A Comparative Study on the Applicability of Different Sand Emission Threshold Determination Schemes in the Taklamakan Desert (Postprint)

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Abstract

Aeolian sand transport is a significant surface process in regional and global change studies. The sand initiation threshold (critical wind speed for sand initiation, critical friction velocity for sand initiation) is a key parameter for determining the onset of aeolian sand transport and a core issue in aeolian transport research. Using simultaneous field observations of sand transport and meteorological data from the hinterland of the Taklamakan Desert combined with mathematical modeling, the applicability of Stout, Kurosaki and Mikami (KM), Li Xiaolan and Zhang Hongsheng (LZ), Mar ticorena and Bergametti (MB), Shao and Lu (SL) five sand-initiation threshold determination schemes were quantitatively evaluated, and the optimal scheme was used to determine a new sand-initiation threshold for the study area. The results show: (1) All five schemes involve uncertainties; the sand-initiation threshold determined by the KM scheme overestimates the duration of sand entrainment and the horizontal dust flux to a certain extent, while the other four schemes produce the opposite effect, but the KM scheme is optimal. (2) In the hinterland of the Taklamakan Desert, the critical wind speed for sand initiation at 2 m height ranges from 4.0~ 6.0 m · s-1, and the critical friction velocity for sand initiation ranges from 0.24~0.36 m · s-1; the sand-initiation threshold exhibits seasonal variation, conforming to summer > autumn > spring > winter variation pattern.

Full Text

Comparative Study of the Applicability of Different Emission Threshold Determination Schemes in the Taklimakan Desert

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Abstract

Wind-blown sand movement is a crucial surface process that cannot be ignored in regional and global change research. The emission threshold (critical threshold wind speed, critical threshold friction velocity), as a key parameter for determining whether wind-sand movement occurs, represents a core issue in wind-sand movement research. Using synchronously observed wind-sand movement and meteorological data from the hinterland of the Taklimakan Desert, combined with mathematical model calculations, this study quantitatively evaluated the applicability of five emission threshold judgment schemes from Stout, Kurosaki and Mikami (KM), Li Xiaolan and Zhang Hongsheng (LZ), Marticorena and Bergametti (MB), and Shao and Lu (SL). The results show that: (1) All five schemes have uncertainties. The KM scheme overestimates dust emission duration and horizontal dust flux to a certain extent, while the other four schemes underestimate them, but the KM scheme performs best. (2) The 2 m threshold velocity in the hinterland of the Taklimakan Desert varies from 4.0 $\mathrm{m \cdot s^{-1}}$ to 6.0 $\mathrm{m \cdot s^{-1}}$, and the threshold friction velocity varies from 0.24 $\mathrm{m \cdot s^{-1}}$ to 0.36 $\mathrm{m \cdot s^{-1}}$. The emission threshold exhibits seasonal differences, following the pattern of summer > autumn > spring > winter.

Keywords: wind-blown sand movement; threshold velocity; threshold friction velocity; Taklimakan Desert

Introduction

Wind-blown sand movement is one of the important surface processes in global arid and semi-arid regions. It can cause desertification and soil erosion, bury roads, farmland, and villages. Meanwhile, dust aerosol emissions, transport, and deposition caused by wind-sand movement significantly impact regional and global climate change, ecological environments, and human health. Therefore, research on wind-sand movement has received widespread attention in fields such as geomorphology, meteorology and climate, and ecology and environment.

Wind is the critical dynamic factor for wind-sand movement. Only when wind speed (u) or friction velocity (u_*) reaches a certain critical value does wind-sand movement occur. This value is the threshold velocity (u_t) or threshold friction velocity (u_{*t}). These two parameters have the same physical meaning, with the former determined directly from wind speed and sand movement observations, while the latter requires converting wind speed to friction velocity and then combining with sand movement observation data. Scholars from different disciplines use these terms differently: geographers typically use threshold velocity, while meteorologists and environmental scientists prefer threshold friction velocity.

This study collectively refers to both as the emission threshold.

The emission threshold is not only a key indicator for determining whether wind-sand movement can occur but also a core parameter in soil wind erosion models and dust storm forecasting models, determining the calculation of wind erosion intensity and dust flux. Studies have shown that under the same conditions, a reduction in the emission threshold can increase sand emissions by 32.1% to 69.2%.

The magnitude of the emission threshold is closely related to soil properties (such as soil moisture, particle size, and composition), vegetation (such as coverage), and atmospheric conditions (such as wind, temperature, and humidity). When soil moisture exceeds the critical value affecting sand emission (approximately 0.005 $m^3 \cdot m^{-3}$), the emission threshold increases with soil moisture. In dust emission parameterization schemes, the emission threshold is expressed as a function of soil particle size, with the minimum threshold corresponding to a particle size of approximately 74 m; thresholds increase for particle sizes smaller or larger than this value. Salt crusts or crusts formed by salt content on the surface can increase the emission threshold by 3 to 8 times. Vegetation coverage can reduce sand supply and decrease wind shear stress on the surface, thereby reducing the probability of sand emission and increasing the threshold. Increased air humidity can raise surface soil moisture or increase viscosity between soil particles, leading to higher emission thresholds. Temperature changes can alter air humidity, thereby affecting the emission threshold.

Research on emission threshold determination methods has been extensive, with Li Xiaolan classifying them into observation methods (including wind tunnel experiments and field experiments), statistical methods, and parameterization. However, comparative studies of various methods are still limited, making it unclear which method holds greater advantages.

China has 2.6116$×10^{6}$ km^2 of desertified land, making it one of the countries severely affected by wind-sand movement. The Taklimakan Desert is China's largest desert, with wind-sand activity intensity ranking among the highest in the world. Meanwhile, the Tarim Basin where it is located serves as an important carrier for Xinjiang's society, economy, and culture. The Taklimakan Desert and its surrounding areas contain 53.5% of Xinjiang's oases, house 48.07% of Xinjiang's population, and store abundant oil, gas, and other mineral resources. Therefore, conducting emission threshold research in this region to provide forecasting and early warning for wind-sand disasters and dust weather events holds significant importance for local economic and social development and ecological environmental protection.

Previous research on emission thresholds in the Taklimakan Desert includes: Chen Weinan et al. determined the instantaneous impact threshold velocity at 2 m height to be 5.0 $m \cdot s^{-1}$ in the Xiaotang area on the desert's northern edge through visual observation of sand movement synchronized with wind speed data, a value widely used in Taklimakan Desert wind-sand research. Ishizuka et al. measured threshold velocities at 1 m height in the Cele area on the desert's southern edge using optical sensors, obtaining values of 7.5 $\mathrm{m\cdot s^{-1}}$ for dry sand and 9.5 $\mathrm{m\cdot s^{-1}}$ for wet sand. Kurosaki and Mikami statistically derived 2 m threshold velocities of 5.2–8.2 $\mathrm{m\cdot s^{-1}}$ (mean 6.3 $\mathrm{m\cdot s^{-1}}$) based on meteorological station wind speed and dust storm data around the desert. Yang et al. calculated 2 m threshold velocities of 3.5–10.9 $\mathrm{m\cdot s^{-1}}$ using measured saltation data from the desert hinterland. Zhou et al. compared differences among several commonly used emission threshold determination methods based on field observation data.

Nevertheless, research on emission thresholds in the Taklimakan Desert still has the following deficiencies: short observation periods, lack of understanding of seasonal variations in emission thresholds, and no evaluation of the applicability of determination methods in the study area. This study, based on long-term field observation data from the Taklimakan Desert hinterland, evaluates the applicability of five commonly used emission threshold determination methods, selects the optimal method, and subsequently determines new emission thresholds to provide more accurate criteria for determining wind-sand movement in the study area.

Study Area

The experimental site of this study is located in the Tazhong area (39°00 N, 83°38 E, elevation 1103 m) in the hinterland of the Taklimakan Desert. The geomorphology of Tazhong features alternating longitudinal sand ridges and inter-ridge areas. The sand ridges primarily trend NE-SW, with relative heights of 1–3 km, while the inter-ridge areas are about 40–50 m wide and relatively open and flat. The experimental site is situated on flat sand ground between sand ridges. Using meteorological observation data from the Tazhong Meteorological Station from 2005 to 2017, the study area has an average annual temperature of 11.7 °C, with a recorded maximum temperature of 46.0 °C and minimum of -32.6 °C. The average annual precipitation is 27.6 mm, with June–August precipitation accounting for approximately 87.6% of the annual total. The average annual evaporation reaches 3741.8 mm. The average annual wind speed is 2.2 $\mathrm{m\cdot s^{-1}}$, with 10.7 days of strong winds per year on average. The average annual days of dust storms, blowing sand, and floating dust are 17.0, 68.0, and 122.0 days respectively, with spring and summer being the high-incidence seasons.

Methods

Wind-Blown Sand Movement Data

Wind-blown sand movement was observed using Sensit piezoelectric wind erosion sensors and Big Spring Number Eight sand traps [Figure 1: see original paper]. When sand particles impact the sensor's crystal, a pulse signal is output to a Campbell CR1000 data logger, which records the number of impacting particles; when no particles impact, it records zero. The data collection time step is 1 min, enabling continuous observation of particle impact counts. When the impact count in a given minute exceeds zero, that minute is recorded as sand movement duration, allowing statistics on total impact counts and duration for each dust storm event. The wind erosion sensors were installed at a height of 10 cm, and this study uses only the 10 cm height measurements. Sensit wind erosion sensors have been validated through long-term field experiments and perform well in measuring sand emission processes in the study area. To compensate for the sensor's inability to measure dust transport flux, a sand collection tower was erected beside it. The tower height is 200 cm, with five sand traps installed on the 200 cm cross-section at heights of 10 cm, 50 cm, 100 cm, 150 cm, and 200 cm above ground. The sampling frequency corresponds to individual dust storm or blowing sand events. The combined data from the five instruments can obtain horizontal dust flux across the 100 cm × 200 cm cross-section at the observation point for different time steps, used to validate calculations from dust flux parameterization schemes.

Near-Surface Micrometeorological and Dust Concentration Data

Near-surface micrometeorological and dust concentration observations were conducted using a 10 m gradient detection platform. The platform is equipped with seven levels of gradient wind speed sensors (at 0.5 m, 1 m, 2 m, 4 m, 6 m, 8 m, and 10 m), wind direction sensors (at 10 m), air temperature and humidity sensors (at 1.5 m and 5.0 m), and a dust concentration monitor (Grimm1.108) at 2 m height. The platform also includes one soil moisture probe (at 10 cm depth). Micrometeorological measurement data are stored in a Campbell CR1000 data logger with a 30 min time step. The Grimm1.108 measures dust concentrations of particles below 20 m at a frequency of 1 min. Dust weather data are derived from 5 min weather phenomenon observation records at the Tazhong Meteorological Station.

Emission Threshold Determination Methods

Based on the experimental content, five schemes were selected: Stout, Kurosaki and Mikami (KM), Li Xiaolan and Zhang Hongsheng (LZ), Marticorena and Bergametti (MB), and Shao and Lu (SL). The Stout scheme represents field observation methods, KM represents statistical methods, and LZ, MB, and SL represent parameterization methods.

Stout Method: Stout developed a method for determining threshold velocity based on wind erosion sensor measurements of sand movement:

$$u_t = \bar{u} + \sigma\Phi^{-1}(\gamma)$$

where u_t is the minute threshold velocity ($\mathrm{m \cdot s^{-1}}$), $\bar{u}$ is the minute average wind speed, σ is the standard deviation of minute average wind speed, γ is the sand movement intensity coefficient representing the proportion of sand occurrence time within a unit time, with a value range of 0–1. When $\gamma = 1$, it indicates continuous sand movement; when $\gamma = 0$, it indicates no sand movement; and Φ^{-1} is the inverse normal distribution function. This method has been applied to threshold determination in multiple regions.

KM Method: Kurosaki and Mikami developed a threshold determination method based on wind speed and dust storm observation data:

$$P_i = \frac{n_i}{N_i} \times 100$$

where P_i is the percentage, n_i is the frequency of sand movement occurrence at wind speed level i, N_i is the total frequency at wind speed level i, the wind speed level i has a grouping interval of 0.2 $\mathrm{m \cdot s^{-1}}$, and the wind speed level at which P_i is 50% is defined as the threshold velocity u_t.

LZ Method: Li Xiaolan and Zhang Hongsheng, based on dust emission test data from the Horqin Sandy Land in Inner Mongolia, determined the threshold velocity as the wind speed at which dust concentration at a certain observation height begins to increase rapidly and continuously.

MB and SL Methods: The parameterization schemes developed by Marticorena and Bergametti and Shao and Lu are the most widely used in current dust storm models. Both schemes can be expressed as:

$$u_{*t} = u_{*ts} \cdot f_\lambda \cdot f_w$$

where u_{*t} is the threshold friction velocity, u_{*ts} is the threshold friction velocity for a smooth surface, f_λ is the surface roughness element correction equation, and f_w is the soil moisture correction equation.

The specific formulas for the MB scheme are:

$$u_{*ts} = 0.092 \left(\frac{\rho_s}{\rho_a}\right)^{0.5} g d_p \left(1.928 \left(\frac{d_p}{d_{p0}}\right)^{-0.0617} - 1\right)^{0.5}$$

$$f_\lambda = \begin{cases} 1 & \lambda \leq 0.03 \\ 1 + 1.21\lambda & 0.03 < \lambda \leq 0.7 \\ 1.21\lambda & \lambda > 0.7 \end{cases}$$

$$f_w = \begin{cases} 1 & w < 0.0014 \\ 1.0 + 1.21(w - 0.0014)^{0.68} & w \geq 0.0014 \end{cases}$$

The specific formulas for the SL scheme are:

$$u_{*ts} = 0.092\left(\frac{\rho_s}{\rho_a}\right)^{0.5} g d_p \left(1 + \frac{0.006}{d_p + 0.001}\right)^{0.5}$$

$$f_\lambda = \frac{(1-m_r)^{0.5}(1+\sigma_r\lambda)^{0.5}}{1+\beta_r\lambda}$$

$$f_w = \begin{cases} 1 & w < 0.03 \\ (1+aw^b)^{0.5} & w \geq 0.03 \end{cases}$$

Both schemes calculate the threshold friction velocity u_{*t}, which can be converted to u_t using the following formula for comparison with thresholds determined by other methods:

$$u_t = \frac{u_{*t}}{k} \ln \frac{z}{z_0}$$

where k is the von Kármán constant (0.4), z is the measurement height (2.0 m), and z_0 is the surface roughness length.

Horizontal Dust Flux Determination Method

Horizontal dust flux is calculated using the Owen scheme:

$$Q_i(z) = E \cdot c_i \cdot \frac{\rho_a}{g} u_*^3 \left(1 + \frac{u_{*t}}{u_*}\right)\left(1 - \frac{u_{*t}^2}{u_*^2}\right)$$

where $Q_i(z)$ is the horizontal dust flux for particle size group i ($\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$), c_i is a coefficient, ρ_a is air density, g is gravitational acceleration, u_* is friction velocity, and u_{*t} is threshold friction velocity. Since the threshold obtained in this study represents the overall particle size group, Q_i is taken as Q.

Results

Applicability Assessment of Emission Threshold Determination Methods

Based on data completeness, this study selected the dust storm process on July 17, 2009, as an example to validate the applicability of each emission threshold determination method in the study area. Figure 2 shows the wind speed and sand movement changes during this dust storm. The wind speed began to increase from around 5.0 $\mathrm{m \cdot s^{-1}}$ at 4:00–5:00, when weak sand movement could already be detected. When wind speed increased to above 6.0 $\mathrm{m \cdot s^{-1}}$ around 7:00, sand movement intensity increased rapidly and continued until around 19:00. As wind speed decreased, sand movement weakened and ended. The total duration of this dust storm event was 735 minutes, with minimum minute-average wind speed of 3.1 $\mathrm{m \cdot s^{-1}}$, maximum of 11.2 $\mathrm{m \cdot s^{-1}}$, and mean of 7.5 $\mathrm{m \cdot s^{-1}}$.

The minute threshold velocities determined by the Stout method varied from 3.1–9.1 $\mathrm{m \cdot s^{-1}}$ with a mean of 6.4 $\mathrm{m \cdot s^{-1}}$. The minute threshold friction velocities varied from 0.19–0.54 $\mathrm{m \cdot s^{-1}}$ with a mean of 0.38 $\mathrm{m \cdot s^{-1}}$. Using the minute threshold velocity as the criterion for sand movement, the duration was 517 minutes, or 70.3% of the actual duration. Using the mean value as the criterion, the duration was 614 minutes, or 83.5% of the actual duration.

The KM method determined a threshold velocity of approximately 4.8 $\mathrm{m \cdot s^{-1}}$ and threshold friction velocity of about 0.29 $\mathrm{m \cdot s^{-1}}$. Using these values, the sand movement duration was 756 minutes, or 102.9% of the actual duration.

The LZ method determined a threshold velocity of approximately 6.8 $\mathrm{m \cdot s^{-1}}$ and threshold friction velocity of about 0.41 $\mathrm{m \cdot s^{-1}}$. Using these values, the duration was 457 minutes, or 62.2% of the actual duration.

The MB method calculated nearly constant minute threshold velocities of 5.4–6.0 $\mathrm{m \cdot s^{-1}}$ (mean 5.6 $\mathrm{m \cdot s^{-1}}$) and threshold friction velocities of 0.32–0.36 $\mathrm{m \cdot s^{-1}}$ (mean 0.33 $\mathrm{m \cdot s^{-1}}$). Using these values, the duration was 495 minutes, or 67.3% of the actual duration.

The SL method calculated minute threshold velocities of 5.4–6.0 $\mathrm{m \cdot s^{-1}}$ (mean 5.6 $\mathrm{m \cdot s^{-1}}$) and threshold friction velocities of 0.32–0.36 $\mathrm{m \cdot s^{-1}}$ (mean 0.33 $\mathrm{m \cdot s^{-1}}$). Using these values, the duration was 495 minutes, or 67.3% of the actual duration.

These results indicate that except for the KM scheme, which overestimates sand movement duration, the other four schemes underestimate it to varying degrees.

To further validate the applicability, this study calculated minute horizontal dust flux for the July 17, 2009 dust storm using each scheme's threshold values combined with the dust flux calculation scheme, and compared them with measured results [Figure 4: see original paper]. The measured horizontal dust flux was 314.1 $\mathrm{kg \cdot m^{-1}}$. The calculated fluxes were: Stout scheme 122.9 $\mathrm{kg \cdot m^{-1}}$ (39.1% of measured), KM scheme 179.2 $\mathrm{kg \cdot m^{-1}}$ (57.1%), LZ scheme 178.3 $\mathrm{kg \cdot m^{-1}}$ (56.8%), MB scheme 244.7 $\mathrm{kg \cdot m^{-1}}$ (77.9%), and SL scheme 115.8 $\mathrm{kg \cdot m^{-1}}$ (36.9%). Similar to duration results, the KM scheme overestimates dust flux while the other schemes underestimate it. Correlation analysis shows the MB scheme performs best with correlation coefficient $r = 0.87$.

Emission Threshold of the Taklimakan Desert

Using the five schemes, this study determined emission thresholds for 20 dust storm events in 2009 [Figure 5: see original paper]. The threshold velocities varied from 4.0–6.0 $\mathrm{m \cdot s^{-1}}$ (mean 5.0 $\mathrm{m \cdot s^{-1}}$), and threshold friction velocities varied from 0.24–0.36 $\mathrm{m \cdot s^{-1}}$ (mean 0.30 $\mathrm{m \cdot s^{-1}}$). The thresholds show significant seasonal variation: spring (4.9 $\mathrm{m \cdot s^{-1}}$, 0.30 $\mathrm{m \cdot s^{-1}}$), summer (5.4 $\mathrm{m \cdot s^{-1}}$, 0.33 $\mathrm{m \cdot s^{-1}}$), autumn (5.1 $\mathrm{m \cdot s^{-1}}$, 0.32 $\mathrm{m \cdot s^{-1}}$), and winter (4.6 $\mathrm{m \cdot s^{-1}}$, 0.27 $\mathrm{m \cdot s^{-1}}$), following the pattern summer > autumn > spring > winter .

Comparison with Kurosaki and Mikami's results shows their threshold velocities of 5.0–7.6 $\mathrm{m \cdot s^{-1}}$ (mean 6.7 $\mathrm{m \cdot s^{-1}}$) are slightly higher than this study's results. This is because their data used dust storm hourly wind speeds, which are necessarily higher than threshold velocities, while this study's results are based on 10 cm sand movement data synchronized with wind speed statistics, more realistically reflecting actual threshold variations.

Discussion

This study evaluated five commonly used emission threshold determination methods based on field observation data. Although these methods have been applied in wind-sand research worldwide, comparative studies for the same region are limited. The results show significant differences between methods, creating considerable uncertainty for wind-sand movement determination, making applicability assessments necessary.

The Stout method can quickly obtain thresholds using field sand movement data, but it is based on the normal distribution of wind speed fluctuations, which may not hold true in real field conditions. The KM scheme defines threshold as the wind speed at which sand movement probability reaches 50%, which is statistically reasonable but requires large sample sizes. The LZ method determines threshold based on dust concentration changes, which involves some subjectivity. The MB and SL schemes have relatively complete theoretical foundations but involve complicated calculations, require many parameters, and many coefficients come from wind tunnel or field experiments with regional applicability issues.

Compared with other deserts, the Taklimakan Desert has the smallest emission thresholds due to: minimal precipitation, dry climate, no vegetation coverage, fine sand and very fine sand particles (mean size around 100 m, at the low end of threshold values), and flat terrain between sand ridges providing favorable conditions for wind-sand movement.

Conclusion

Through field observation data of sand movement duration and horizontal dust flux, this study evaluated the applicability of five emission threshold determination schemes in the Taklimakan Desert hinterland and determined the emission thresholds based on the optimal scheme. The main conclusions are:

1. All five schemes have uncertainties. The Stout, LZ, MB, and SL schemes overestimate the emission threshold to varying degrees, leading to underestimation of sand movement duration and horizontal dust flux. The KM scheme performs best, with determined sand movement duration closest

to measured values and horizontal dust flux showing good correlation with measured values.

2. The 2 m threshold velocity in the Taklimakan Desert hinterland ranges from 4.0–6.0 $\mathrm{m \cdot s^{-1}}$ (mean 5.0 $\mathrm{m \cdot s^{-1}}$), and the threshold friction velocity ranges from 0.24–0.36 $\mathrm{m \cdot s^{-1}}$ (mean 0.30 $\mathrm{m \cdot s^{-1}}$). The emission threshold shows seasonal variation following summer > autumn > spring > winter.

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