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Interactive comment on "Dust emission in farmland caused by aerodynamic entrainment and surface renewal" *by* Hongchao Dun and Ning Huang

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This paper presents a theoretical modeling study of dust emission from aerodynamic entrainment and saltation including an implementation of the surface renewal mechanism. Specifically, a parameterization of the free dust layer and a soil moisture transport module are developed and incorporated. The model simulated dust emission rates are compared with the observations from a field study. It is an interesting modeling study, as it illustrates the time evolution of dust emission rates on the process level, governed by the ambient conditions such as surface wind speeds and soil moisture. The effects of wind erosion and soil moisture changes due to evaporation are

modeled in both aerodynamic entrainment and saltation processes. While the quantitative results may depend on the model specifications, it characterizes the relative importance and temporal dependence of the surface wind and soil properties in dust emission processes. However, the manuscript needs major revisions in model description and evaluation before it could be considered for publication. There are two major concerns. First, a main contribution of this work is the development of this process model for dust emission. But the discussions about the model formulation and uncertainties in parameters are insufficient (detailed below in specific comments), making it difficult to determine if the results/conclusions are reasonable and where the model is applicable (or not). Further, the model evaluation includes one case study only comparing the simulated dust emission fluxes with a dust experiment. And the analysis of the model-data comparison is ad hoc and insubstantial.

Response: Thanks for the positive comments and useful suggestions. According to the reviewer's suggestions, we had discussed more about the model formulation and uncertainties in parameters, provided more data and explanations, and improved the quality of whole manuscript. Please see the responses to the following questions.

Specific comments are given below: 1. The parameterization of the free dust area in Equation (1) is introduced the first time by this study. It is not justified how it is formulated: is it physically based or empirically fitting based on the experimental data? The equation implies a sharp decrease in available free dust fraction close to the surface. Since the predicted changes of dust emissions due to the aerodynamic entrainment is sensitive to the function, verification of the predicted free dust area with the experimental data or theoretical justification is necessary.

Response: Thanks for the comment and suggestion. The parameterization of the free dust area in Equation (1) is physically based. According to the reviewer's suggestions, we added the sentence "we simplify the soil aggregate particles to spheres, and the free fine dust grains are filled in the particle gaps" in lines 69 of the revised manuscript. We added the verification of the predicted free dust area with the experimental data in lines 245-271, in which the aerodynamic entrainment caused by fine dust is accord with the wind tunnel experiments by Zhang et al. (2016):

Figure 5: Sensitivity of dust emission flux F to friction velocity, specific humidity and initial soil moisture content. Three main phases in dust emission process: (i) aerodynamic entrainment is the primary mechanism in first phase, and the dust emission rate decreases rapidly in a few minutes, (ii) saltation transport is the main mechanism in the second phase, and the dust emission rate maintains at a relatively high level, (iii) soil moisture becomes the dominating limit factor in the third phase, and forms little dust emission.

Fig. 5 shows different phases in the dynamic dust emission process. During the dust dynamic emission, the dust emission rate curve under different wind velocities showed a similar change trend, which could be divided into three main emission phases. The first phase was supplied by free fine dust mainly and aerodynamic entrainment emission was the primary mechanism. Due to the smaller grain size of free dust and the lower cohesive forces reduced by soil aggregates, the dust emission rate was very high in this phase. However, because the uneven distribution of free dust content in the vertical direction, the dust emission rate in this phase was decreased rapidly with time, reflecting the supply limitation of free dust. Klose and Shao (2012) study the aerodynamic entrainment in the absence of saltation as large eddies intermittently produce strong shear stresses on the surface and entrain dust particles into the air, in which convective atmospheric condition is major influence factor rather than soil property. While the free dust layer was consumed by wind erosion, saltation transport became the main mechanism in this phase. Because dust emission from big grains was relatively high and erosion processes were restrained accordingly in this phase, the dust emission rates were decreased significantly compared with that in the first phase. Therefore, the thickness of dry soil layer was main limiting factor of the dust emission in this phase. After the dry soil layer disappeared, the dust emission turned into the third phase, in which wet soil was the limit factor and saltation transport was the main mechanism.

The existence of water between the soil grains hindered the releasing process of wind erosion and further reduced the dust emission rate. In this phase, soil moisture content became the main limiting factor of dust emission rate. Zhang et al. (2016) study the first two phases in wind tunnel experiments, but the third phase is difficult be rebuilt due to the time limit for wind tunnel operation. Tests are performed to investigate the dependency of dust emission F on friction velocity, specific humidity and initial soil moisture content. For constant friction velocity and initial soil moisture content, F has a small difference with large specific humidity, and clearly increases for in small specific humidity. Figure 5c also shows that final dust emission rate F is insensitivity with initial soil moisture content.

2. Also, in Equation (1), it is unclear what the R value is used for the radius of free dust grains and how it is determined; and is this parameter variable, depending on the surface type? How does this equation relate to the results in Section 3.1 and Section 3.2, Figures 2 and 3, i.e., is the dry soil thickness (H_d) sensitive to R in Equation (1)?

Response: Thanks for the comment. R is average radius for soil aggregates and determined by the soil grain size distribution. We modified this part in lines 71: “where R is the highest proportion radius of soil particle size distribution”. R mainly affects the dust emission rate in aerodynamic entrainment process, and Figure 4 is a good example. Soil moisture distribution and soil structure in Figures 2 and 3 are not sensitive to R.

3. Equation (10) and (11): what is the definition of m and what is its typical value?

Response: Thanks for the comment. m is a soil property parameter in famous Van Genuchten model. It presents the effect of soil porosity and usually determined by experiment. We added the definition and value in lines 137: “ m=0.274 is the soil property parameter presenting the effect of soil porosity”.

4. Equation (12): is the calculation of theta and evaporation rate applicable only over the wet soil? If the fraction of dry soil is > 0, i.e.,f_dust in Equation (1), will the theta and evaporation rate be calculated for that layer and how?

Response: Thanks for the comment. Theta and evaporation rate are calculated over the whole soil during dust emission event, even when the fraction of dry soil is > 0.

5. Section 2.4: a flow diagram would help illustrate the procedure. Lots of the detail about the model experiment are omitted. As mentioned in the main comment above, without those detail it is difficult to determine whether the results are reasonable. For instance, what is the initial soil moisture profile used? Is it representative for farmland, which seems to be the land surface type of interest? The model domain is unclear: is it a 1-D or 3-D model? What is the model horizonal and vertical resolution? Are there any horizonal variability in the initial conditions of soil moisture content and surface winds?

Response: Thanks for the comment. We added a flow diagram to help illustrate the procedure. In addition, 0.15 is set as an initial soil moisture in the whole soil to present a sufficient water condition after rainfall or irrigation, this is a vertical 1D model and the whole thickness of soil is 1m and the grid size is 1mm. Our dust emission model is established to simulate bare farmland condition, which horizontal variabilities in the initial conditions of soil moisture content and surface winds are not principal influence factors. More details please look at section 2.4. The calculation procedures can be seen in section 2.4, we have modified this part and add a flow diagram to make it easier for readers to understand in lines 163-165.

Figure 2. The flow diagram for dust emission model considering aerodynamic entrainment and surface renewal processes in a single time step.

6. Figure 3: there is no black lines plotted in any of the panels (a)-(c). During the first hour when H_d>0, why the soil moisture remains constant but there is a slow increase in evaporation rate? is the stepwise increase in evaporation rate and soil moisture related to the initial soil moisture profile assumed?

Response: Thanks for the comment. We corrected the title of Fig. 3 in lines 203-205: “Figure 4: Temporal changes for evaporation and soil structure with different friction

velocity u_*: (a) u_*=0.4m/s; (b) u_*=0.45m/s; (c) u_*=0.5m/s. Green lines are dry soil layer thicknesses; blue lines are the evaporation rates; pink lines are the soil moisture on wet layer surface, which determine the evaporation rates.”. It can be seen from Eq. 9 and Eq. 12 that the evaporation rate is higher with lower dry soil layer thicknesses, and the soil surface moisture becomes larger when underground water is enough. So, there is a slow increase in evaporation rate with the decreasing dry soil layer thicknesses. The initial soil moisture profile affects the initial values of evaporation rate and soil surface moisture, but the wind velocity is a more important factor determined the increasing rate.

7. Figure 4: in order to attribute the dust emission flux to a primary mechanism, it would make sense to plot the contribution of aerodynamic entrainment separately from that due to saltation transport. Sensitivity studies of other important parameters in the model such as soil moisture profile and surface air temperature/humidity would help in strengthening the findings from the model simulations.

Response: Thanks for the suggestions. We constructed more sensitivity tests on u*, specific humidity and initial soil moisture content in lines 220-222.

Figure 5: Sensitivity of dust emission flux F to friction velocity, specific humidity and initial soil moisture content. Three main phases in dust emission process: (i) aerodynamic entrainment is the primary mechanism in first phase, and the dust emission rate decreases rapidly in a few minutes, (ii) saltation transport is the main mechanism in the second phase, and the dust emission rate maintains at a relatively high level, (iii) soil moisture becomes the dominating limit factor in the third phase, and forms little dust emission.

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8. Section 3.4: this model evaluation section needs to be expanded. As mentioned in the main comment, it is unclear if the model configuration is comparable to the experimental conditions such as soil type, moisture content and profile. More quantitative analysis of the model-data differences is needed, for instance, in terms of RMSE, correlation, or other statistical measures. The impact due to Surface Renewal and Evaporation (SRE) is visible only after 6 hours; however, this seems to be inconsistent with the model simulations in Section 3.1-3.3, which show that the SRE effects occur within âĹij 1hr. Why is that? Even after including the SRE effect, the differences between the model and observations are still quite large. It is not very convincing that the developed model captures the time evolution of the dust emission fluxes effectively in this case study. Furthermore, to attribute the changes of dust emission to a specific process: aerodynamic entrainment of free dust or saltation transport due to wind erosion, it is necessary to decompose the predicted dust emission fluxes by process.

Response: Thanks for the comment. In this version, we added some field experiment results and recalculated the model with consideration of the experimental conditions such as soil type, moisture content and profile in lines 254-257: "The model is calibrated and validated with field data from a sand storm monitoring station in the Horqin Sandy Land in China in 2011 (Li et al., 2014). The Horqin station has a 20 m observational tower, and the observations included wind speed at heights of 2, 4, 16, and 20 m; soil moisture at depths of 5, 20, and 50 cm; dust (particulate matter 10 (PM10)) concentration at heights of 3 and 18 m.". In fact, the third phase, which surface renewal caused by soil moisture, occurs after several hours in general due to the erosion process of dry soil layer. In addition, we added some field experiment results, which show the change of dust emission flux with time and the significant influence of surface renewal process in fig. 6:

Figure 6: (left) Time series of observed and modeled dust emission flux. The time is given in observation days (local time). Green triangles are wind velocity data measured

at the height of 2 m; red circles are the measured air dust emission rate. Black solid lines are the simulated dust emission flux considering surface renewal; black dotted lines are the cases without considering surface renewal. (right) Corresponding modeled versus observed fluxes for determination.

The model is calibrated and validated with field data from a sand storm monitoring station in the Horqin Sandy Land in China in 2011 (Li et al., 2014). The Horqin station has a 20 m observational tower, and the observations included wind speed at heights of 2, 4, 16, and 20 m; soil moisture at depths of 5, 20, and 50 cm; dust (particulate matter 10 (PM10)) concentration at heights of 3 and 18 m. Figure 6 shows the time series and scatterplots of the observations and the model results for four of the Horqin cases. At Horqin, fluxes of dust particles with diameters < 10 μm were estimated from the PM10 concentration profile measurements. As seen, there is a good agreement between the model predictions and observations and the temporal evolutions match well. For the three cases shown, the coefficient of determination, r2, is the lowest for the case of 2 May 2011 with r2 = 0.85 and the highest for the case of 19 May 2011 with r2 = 0.92. In the former case, the low r2 is caused by the poor model-observation agreement at about 16:00. For the remaining time, the predictions and observations differ only slightly in magnitude. In the latter case, the temporal evolution is well reproduced by the model with only slight discrepancies at about 14:00 and 18:00. Overall, in the four cases, the model predictions and observations agree with regard to onset and cessation as well as overall characteristics. Especially, in the latest case, the dust emission flux decreases obviously after 20:00 even though the wind velocity increases slightly, which indicates that u*t increases due to surface renewal process. As a contrast, the simulated dust emission flux without considering surface renewal increases with the wind velocity and is contrary to the observed dust flux due to the traditional models can't presents the change of soil property and u*.

9. Page 9, lines 14-15: dust emission caused by aerodynamic entrainment has been demonstrated in a number of previous studies such as Klose and Shao (2012) and

Zhang et al. (2016). For the statement “this model simulated the dust emission process caused by aerodynamic entrainment in nature for the first time”, clarification about how this study is different from previous studies on this process is needed.

Response: Thanks for the comment. This is an unclear statement and we have modified this part in lines 227-243: “Fig. 5 shows different phases in the dynamic dust emission process. During the dust dynamic emission, the dust emission rate curve under different wind velocities showed a similar change trend, which could be divided into three main emission phases. The first phase was supplied by free fine dust mainly and aerodynamic entrainment emission was the primary mechanism. Due to the smaller grain size of free dust and the lower cohesive forces reduced by soil aggregates, the dust emission rate was very high in this phase. However, because the uneven distribution of free dust content in the vertical direction, the dust emission rate in this phase was decreased rapidly with time, reflecting the supply limitation of free dust. Klose and Shao (2012) study the aerodynamic entrainment in the absence of saltation as large eddies intermittently produce strong shear stresses on the surface and entrain dust particles into the air, in which convective atmospheric condition is major influence factor rather than soil property. While the free dust layer was consumed by wind erosion, saltation transport became the main mechanism in this phase. Because dust emission from big grains was relatively high and erosion processes were restrained accordingly in this phase, the dust emission rates were decreased significantly compared with that in the first phase. Therefore, the thickness of dry soil layer was main limiting factor of the dust emission in this phase. After the dry soil layer disappeared, the dust emission turned into the third phase, in which wet soil was the limit factor and saltation transport was the main mechanism. The existence of water between the soil grains hindered the releasing process of wind erosion and further reduced the dust emission rate. In this phase, soil moisture content became the main limiting factor of dust emission rate. Zhang et al. (2016) study the first two phases in wind tunnel experiments, but the third phase is difficult be rebuilt due to the time limit for wind tunnel operation.”.

Overall, the manuscript is an interesting modeling study of dust emission processes based on the theoretical understanding. However, it requires significant improvement and justification in model description and evaluation, in order to support the findings of their model simulations.

Response: Thanks for the positive comments again, we have improved the quality of whole manuscript according to your suggestions and expect to hear more comments and suggestions from you.

Interactive comment on Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2020-1021, 2020.

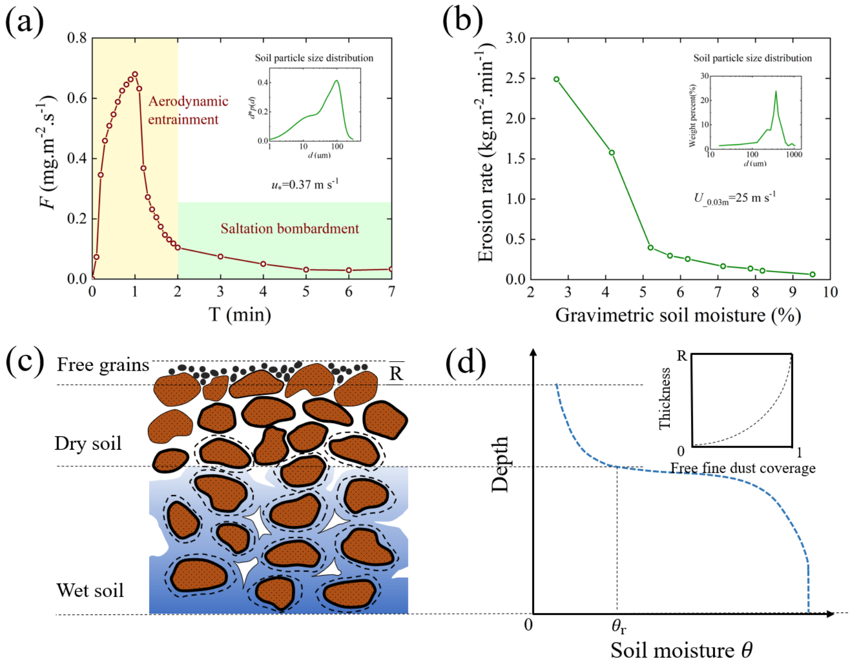
(a)
0.8
0.6
0.4
0.2
0.0
F (mg.m^{-2}.s^{-1})
0
1
2
3
4
5
6
7
T (min)
Aerodynamic entrainment
Saltation bombardment
Soil particle size distribution
$d*p(d)$
0.4
0.2
0.0
1
10
100
d (um)
u_*=0.37 m s^{-1}
(b)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Erosion rate (kg.m^{-2}.min^{-1})
2
3
4
5
6
7
8
9
10
Gravimetric soil moisture (%)
Soil particle size distribution
Weight percent(%)
30
20
10
0
10
100
1000
d (um)
$U_{\_0.03m}$=25 m s^{-1}
(c)
Free grains
R
Dry soil
Wet soil
(d)
Depth
0
θ_r
Soil moisture θ
R
Thickness
0
1
Free fine dust coverage

Fig. 1.

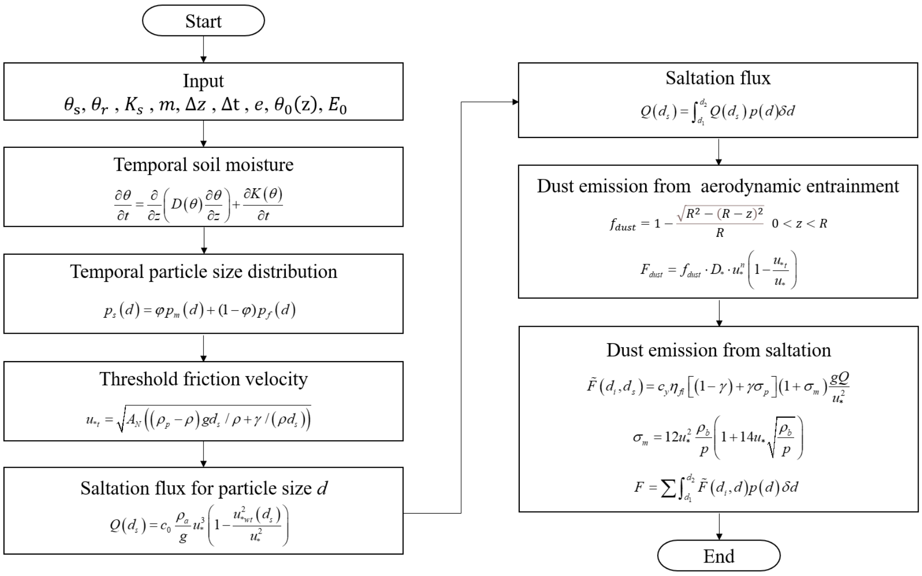
Start
Input
$\theta_s, \theta_r, K_s, m, \Delta z, \Delta t, e, \theta_0(z), E_0$
Temporal soil moisture
$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left(D(\theta)\frac{\partial\theta}{\partial z}\right)+\frac{\partial K(\theta)}{\partial t}$
Temporal particle size distribution
$p_s(d)=\varphi p_m(d)+(1-\varphi)p_f(d)$
Threshold friction velocity
$u_{*t}=\sqrt{A_N\left((\rho_p-\rho)gd_s/\rho+\gamma/(\rho d_s)\right)}$
Saltation flux for particle size d
$Q(d_s)=c_0\frac{\rho_a}{g}u_*^3\left(1-\frac{u_{*wt}^2(d_s)}{u_*^2}\right)$
Saltation flux
$Q(d_s)=\int_{d_1}^{d_2}Q(d_s)p(d)\delta d$
Dust emission from aerodynamic entrainment
$f_{dust}=1-\frac{\sqrt{R^2-(R-z)^2}}{R}\quad 0<z<R$
$F_{dust}=f_{dust}\cdot D_*\cdot u_*^n\left(1-\frac{u_{*t}}{u_*}\right)$
Dust emission from saltation
$\tilde{F}(d_i,d_s)=c_y\eta_{fi}\left[(1-\gamma)+\gamma\sigma_p\right](1+\sigma_m)\frac{gQ}{u_*^2}$
$\sigma_m=12u_*^2\frac{\rho_b}{p}\left(1+14u_*\sqrt{\frac{\rho_b}{p}}\right)$
$F=\sum\int_{d_1}^{d_2}\tilde{F}(d_i,d)p(d)\delta d$
End

Fig. 2.

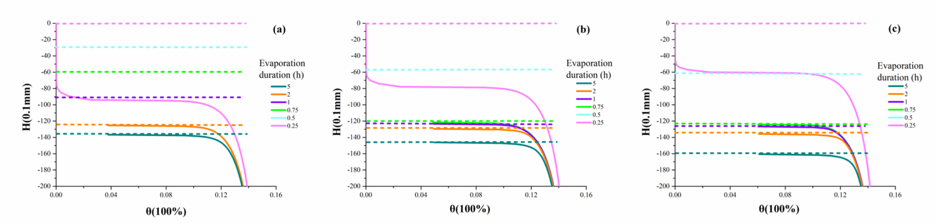
(a)
(b)
(c)
H(0.1mm)
θ(100%)
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
0.00
0.04
0.08
0.12
0.16
Evaporation duration (h)
5
2
1
0.75
0.5
0.25

Fig. 3.

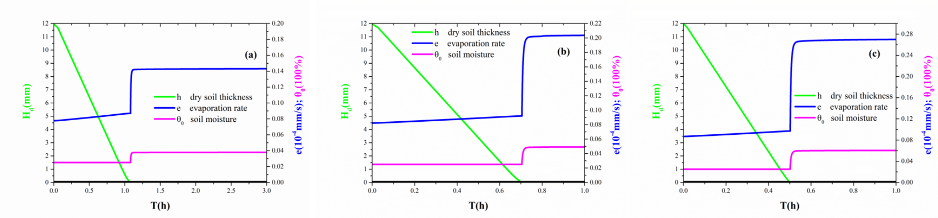
(a)
(b)
(c)
H_d(mm)
$e(10^{-4}$mm/s); θ_0(100%)
T(h)
h dry soil thickness
e evaporation rate
θ_0 soil moisture
0
1
2
3
4
5
6
7
8
9
10
11
12
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0.2
0.4
0.6
0.8
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
0.28

Fig. 4.

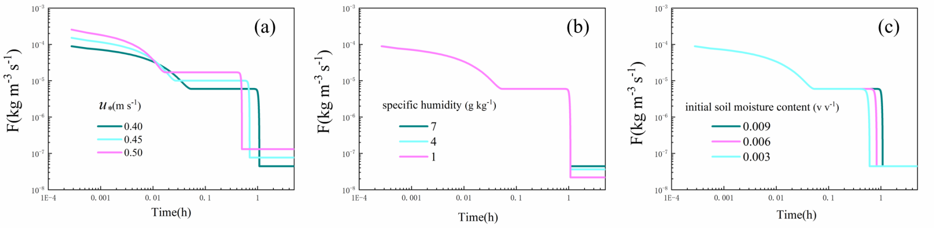
(a)
F(kg m^{-3} s^{-1})
u_*(m s^{-1})
0.40
0.45
0.50
Time(h)
(b)
specific humidity (g kg^{-1})
7
4
1
(c)
initial soil moisture content (v v^{-1})
0.009
0.006
0.003
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
1E-4
0.001
0.01
0.1
1

Fig. 5.

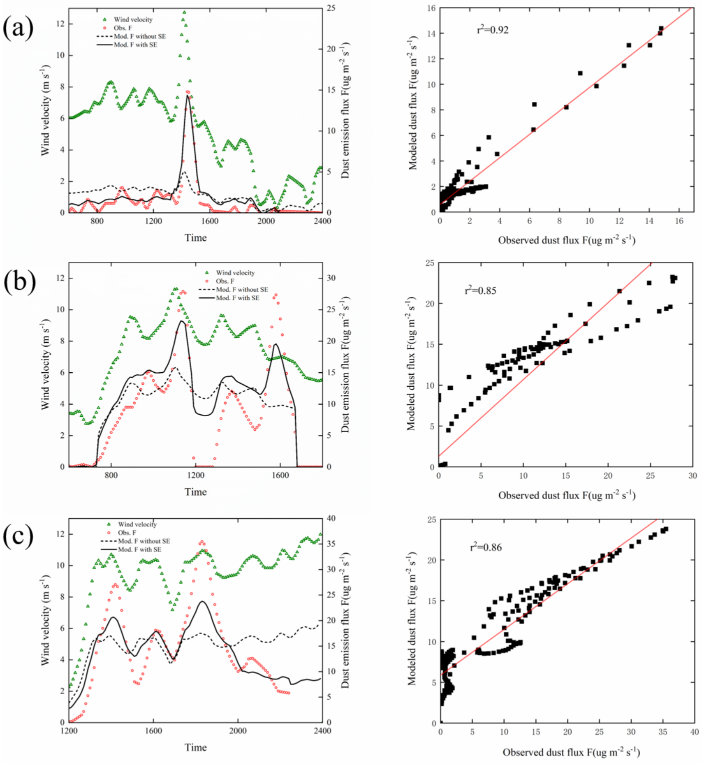
(a)
(b)
(c)
Wind velocity
Obs. F
Mod. F without SE
Mod. F with SE
Wind velocity (m s^{-1})
Dust emission flux F(ug m^{-2} s^{-1})
Time
r^2=0.92
r^2=0.85
r^2=0.86
Modeled dust flux F(ug m^{-2} s^{-1})
Observed dust flux F(ug m^{-2} s^{-1})

Fig. 6.