Insights into dust emission mechanisms from field measurements, theory, and modeling

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Rangeland Research Programs

Dust in the Earth system

- Dust events occur on different spatio-temporal scales,
  - **Dust storms**: ~100-1000km, ~1-10 days
  - **Dust devils/plumes**: ~1-100m, 1-10 min
- Mineral dust contributes substantially to total aerosol mass

  → Effects on human daily life

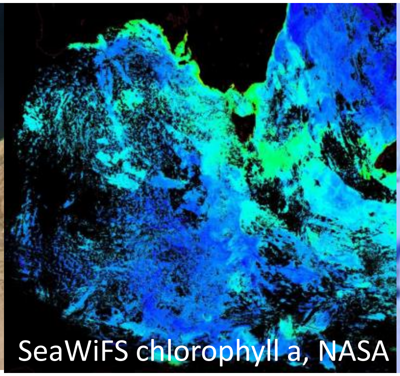
  → Interactions with radiation and clouds

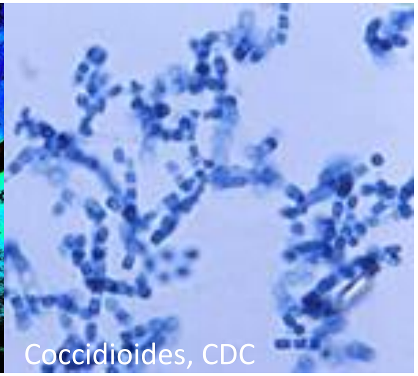
  → Redistribution of soil nutrients, minerals, carbon

  → Substrate for contaminants, microorganisms, and viruses


I-10 Arizona, KOLD News 13

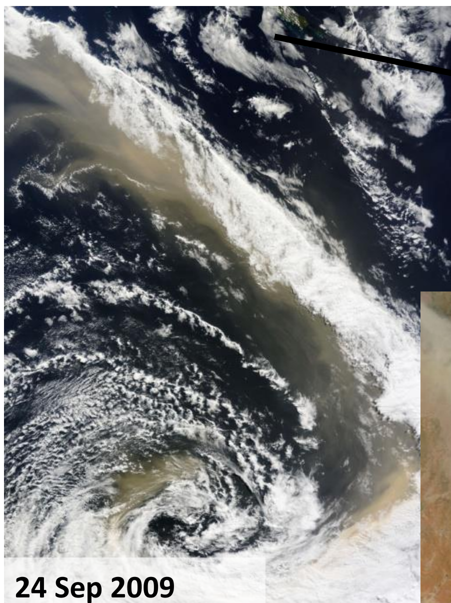

MODIS, NASA

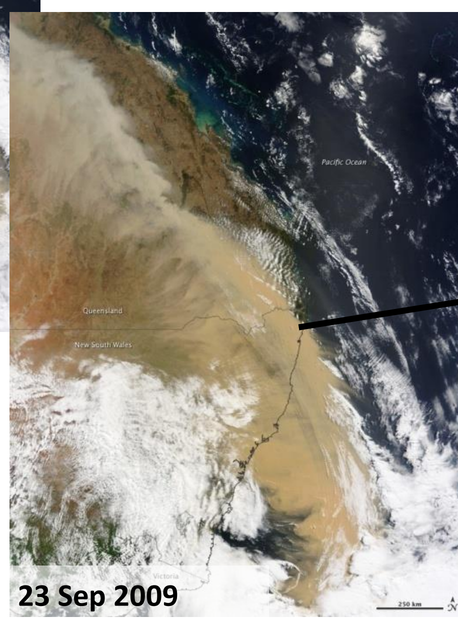

SeaWiFS chlorophyll a, NASA


Coccidioides, CDC

Dust in the Earth system

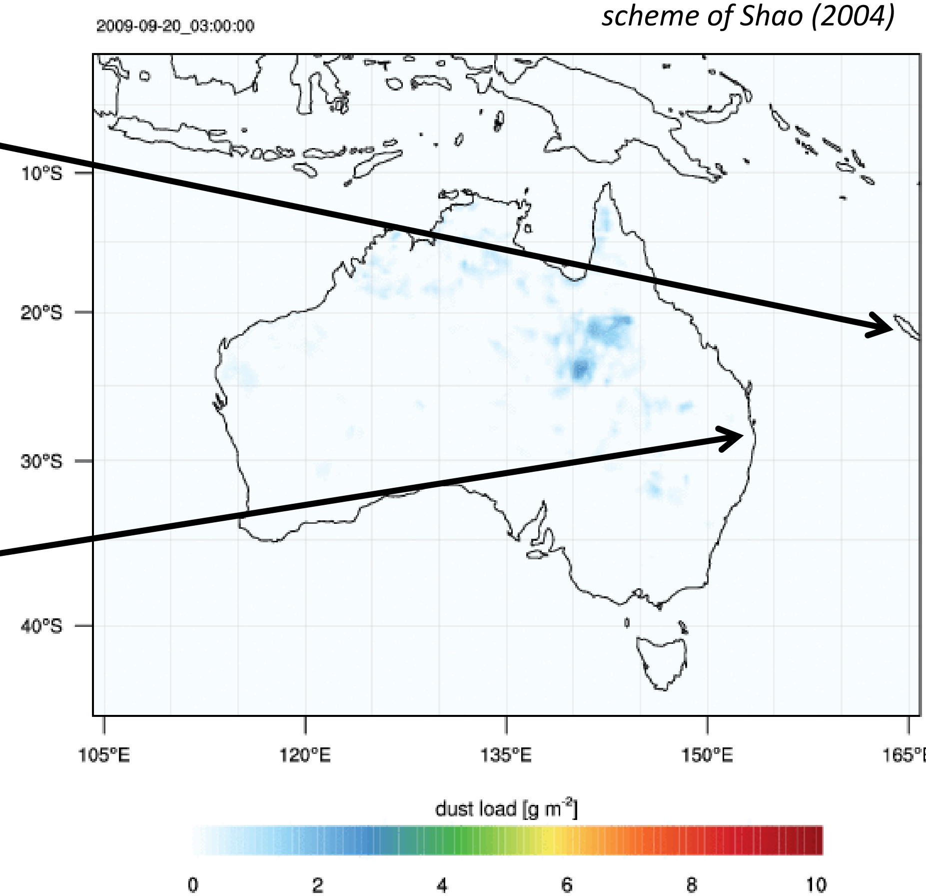
- Study of dust aerosol and its impacts relies on dust models



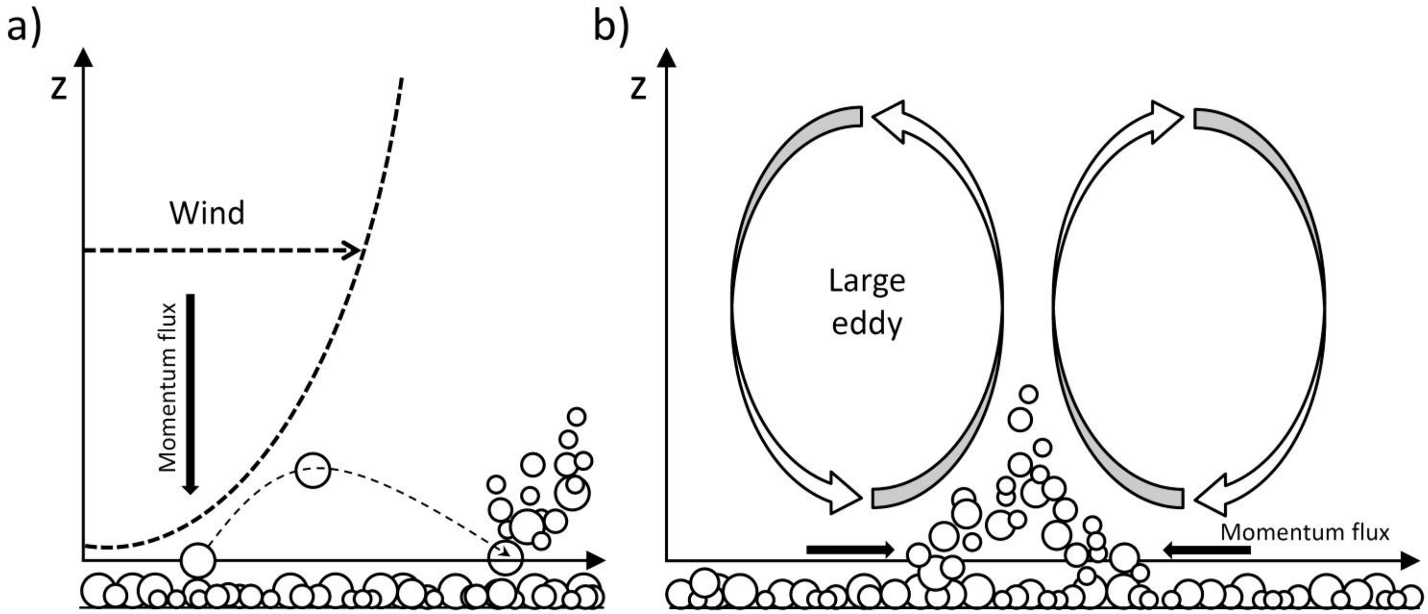


MODIS images, 23 and 24 Sep 2009, MODIS Rapid Response Team, NASA GSFC

Dust load modeled with WRF-Chem, dust emission scheme of Shao (2004)



Dust emission mechanisms in models



from *Klose and Shao* (2013)

a) Saltation and disaggregation induced by mean wind momentum
b) Aerodynamic entrainment induced by intermittent large-eddy momentum

Dust in the Earth system

- Field measurements are needed to test theories on dust emission.
- Measurements often
  - do not provide enough information to determine which dust emission mechanism occurred and hence the **applicability of a parameterization** to simulate an observed event is unclear;
  - focus on a **small variety of soil and atmospheric setting** (idealized conditions).

→ No ultimate conclusion can be drawn from a (mis)match between model results and observations.

Objective and idea

Decipher the dust emission mechanism from field measurements for a variety of soil surface conditions.

<u>*Hypotheses:*</u>

- The **mechanism of dust emission** can be identified based on parent soil and transported sediment characteristics.
- The **spatio-temporal variability** of each mechanism is determined by land-surface condition and atmospheric forcing.

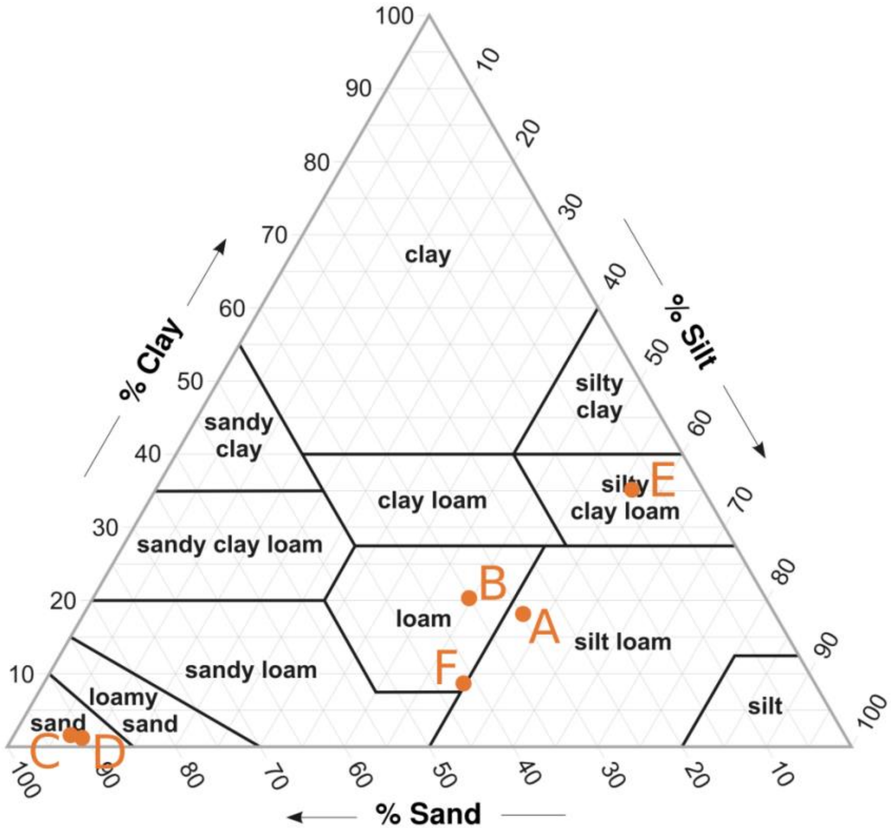
→ *What can differences/similarities between the particle-size distributions (PSDs) of*

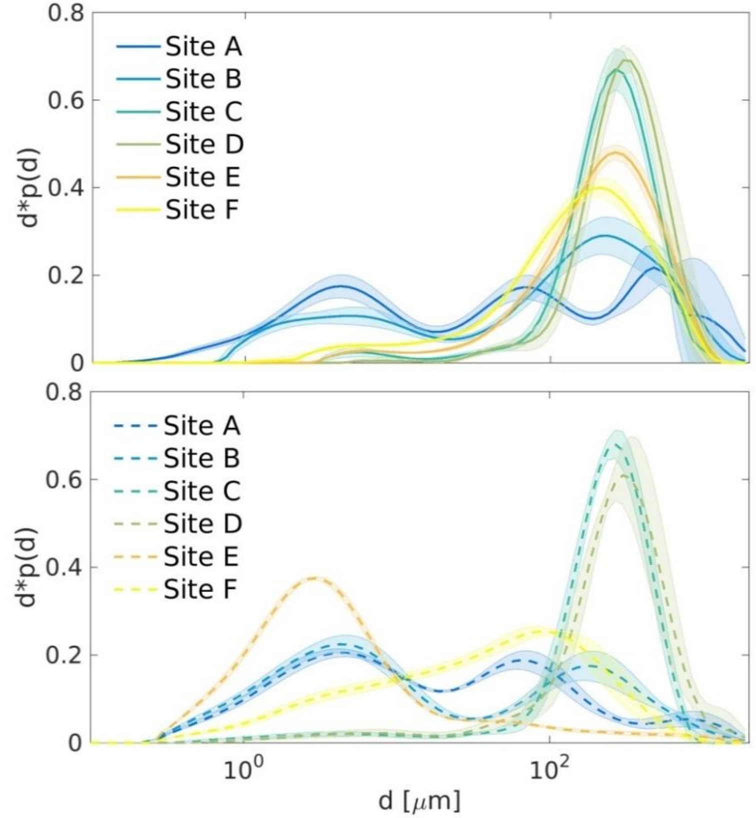
- *transported sediment*
- *loose erodible material (LEM), and*
- *soil crust*

tell about the dust emission mechanism?

Measurement area

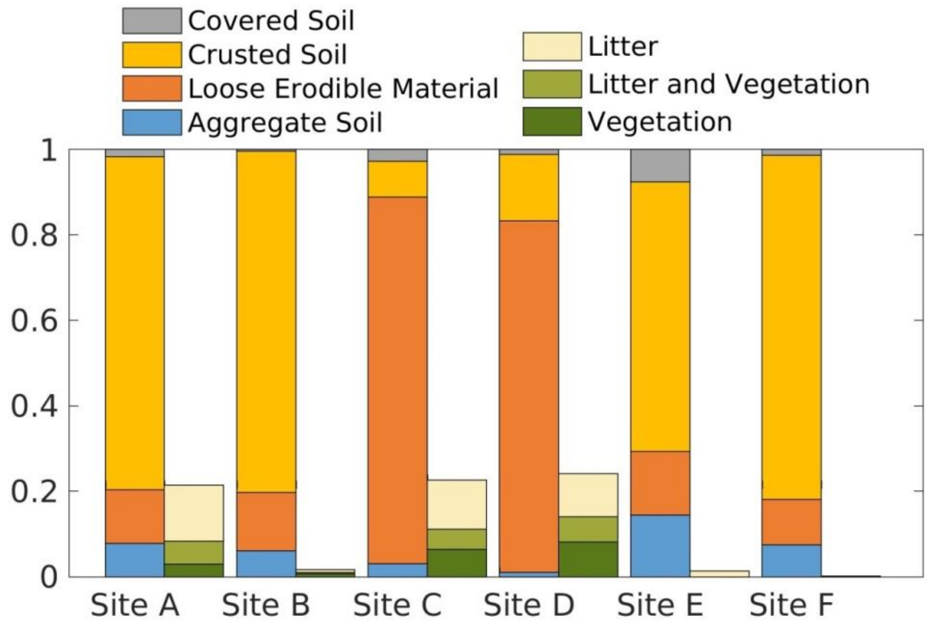
- Southwestern U.S. (Chihuahuan Desert)
- Predominantly shrub- and grassland
- 6 Sites





Land-surface monitoring

- The cover and distribution of LEM, crust, and vegetation is monitored before each event using the **line-point-intercept (LPI*)** method on 3 parallel 50 m transects.



- **Crust samples** were taken at random locations at each site.

Field sampling of loose erodible material

- **Sand and dust entrainment depend on the supply of loose erodible material** (LEM), if atmospheric forcing is sufficient.
- Dust emission mechanisms vary with particle-size spectrum.

→ *Characterization of LEM is pivotal to investigate potential and likelihood of dust emission mechanisms to occur.*

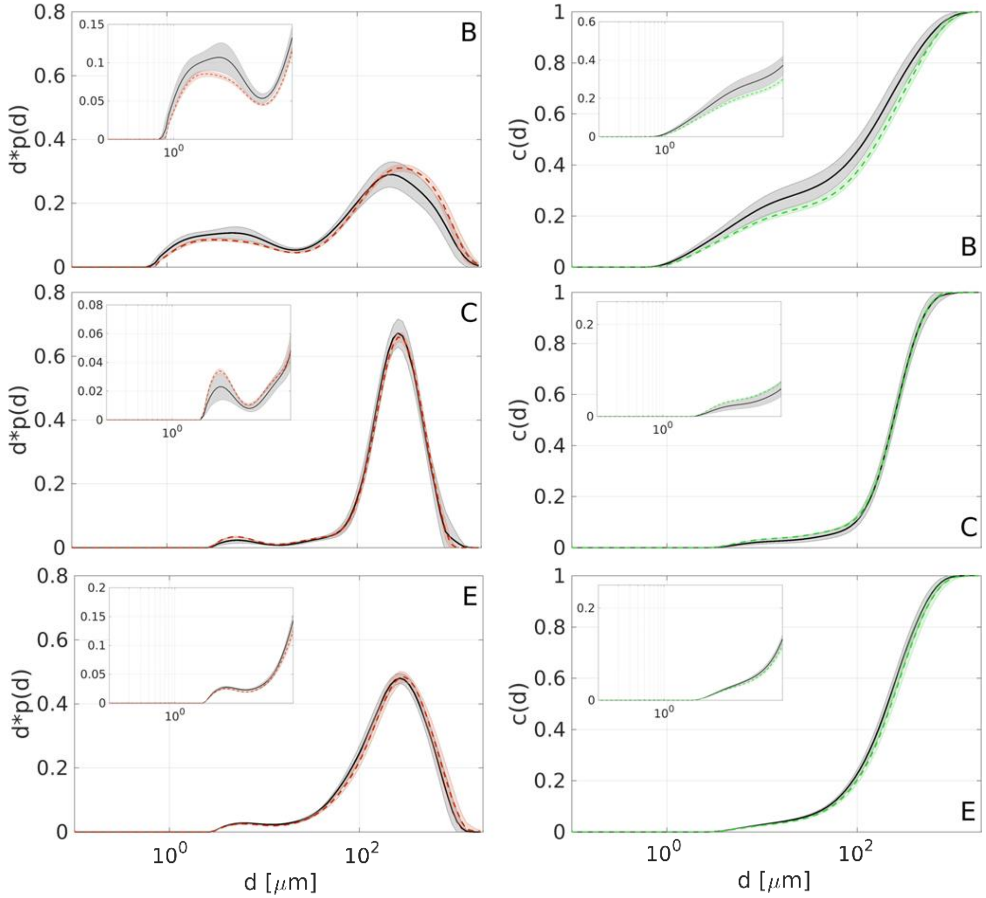
- Existing methods focus on sand-sized particles or erosion potential of a surface.
- *Wanted:*

Method to accurately sample the full particle-size spectrum of LEM.

Vacuuming technique

- A **new vacuum method** has been developed which aims to capture particles in **all size-ranges** including dust-sized particles.
- Utilizes modified **MWAC** (Modified Wilson and Cooke) sampler with **53 µm filter** attached to the outlet on **90^o brass elbow**.
- Inlet is attached to a handheld vacuum using a rubber hose.

Sampling accuracy



- Procedure:
  - vacuum three replicates of a sample (completely);
  - analyze particle-size distribution PSD in dry dispersion;
  - Compare with PSD of soil before vacuuming.
- **PSD shape is well preserved** for all particle sizes.
- In the dust-size range (d < 63µm), **soil loss is usually < 10%**, even for soils with large silt and clay content.
- Soil loss in the dust-size range is typically within or only somewhat larger than the natural variability of the soils' PSDs.

Field sampling of LEM

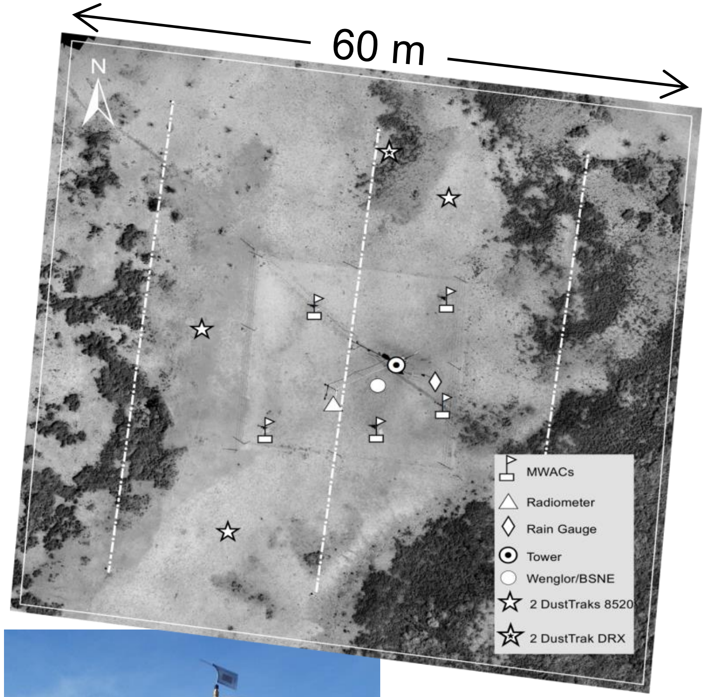
- 6 parallel 30cm transects are vacuumed for each sample.
- Samples are taken for different geomorphic classes present at a site, e.g. around shrubs, grasses, in bare areas, etc.
- Each class is sampled at 9 random locations and composited to 3 samples.

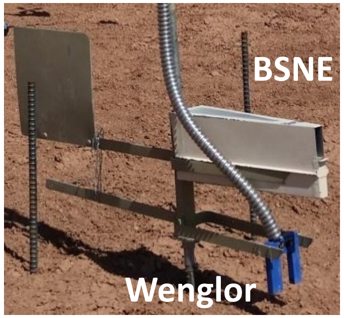
→ **within-site PSD variability**

Measurement Setup

Meteorological instrumentation – 5m tower holding, 5 anemometers, a wind vane, and 2 temperature sensors (radiometer; rain gauge)

Instrumentation for sediment flux measurements – 5 poles each holding Modified Wilson and Cooke (MWAC) samplers at four heights, Wenglor optical particle counter, Big Spring Number Eight (BSNE) sampler, up to 8 DusttTrak aerosol monitors.



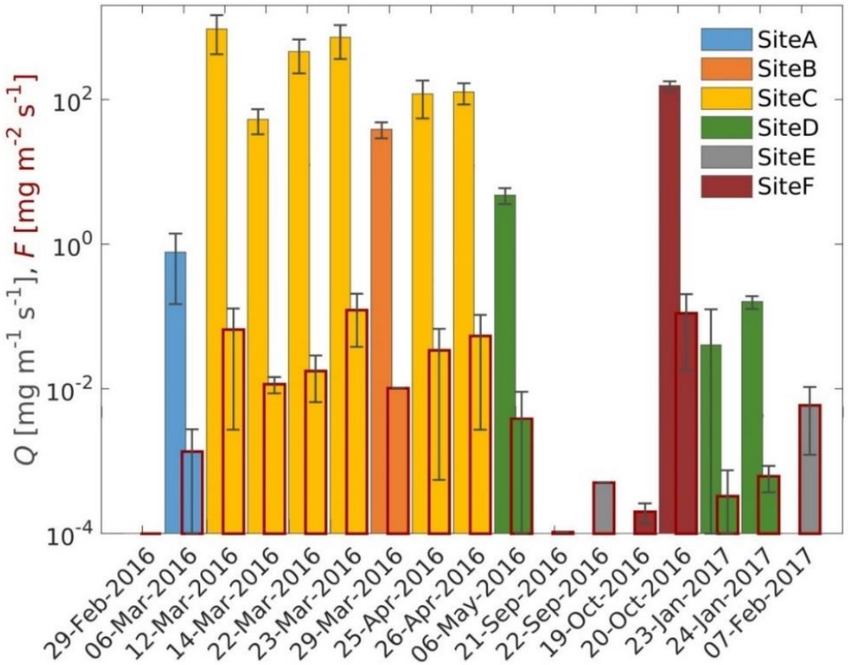


Measurement overview

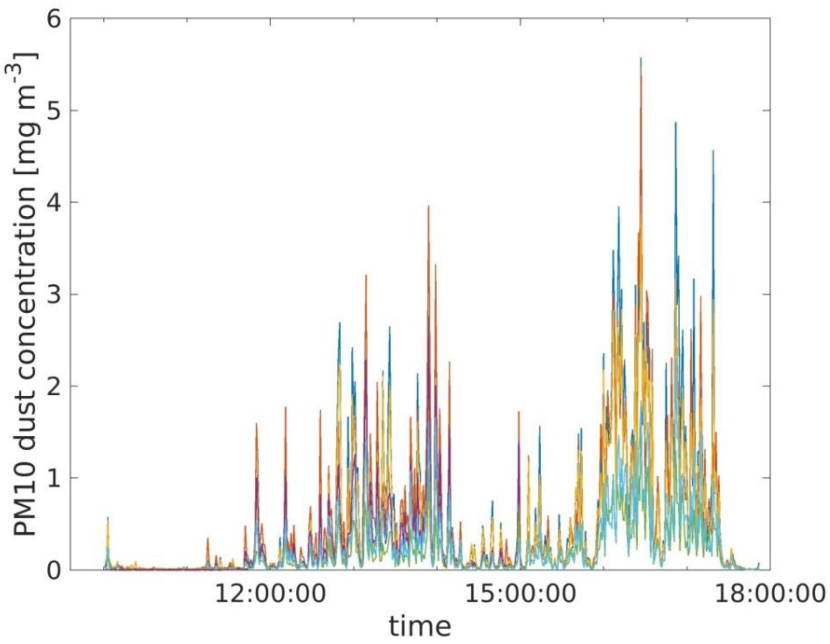
- **17 measurement days** between Feb 2016 and Feb 2017.
- Measurements for conditions that are both **favorable and unfavorable** for dust emission.

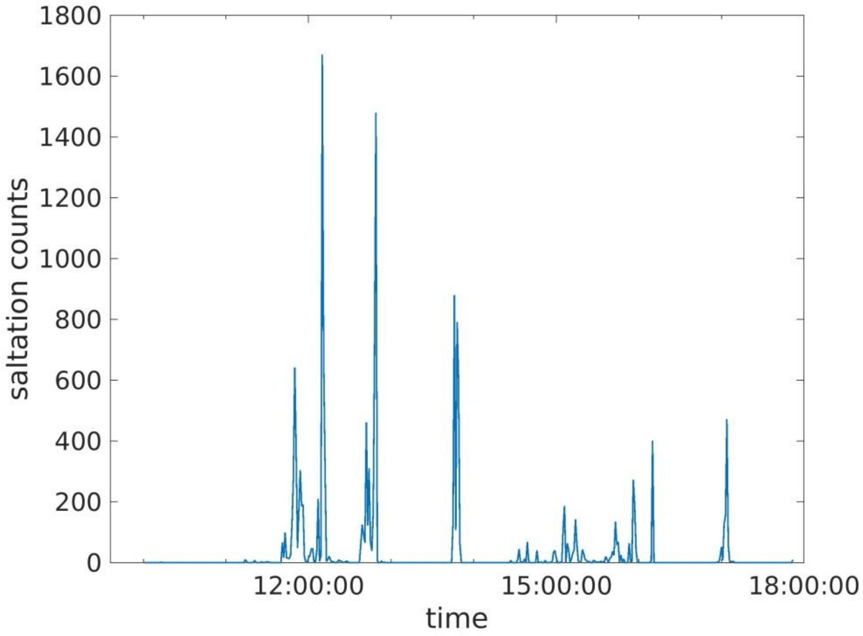
→ Reduce bias arising from selective measurement periods.

- **Event-averaged horizontal sediment flux, $\bar{Q}$,** ranged from < 1 to ~1000 mg m^{-2} s^{-1}.
- **Event-averaged PM10 dust emission flux, $\bar{F}$,** shows large spatial (between-instrument) variability.
- Maximum $\bar{F}$ is about 123 µg m^{-2} s^{-1} for the event on 23 March 2016 at Site C.



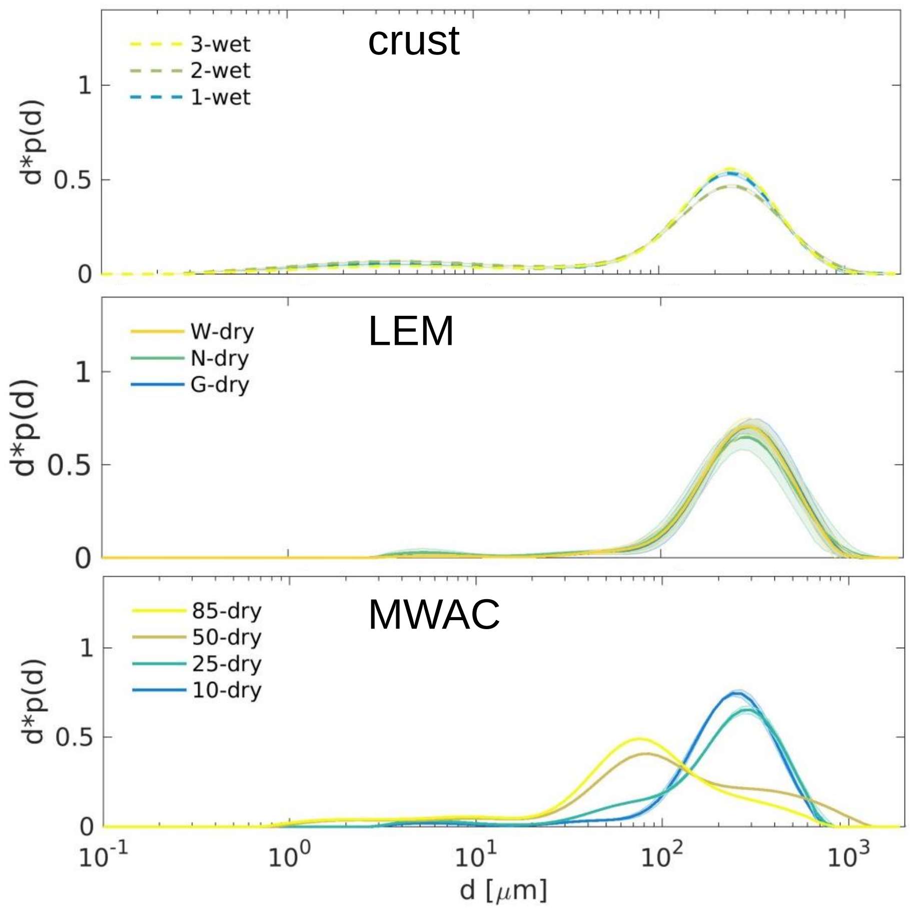
23 March 2016 – Site C





23 March 2016 – Site C

- Sandy soil, patches of weak crust
- Grass and shrub cover
- MWAC samples show coarsening between 10 and 25cm height
- 50 and 85 cm MWAC samples contain much larger dust fraction.
- For small particles:
  - 10 and 25 cm MWAC PSD resembles LEM PSD
  - 50 and 85 cm MWAC PSD resembles crust PSD
- **Saltation bombardment** (abrasion)



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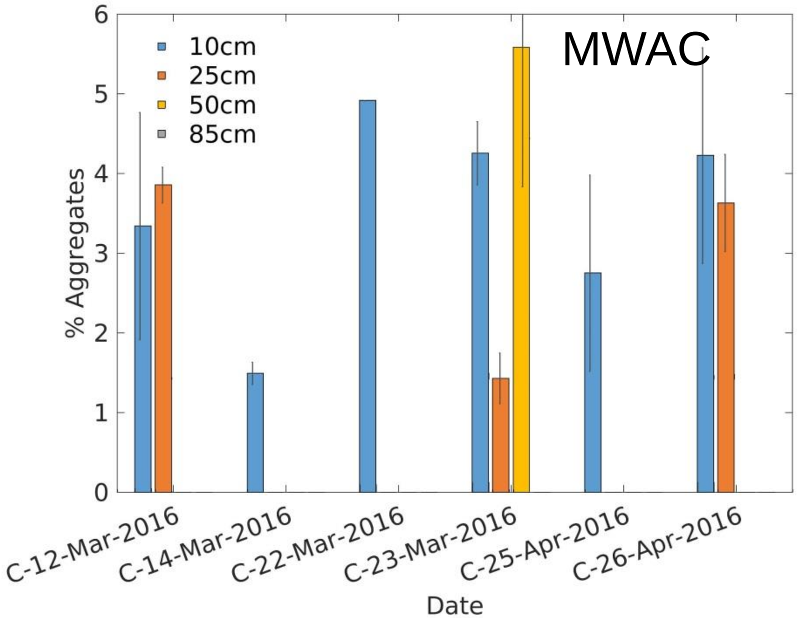
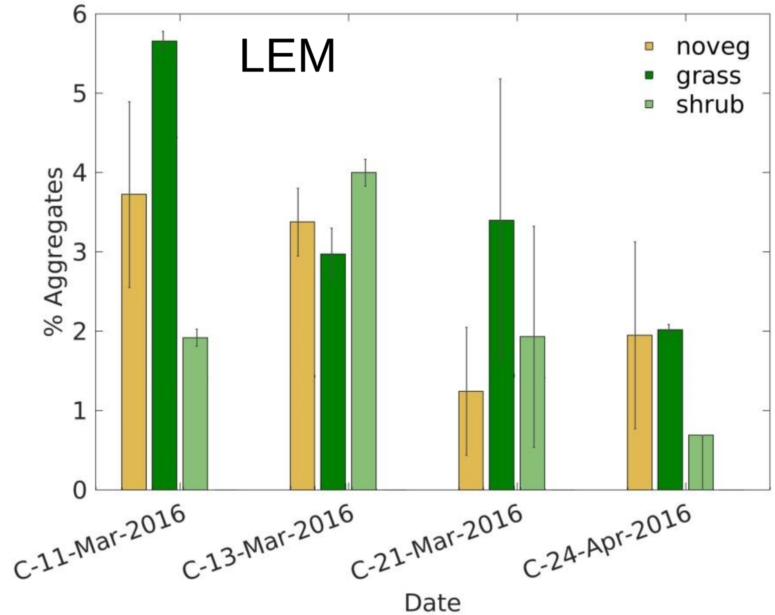
Site C – variability

- 6 events with substantial dust amounts were observed at Site C

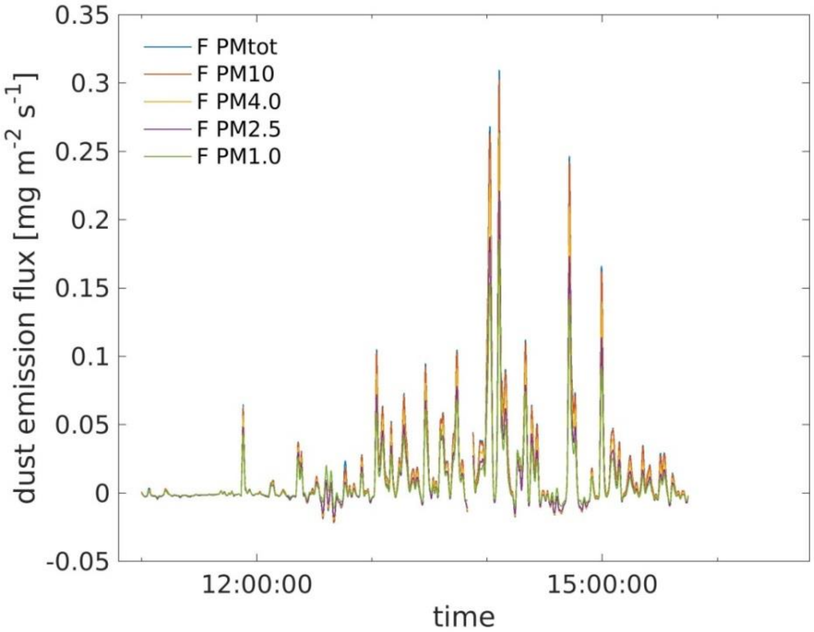
→ Between-event variability





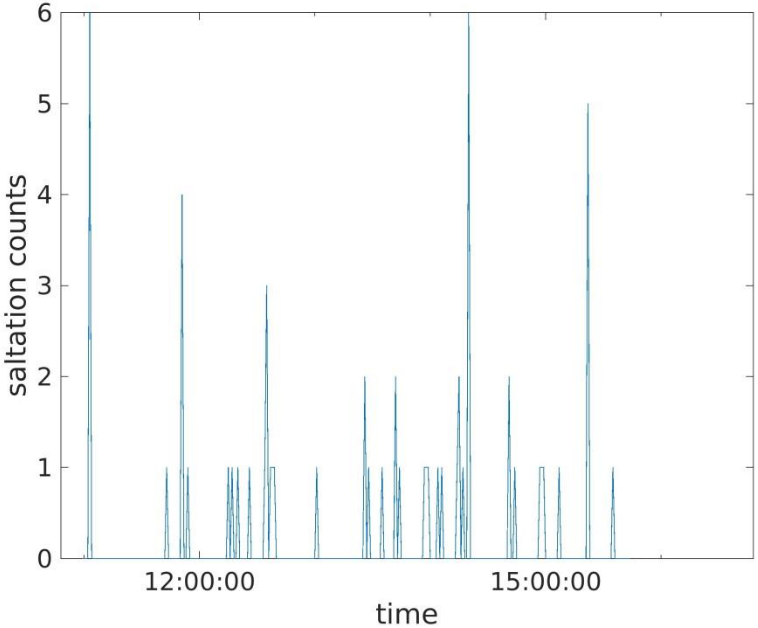
- 1.5 – 5 % Aggregates → Saltation bombardment (abrasion)
- No systematic variation of % Aggregates in MWAC samples, but decrease in LEM samples

29 March 2016 – Site B



- Hard surface crust
- Sand dunes adjacent to the site (normally downwind).
- Crust partly disturbed by cattle.
- Predominantly shrubland with some grass cover.

29 March 2016 – Site B



- Only few saltation counts recorded by the Wenglor
- Saltation likely more substantial at other location at the site
- Supply of grains for saltation very patchy.

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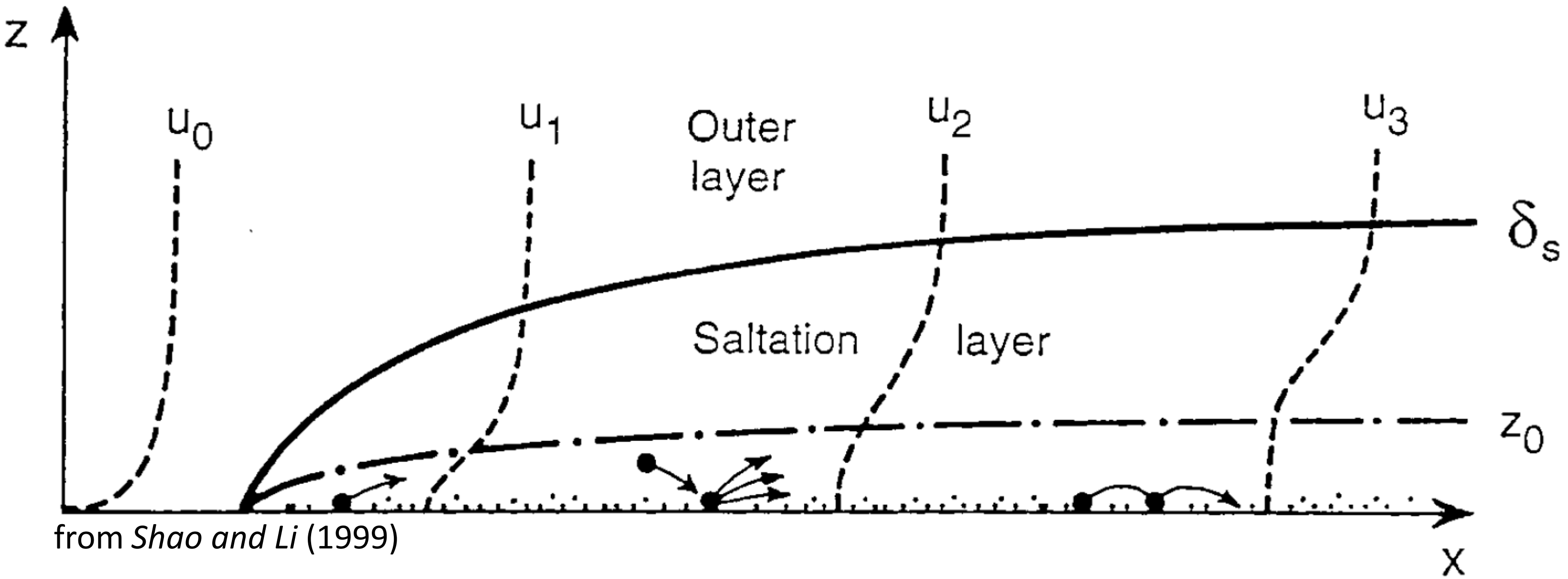
Equilibrium saltation



from *Shao and Li* (1999)

- Parameterizations assume that saltation is in equilibrium with the atmospheric forcing
- Self-limiting cascade process

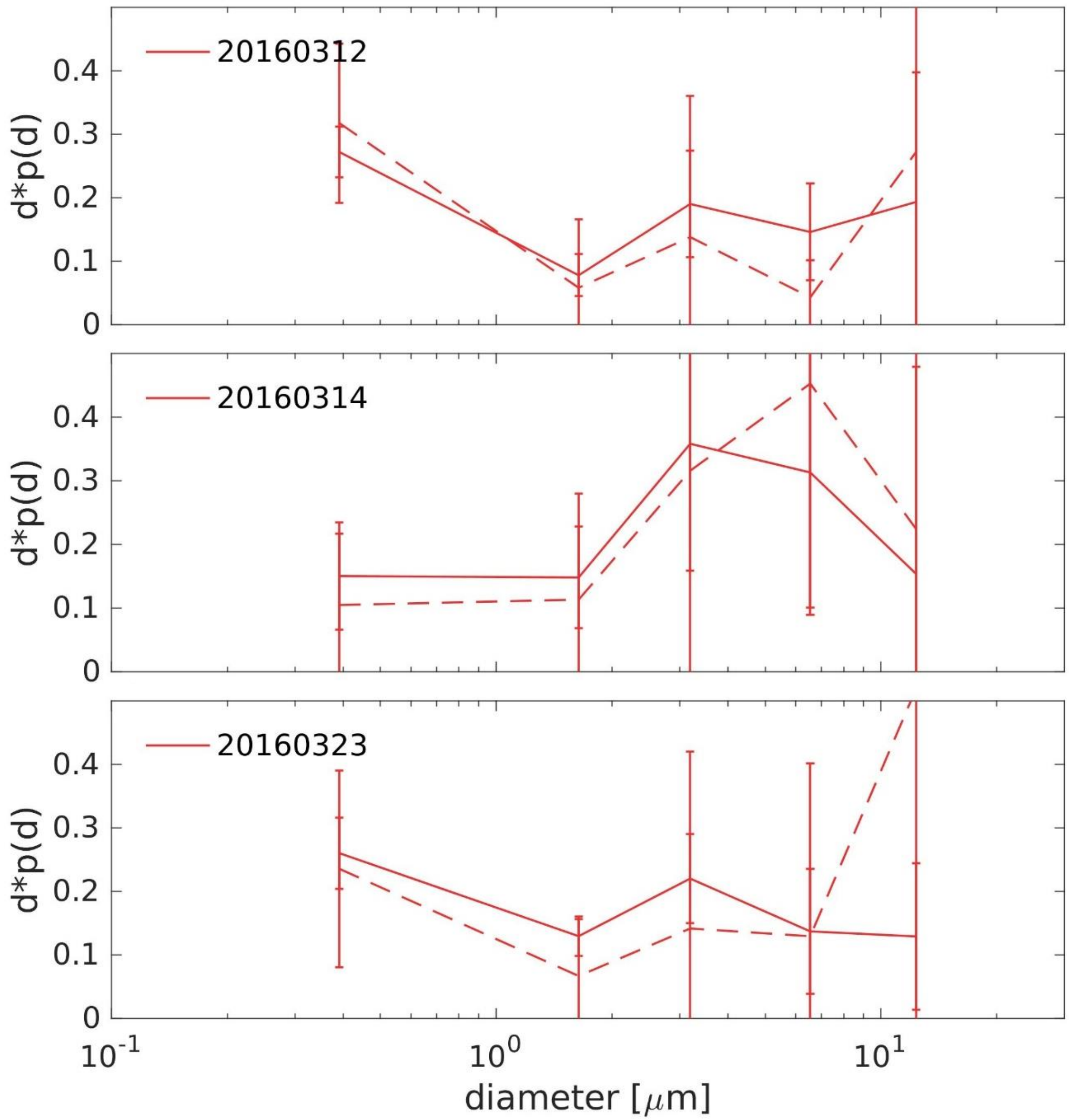
→ Particle supply?

Aerodynamic entrainment?

- Yes! But hard to isolate from other processes in an uncontrolled and heterogeneous environment.
- Can occur as precursor and parallel to other processes at areas with large amount of fines, e.g. walking paths or roads, and on larger scale in the absence of saltation.
- On larger scale, aerodynamic entrainment produces small dust fluxes, which are hard to identify.
- Supply-limited process, but any disturbance (e.g. saltation) will renew supply.

→ *Process needs more attention and focused measurements.*

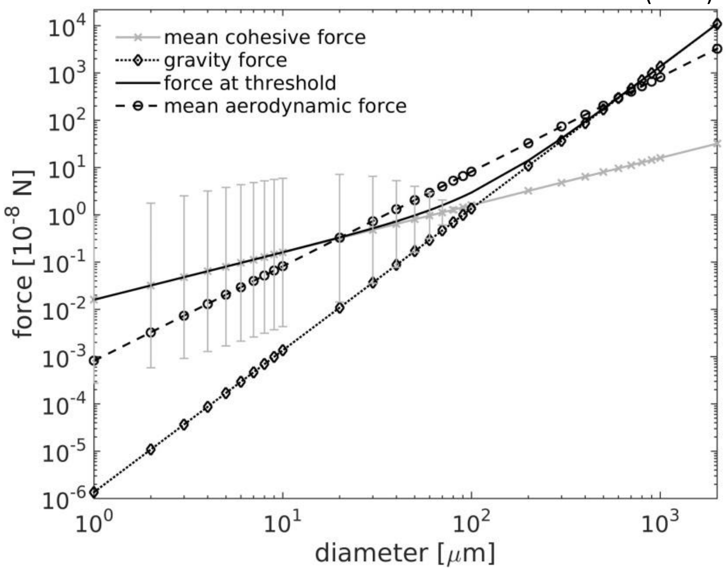
Dust size distribution – Site C



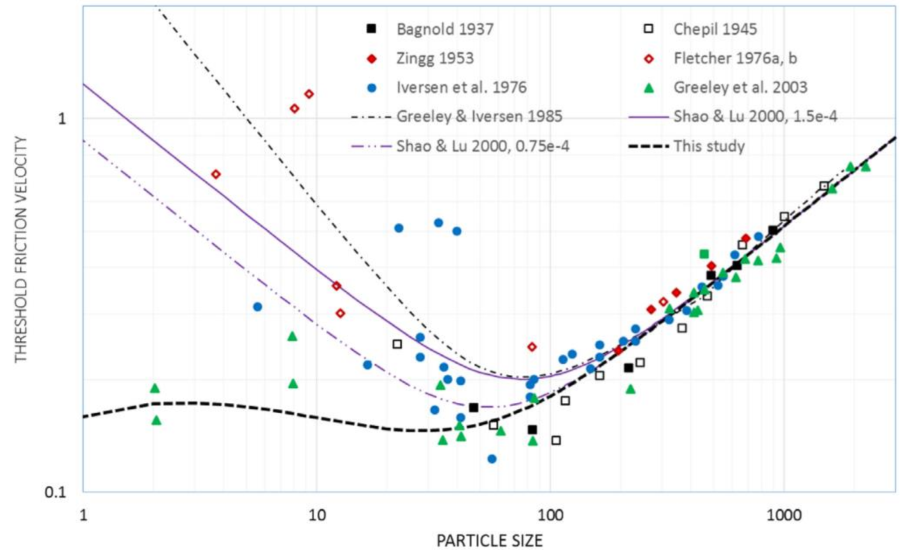
- Event-averaged DustTrak derived dust PSDs vary
- Time-resolved PSD may help to identify dust origin
- Local dust emission vs. dust advection
- Detailed analysis is underway

Cohesive force and u_{*t}

from *Klose* (2014)



from *Shao and Klose* (2016)

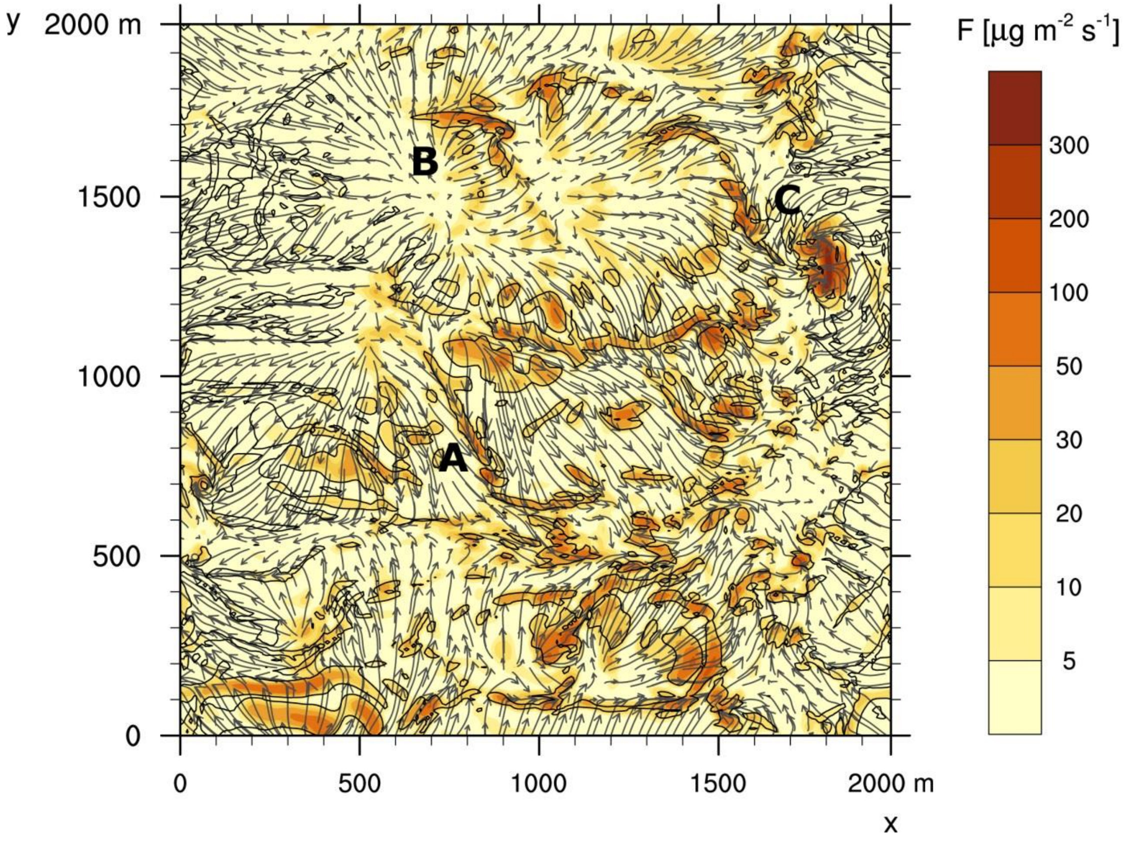


- On average: cohesive force ∝ d
  aerodynamic force ∝ d^2
  gravity force ∝ d^3
- Consideration of **cohesive force as stochastic quantity** in balance of forces for particle lifting

→ **u_{*t} for dust as low as for sand**

Convective turbulent dust emission

from *Shao et al.* (2015); updated from *Klose and Shao* (2013)



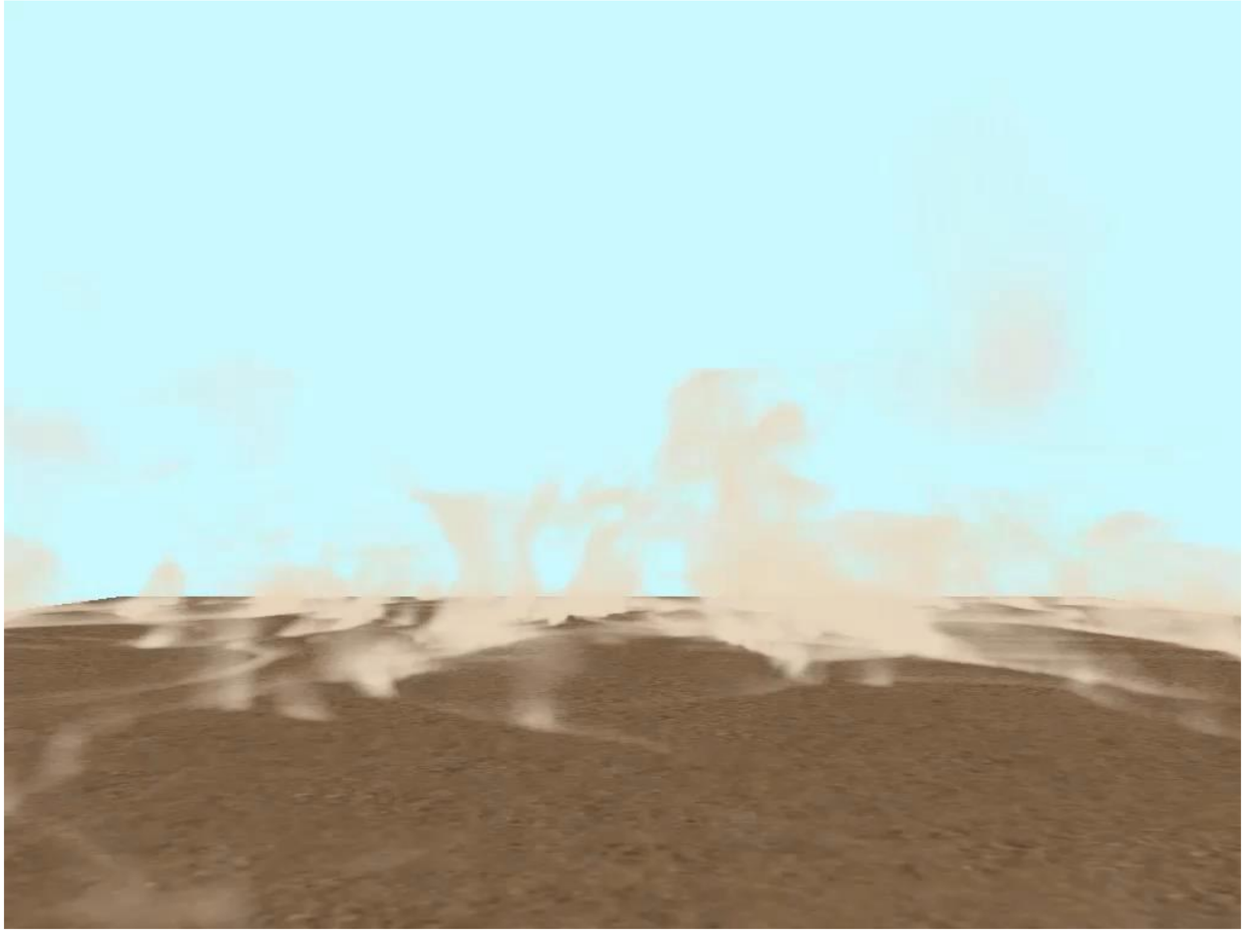
- Large eddies can produce significant dust emission
- Strongest emissions at

  A updraft convergence lines

  B downdraft centers

  C vortices

Convective turbulent dust emission



Dust concentration modeled with WRF/LES_D

Visualization in cooperation with the Regional Computing Centre, University of Cologne

Klose, M. S. Zellmann, Y. Shao, and U. Lang, 2014, **doi:10.5880/SFB806.5**

Dust devil detection and tracking

(I) **SEARCHING** – (II) **TRACKING** – (III) **POST PROCESSING**

(I) **a.** local pressure minimum

b. pressure drop Δp > threshold (0.05, 0.1, 0.2, 0.25 hPa)

c. vorticity ζ > threshold (0.1, 0.2, 0.5, 1.0 s^{-1})

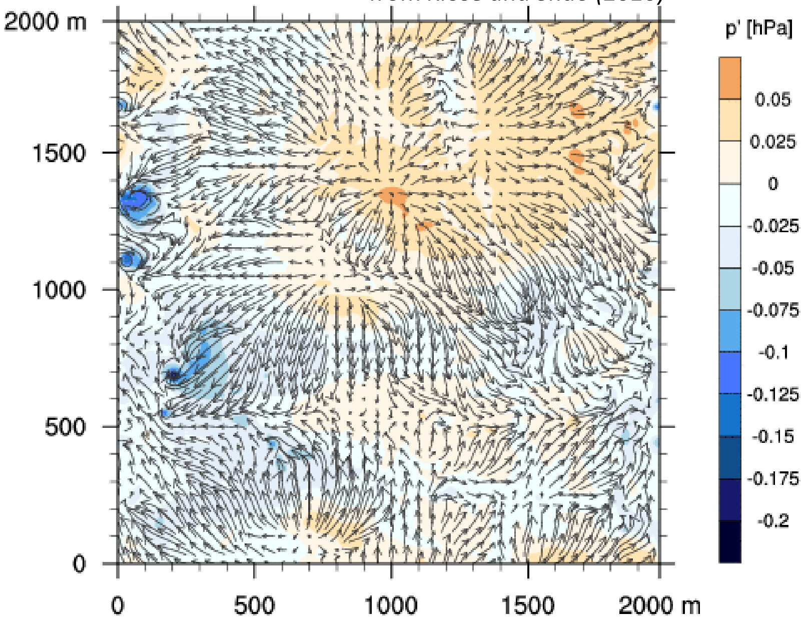
→ **16 combinations of criteria tested for two heights (2m, 10m)**

(II) apply searching criteria to expected position at time *t + Δt*

(III) Fill in gaps (soften thresholds)

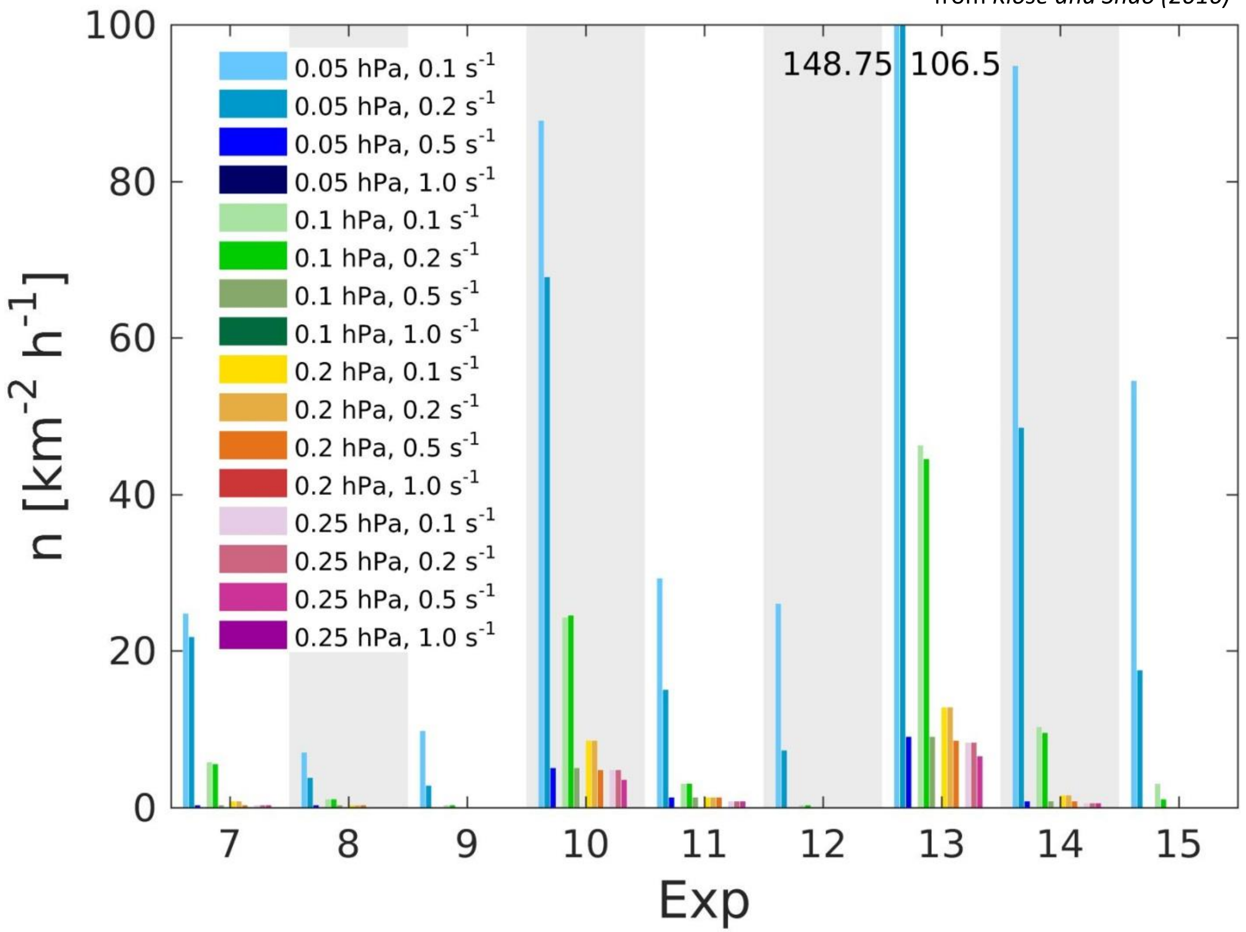
delete short tracks

from *Klose and Shao (2016)*



Dust devil number density

from *Klose and Shao (2016)*



	H	u*
Exp01	-50	0.15
Exp02	-50	0.3
Exp03	-50	0.5
Exp04	0	0.15
Exp05	0	0.3
Exp06	0	0.5
Exp07	200	0.15
Exp08	200	0.3
Exp09	200	0.5
Exp10	400	0.15
Exp11	400	0.3
Exp12	400	0.5
Exp13	600	0.15
Exp14	600	0.3
Exp15	600	0.5

Dust devil number density, *n*

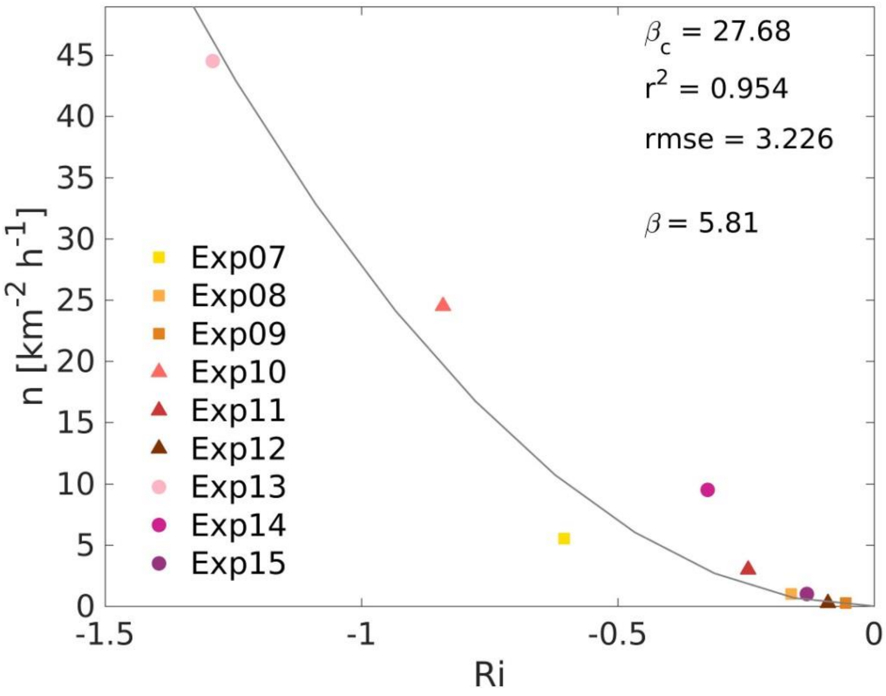
- *n* can be estimated based on Richardson number, *Ri*
- β is approximately constant for a range of identification criteria

$$n \quad = \quad \beta Ri^2 \qquad (\text{with } Ri < 0)$$

- When applied on large-scale, numbers have to be corrected for vegetation cover and (optionally) lapse rate, ΔT:

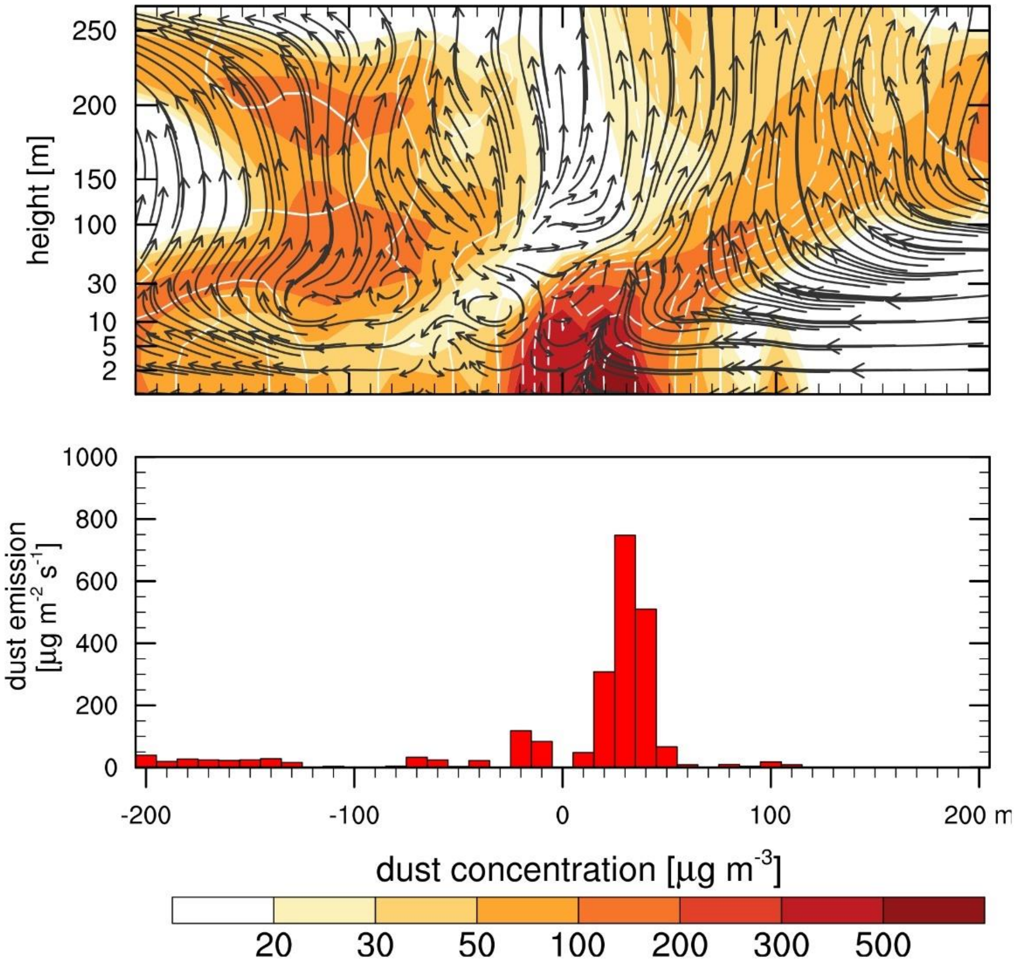
$$n_\sigma = n\,(1-\sigma) \qquad (\text{where } \Delta T > \Delta T_0)$$

from *Klose and Shao (2016)*



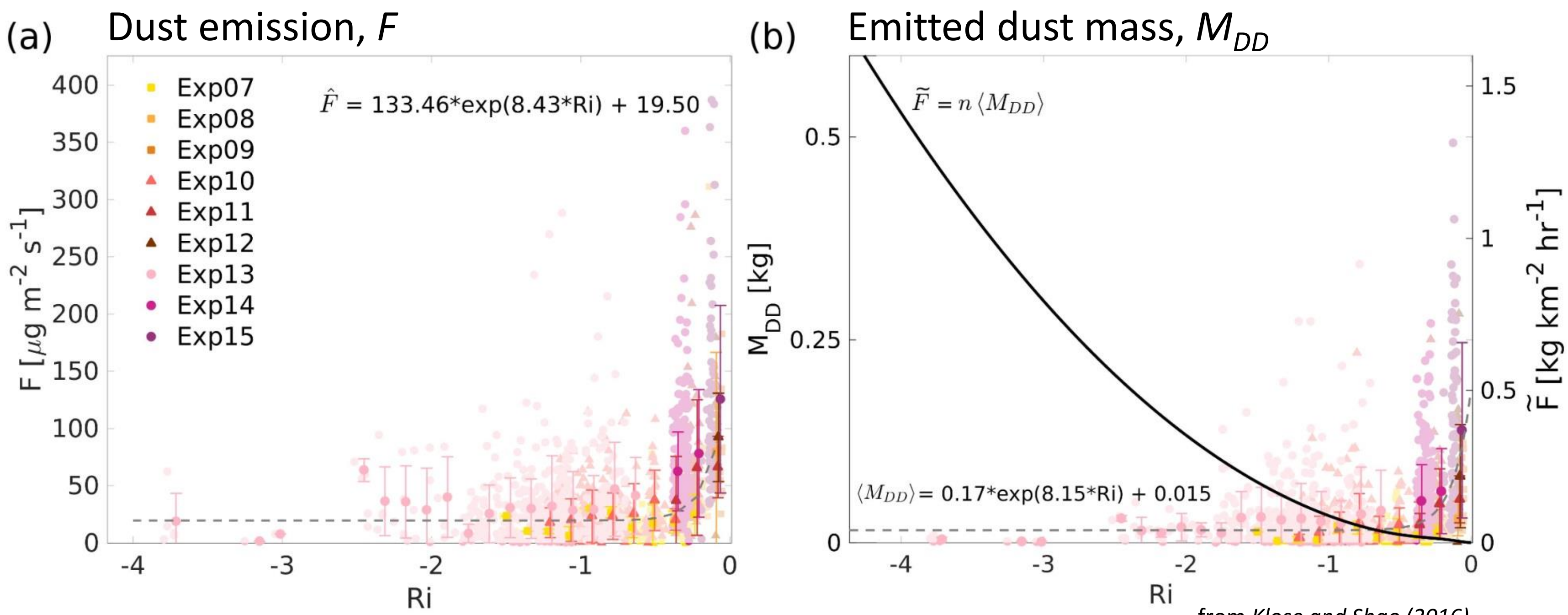
Dust devil dust emission

from *Klose and Shao (2016)*, after *Klose and Shao (2013)*



- Max. **dust concentrations** occur in the dust devil center (max. *Δp*). Local decreases in the center might be masked by model resolution.
- Max. **dust emissions** are around the center where shear stresses are strongest.
- **Dust emissions of up to ~1000 µg m^{-2} s^{-1}.**
- Modeled (surface) dust fluxes **smaller or on the lower edge** of observed (elevated) fluxes.

Dust devil dust emission



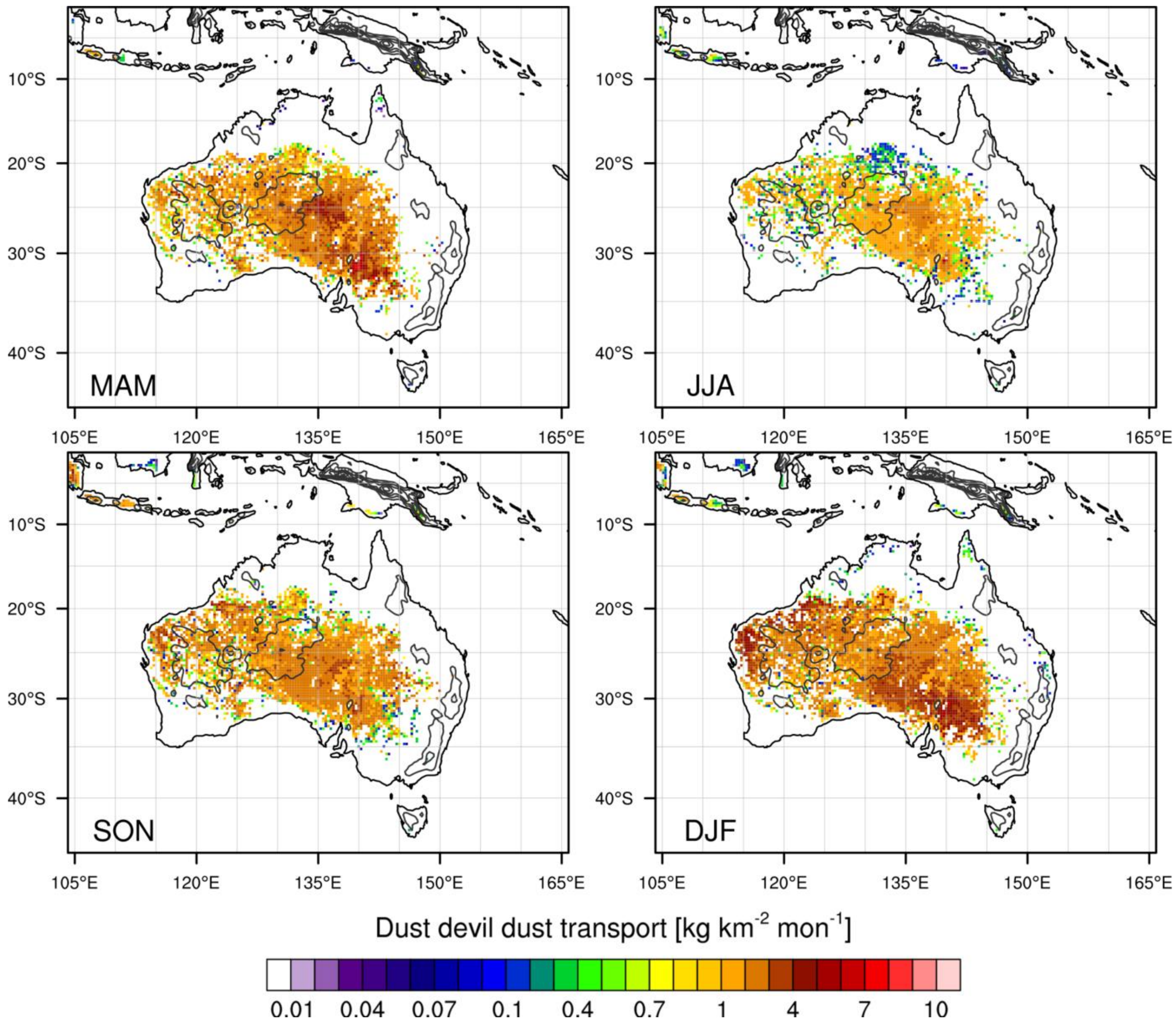
from *Klose and Shao (2016)*

- *F* varies strongly with *Ri*, but maxima are constrained to upper limit envelope.
- The dust devil **dust emission per unit area and unit time,** $\tilde{F}$, can be estimated based on M_{DD} and *n*.

→ **Estimation of large-scale dust devil dust transport based on a dust devil population**

Dust devil dust flux - Australia

after *Klose and Shao (2016), Klose et al. (2016)*



- Fluxes of mostly **1 – 3 kg km^{-2} mon^{-1}**, up to 10 kg km^{-2} mon^{-1}.
- Total dust devil dust emission ~ 0.1 Tg yr^{-1}.
- **Contribution to total dust budget likely < 1%** (reference 59 Tg yr^{-1}).
- Dust devils **can be major dust event type** in particular areas.

Book: Dust Devils, ed. by Reiss et al.

- Space Science Reviews
- Space Science Series of ISSI (Springer), 12 July 2017
- Chapters:
  1) ***Lorenz et al.*** – History and applications of dust devil research
  2) ***Murphy et al.*** – Field measurements of terrestrial and martian dust devils
  3) ***Fenton et al.*** – Orbital observations of dust lofted by daytime convective turbulence
  4) ***Reiss et al.*** – Dust devil tracks
  5) ***Rafkin et al.*** – Dust devil formation
  6) ***Kurgansky et al.*** – Dust devil steady-state structure from a fluid dynamics perspective
  7) ***Spiga et al.*** – Large-eddy simulations of dust devils and convective vortices
  8) ***Lorenz and Jackson*** – Dust devil populations and statistics
  9) ***Harrison et al.*** – Applications of electrified dust and dust devil electrodynamics to martian atmospheric electricity
  10) ***Neakrase et al.*** – Particle lifting processes in dust devils
  11) ***Klose et al.*** – Dust devil sediment transport: From lab to field to global impact

Conclusions

- Considerable dust emission occurs in settings that are not ideal (heterogeneous, patchy, crusted).
- Dust emission in such settings poses challenges for both theory/modeling and measurements.
- Measurements during "sub-optimal" conditions are worthwhile (necessary?) and can help increase the robustness of dust emission parameterizations.
- "Idealized" measurements need to cover a wider range of settings.
- Better representation of land-surface properties needed for larger-scale dust modeling (Crust? LEM?)
- Aerodynamic entrainment needs to receive more attention in field studies.

Thank You!

Near-surface flow estimate

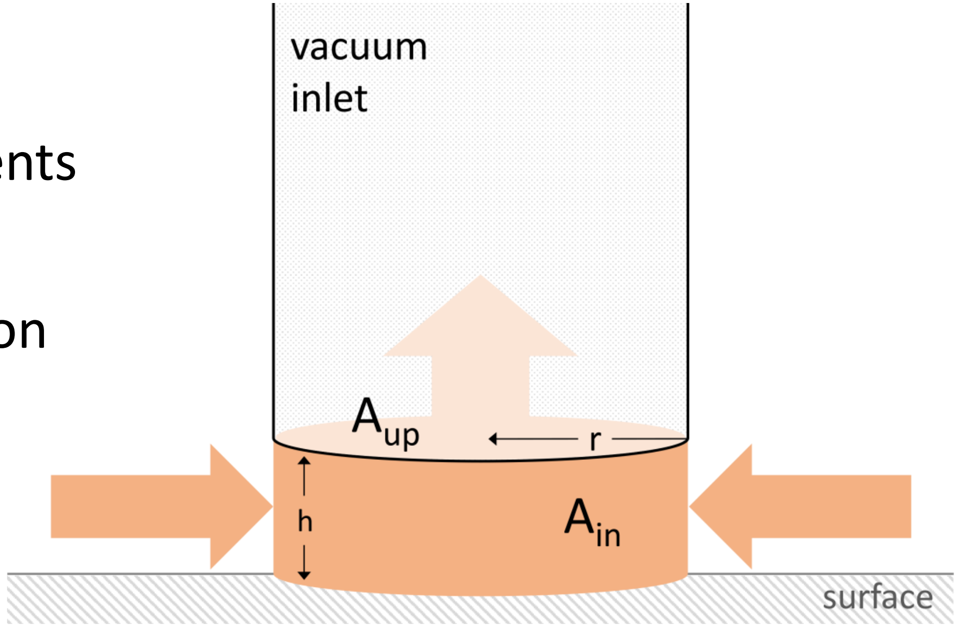
- Inflow into the vacuuming inlet is assumed to be radial and homogeneous.
- Assuming conservation of mass flux through areas $A_{in} = 2\pi rh$ and $A_{up} = \pi r^2$.

→ Average horizontal near-surface flow speed:

$v_h = \frac{v_{up} r}{2h}$

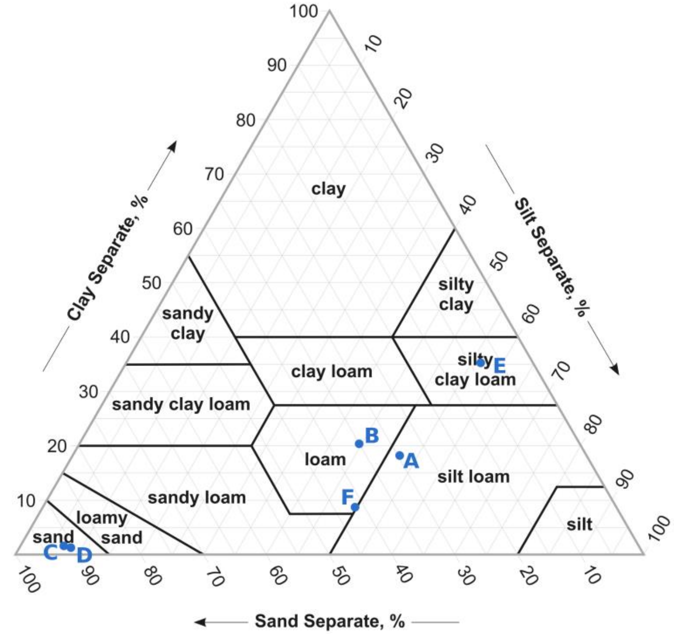
v_h is obtained from measurements using a field rotameter.

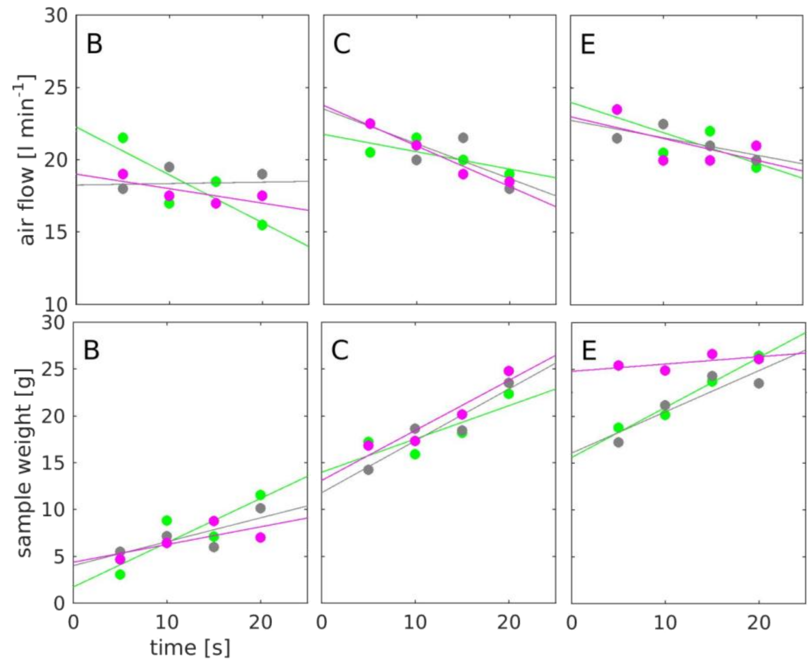
- Friction velocity follows based on logarithmic wind profile and assumptions about *h* and z_0.



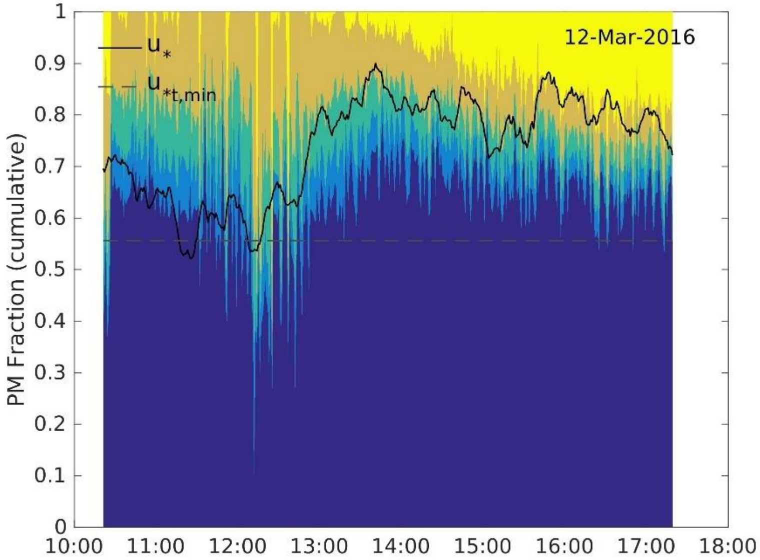
Sampling efficiency

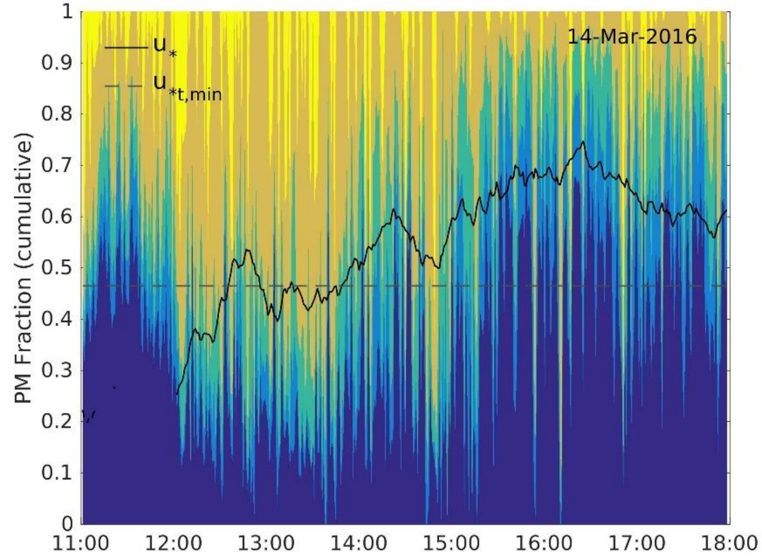
- Procedure:
  - vacuum three replicates of a sample for 5, 10, 15, and 20s;
  - measure flow speed at vacuum inlet;
  - weigh sample.
- **Flow speed decreases** with increasing vacuuming time.
- **Sample weight increases** with soil, but increase depends on soil.
- Friction velocities exerted on the soil surface are between 0.5 – 1 m s^{-1}.

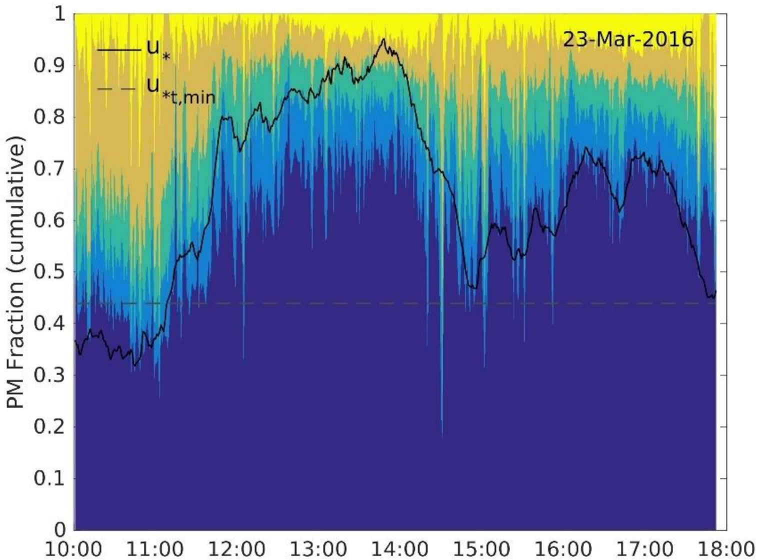




Site C







- PM 1, 2.5, 4, 10, and 15
- Fractions vary slightly with u_*
- Less variation once $u_* >> u_{*t}$; suggests supply limitation might be relevant.
- Dependence on emission, but also advection possible.
- Instrument comparison suggests DustTrak DRX might overestimate small-particle fractions.

Numerical experiments: LES

WRF V3.2 (later 3.5.1) Large-Eddy model coupled with dust mobilization scheme

Land-surface: homogeneous (loam soil)

constant surface heat flux

Atmospheric initialization:

Various atmospheric stability and background-wind conditions determined by

a) surface heat flux *H* (*H* = -50, 0, 200, 400, and 600 W m^{-2}) and

b) initialization with logarithmic wind profile based on friction velocity u_* (u_* = 0.15, 0.3, and 0.5 m s^{-1})

→ **15 different stability and background wind constraints**

Parameterization of AE

- Aerodynamic entrainment by convective turbulence (*Klose et al.*, 2014)
- Dust emission flux:

$$\tilde{F} = \begin{cases} \frac{\alpha_N}{2D}\left\{-w_t m_p + T_p\left(f - f_i \frac{d}{D}\right)\right\} & \text{for } f > f_i + m_p g, \\ 0 & \text{else} \end{cases}$$

$$F_j = \eta_j \int_0^\infty \left(\int_0^f \tilde{F} \cdot p_j(f_i)\, \mathrm{d}f_i \right) p(f)\, \mathrm{d}f$$

f_i ....**cohesive force** follows log-normal distribution (*Zimon*, 1982)

$\rightarrow$ can vary over orders of magnitude for given particle size

f .... **lifting force** determined by instantaneous momentum flux;

$\rightarrow$ resolved in large-eddy simulation (LES)

$\rightarrow$ *p(f)* in regional models

α_N	model parameter
w_t	particle terminal velocity
m_p	particle mass
T_p	particle response time
D	viscous sublayer thickness
η_j	particle fraction in size bin j
g	gravitational acceleration