}(\vec{x},\vec{u},t)d\xi_j \end{cases} \qquad < \mathrm{d}\xi_i(\mathrm{t})\mathrm{d}\xi_j(\mathrm{t}+\tau) >= \delta_{ij}(t)\delta(\tau)\mathrm{dtd}\tau$$

- Inhomogeneous turbulence

$$\begin{cases} dx = Udt \\ dz = wdt \\ \\ dw = \left[-\frac{C_0}{2}\frac{\bar{\varepsilon}}{\sigma_w^2}w + \frac{1}{2}\left(1+\frac{w^2}{\sigma_w^2}\right)\frac{\partial\sigma_w^2}{\partial z}\right]dt + \sqrt{C_0\bar{\varepsilon}}\,d\xi \end{cases}$$

$d\xi$ are random increments of a Wiener process with independent components.

C_0 is the Kolmogorov constant, experimentally estimated to be 2.1

ε is the ensemble average rate of dissipation of turbulent energy

σ_w is the standard deviation of the vertical velocity distribution

Boundary conditions

(1) The wind profiles and the turbulent characteristics get from the observation data:

$$\begin{cases} u(z) = u_{sur} + u_0\left(\frac{z}{\delta}\right)^{0.28} & z \le h^* \\ u = 13\text{m/s} & z > h^* \\ u_{sur} = 1\text{m/s} & \\ u_0 = 12\text{m/s} & \\ h^* = 250\text{m} & \end{cases}$$

$$u_{*_{t-47m}} = 0.8m/s$$

$$\sigma_w = \begin{cases} u_{*_{t-47m}} & if\ z \le 0.2h^* \\ u_{*_{t-47m}}\left(1.2 - \frac{z}{h^*}\right) & if\ 1.2h^* > z > 0.2h^* \\ 0.004u_{*_{t-47m}} & if\ z \ge 1.2h^* \end{cases}$$

$$\bar{w} = -0.0031z + 1.24 \times 10^{-5} z^2$$

(2) The wind gust disturbances (u_g,w_g) get from the parameterization:

$$u_g = A_{gh}\cos[\theta_{u_g} + \frac{2\pi}{\overline{T}_g}(t - \frac{z}{c_\perp})]$$

$$w_g = A_{gw}\sin[\theta_{w_g} + \frac{2\pi}{\overline{T}_g}(t - \frac{z}{c_\perp})]$$

Where A_{gh} and A_{gw} are the profiles of horizontal and vertical amplitudes of wind gust. θ_{ug} and θ_{wg} are the initial horizontal and vertical phase angle of wind gust. T_g is the equivalent period of wind gust which changes with height, $c_\perp$ is the downward speed of wind gust, here is always 1m/s.

Initial conditions

(3) The injection velocity and injection angle are random variables with Gaussian probability density functions.

$$w_p = 2u_{*_e} + u_{*_e}(\chi_w - 0.5) = 1.2 + 0.6(\chi_w - 0.5)$$

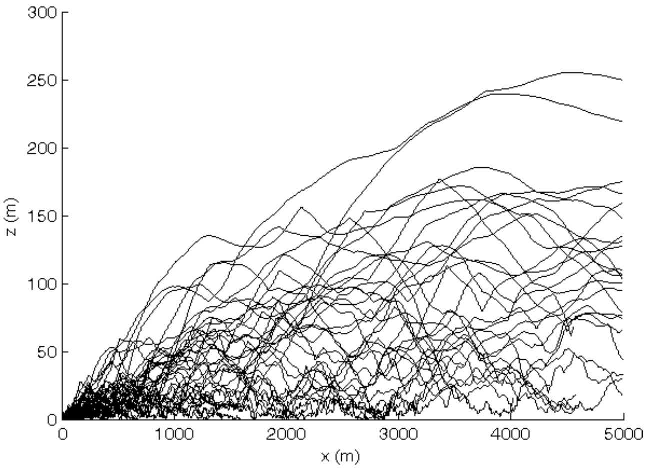
$$\alpha = 45 + 45(\chi_\alpha - 0.5)$$

Other conditions

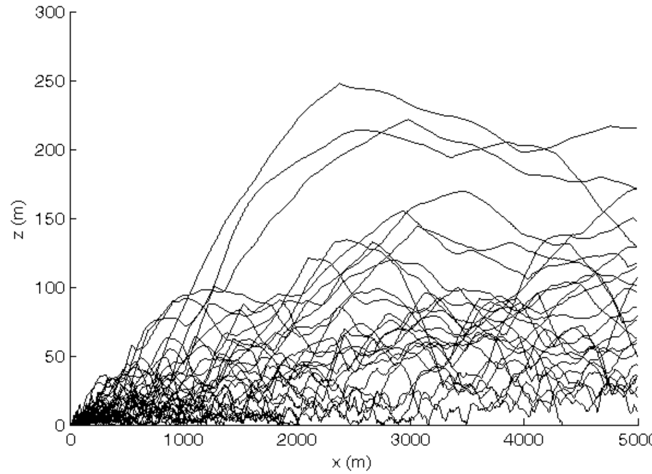
(4) Particles: dust(1500kg/m³), dust and sand (1700kg/m³), sand(2650kg/m³)

(5) Diameters: 5μm, 10μm, 20μm, 40μm (suspension)

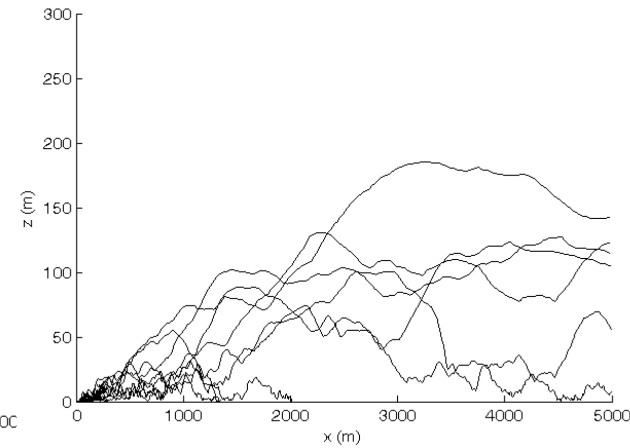
① Under basic horizontal flow with turbulence, but no wind gust



ρ_p=1500kg/m^{-3} d_p=5μm



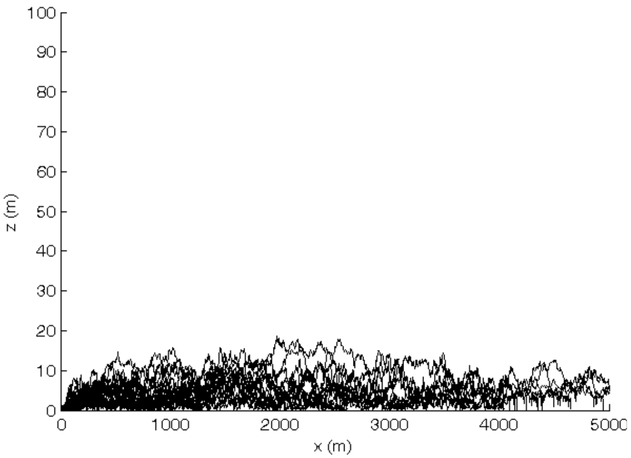
ρ_p=1700kg/m^{-3} d_p=20μm



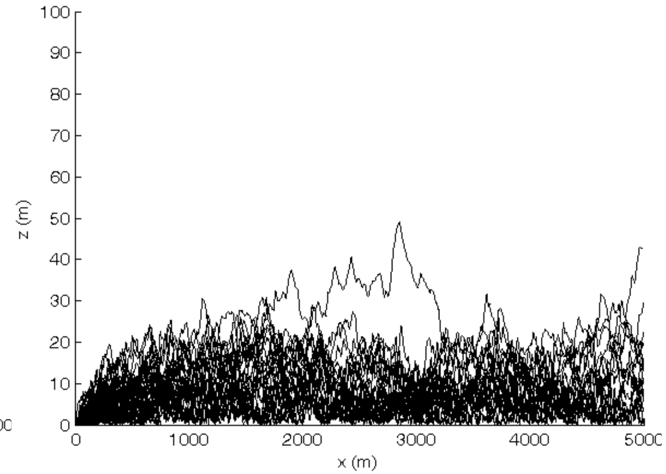
ρ_p=2650kg/m^{-3} d_p=40μm

- Thickness of sand/dust two phase flows in the boundary layer is about 1.5m. 66% dust particles, 52% dust and sand particles, 12% sand particles can reach higher than 1.5m.
- The most height where the dust or dust and sand particles can reach is about 250m, and 180m for sand particles.

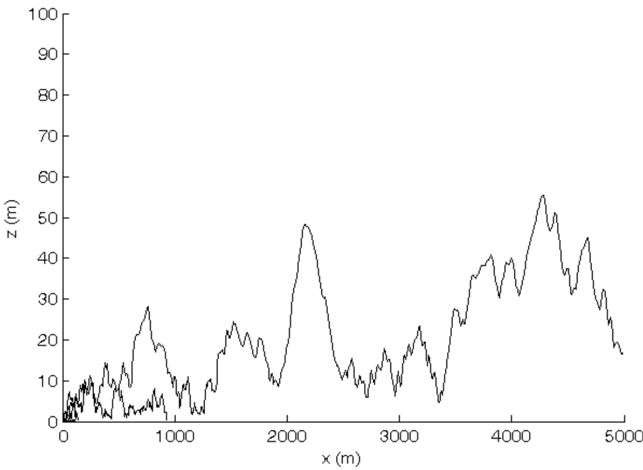
② Under basic horizontal and downward flow with turbulence, also no wind gust



ρ_p=1500kg/m^{-3} d_p=5μm



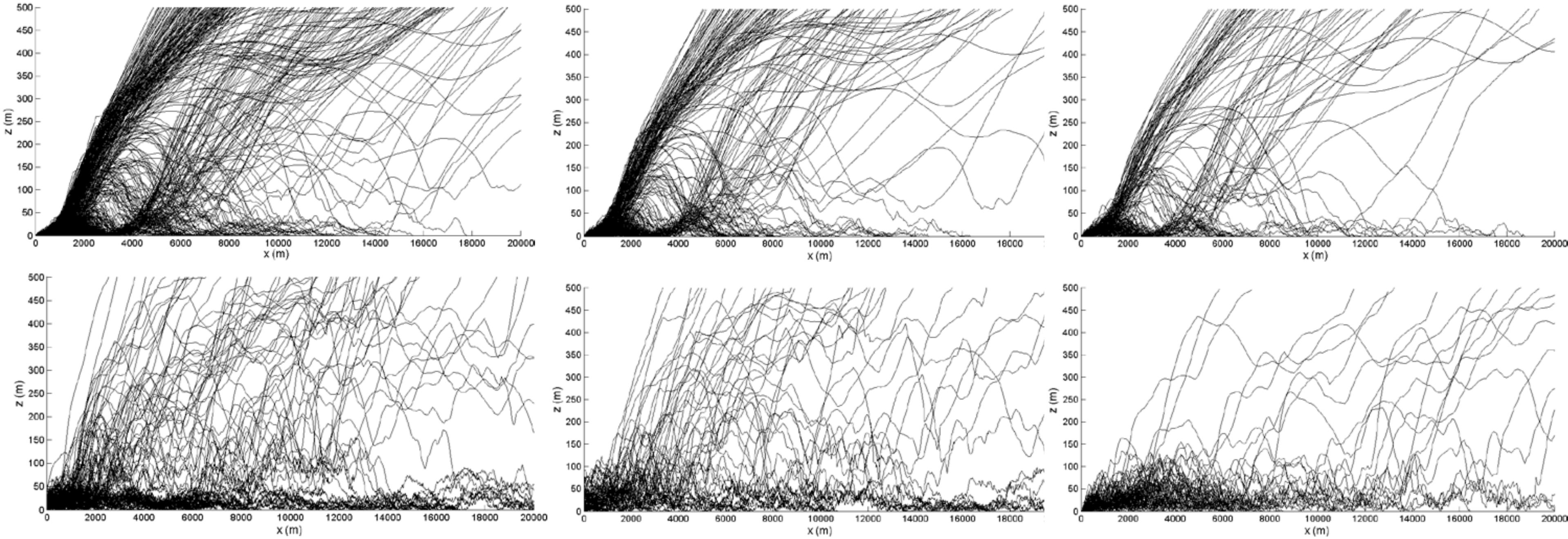
ρ_p=1700kg/m^{-3} d_p=20μm



ρ_p=2650kg/m^{-3} d_p=40μm

- 8% dust particles, 28% dust and sand particles, 2% sand particles can reach higher than 1.5m.
- The most height where the dust particles can reach is about 20m. Except one dust/sand particle, others are below 30m. Except one sand particle, others can reach no more than 1m.

③ Under basic horizontal and downward flow, turbulence, and wind gust

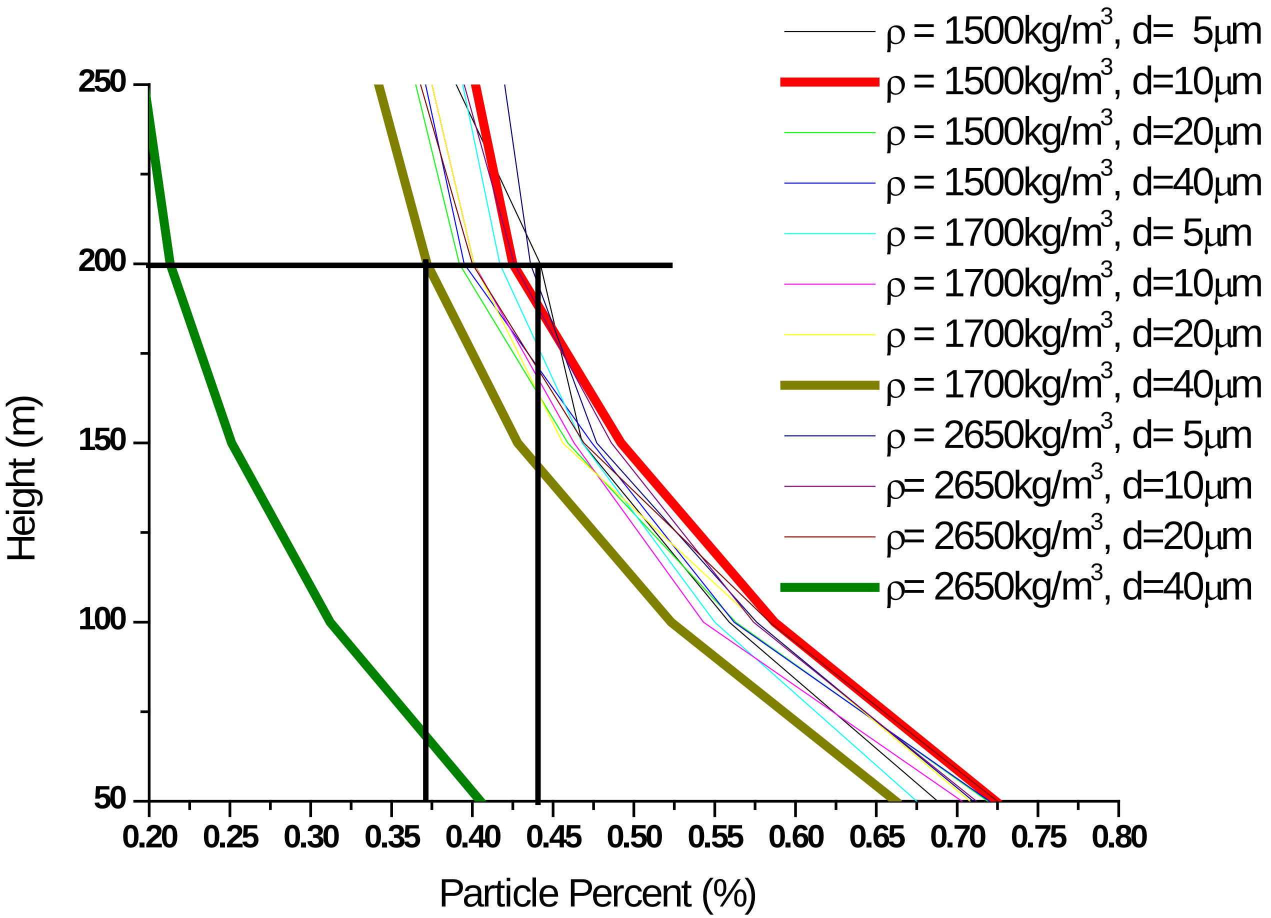


ρ_p=1500kg/m^{-3} d_p=5μm

ρ_p=1700kg/m^{-3} d_p=20μm

ρ_p=2650kg/m^{-3} d_p=40μm

- ➢The particles can reach >500m. Top row is the particle trajectories under the parameterization of wind gust.
- ➢Below is the particle trajectories under the real wind condition, comparing to top row, the particle trajectories look alike. It tests that the parameterizations of wind gust are reasonable.



- The particle is heavier or larger, the numbers which can be entrained into higher level are less.
- 37% -43% dust particles can reach upper layer (200m).

Conclusion

1. In northeast Asia, after cold front passage, strong wind breaks out.
2. Superimposed on average flow are random turbulence and wind gust, it is coherent structure.
3. The descending motion of basic flow is favorable for soil erosion but suppresses the flying-up of dust particles.
4. Turbulence can make particles reach to middle layer.
5. Due to the wind gust, particles can reach to top layer, and then propagate further.

Thank You !