Wind-invariant saltation heights imply linear scaling of aeolian sand flux with shear stress

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Key points:

1. Saltation layer height remains constant with wind shear velocity.
2. Saltation flux increases linearly with excess wind stress (rather than 3/2 power).

Overview of study

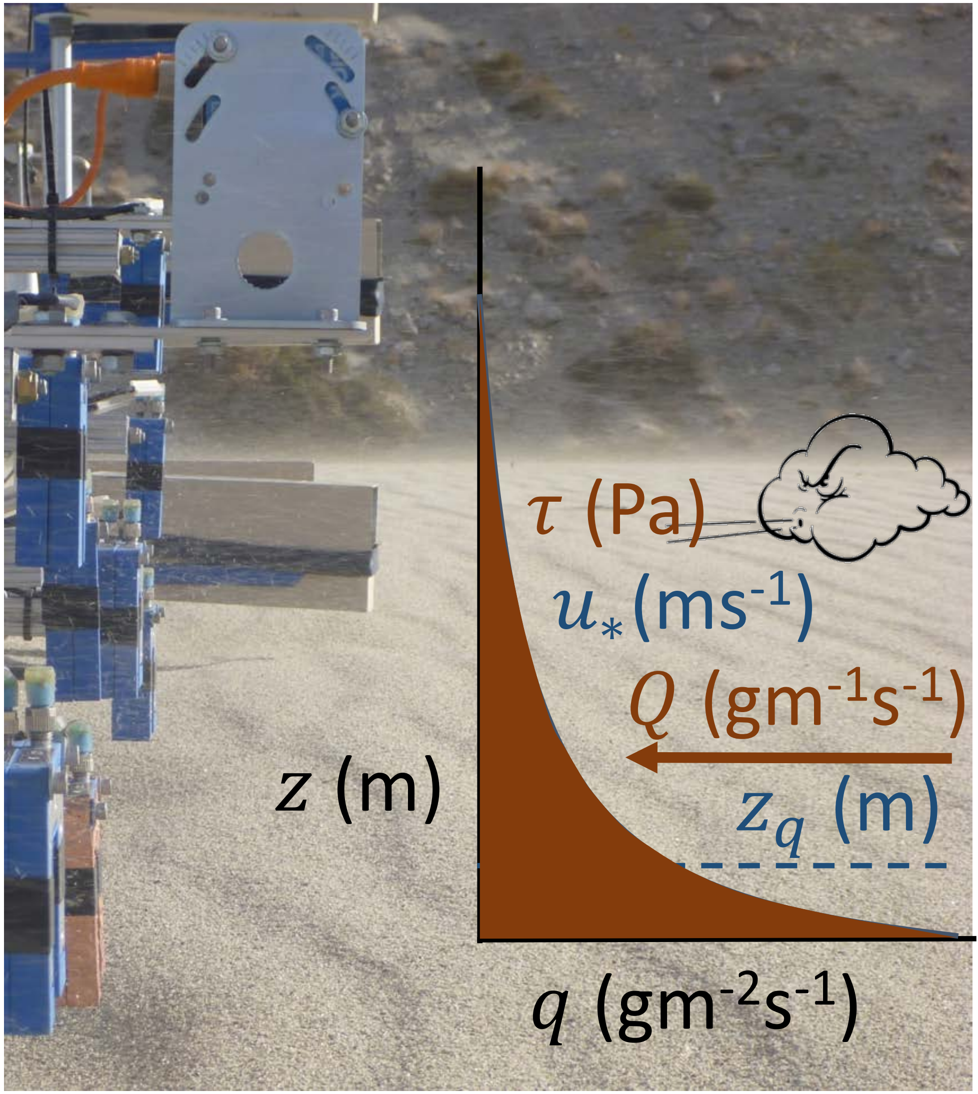
Field-based study of wind-blown sand ("saltation") flux

RESULT 1: Saltation layer height $\boldsymbol{z_q}$ remains constant with wind shear velocity $\boldsymbol{u_*}$:

$$\boldsymbol{z_q \neq f(u_*)}$$

RESULT 2: Saltation flux $\boldsymbol{Q}$ increases linearly with excess wind stress $\boldsymbol{\tau_{ex}}(= \tau - \tau_{it})$:

$$\boldsymbol{Q \propto \tau_{ex}}$$



This **linear scaling** contrasts with prevailing **3/2 scaling** (i.e.: $Q \sim \tau^{3/2}$ or $Q \sim u_*^3$) currently used for most saltation flux predictions.

Saltation flux law: state of research

Two competing forms of flux law for **saltation flux Q** vs **wind stress τ** (or shear velocity u_*)

"3/2 nonlinear scaling"
(Bagnold, 1941; Owen, 1964)

$$Q \sim \tau^{3/2}$$
$$(Q \sim u_*^3)$$

"linear scaling"
(Ungar and Haff, 1987)

$$Q \sim \tau$$
$$(Q \sim u_*^2)$$

Granular physics	**Mostly reject 3/2 scaling and support linear scaling**, but lack field evidence (e.g. Andreotti, 2004; Creyssels et al., 2009; Ho et al., 2011)
Aeolian geomorphology	**Mostly adopt 3/2 flux law for "drift potential"** to predict dune migration (e.g., Fryberger, 1979; Lancaster, 1995; Pye and Tsoar, 2009)
Planetary science	**Widely-used White (1979) equation adopts 3/2 flux law**, but recent work (e.g., Ayoub et al. 2014) considers both flux laws
Atmospheric dust emission	**Mostly adopt 3/2 flux law for saltation bombardment mechanism** to predict dust generation (e.g., Shao, 2008; Marticorena, 2014)

Introduction: Existing saltation models

Saltation flux = particle speed * particle conc.

$$Q = V * \Phi$$

Concentration scales linearly with excess wind stress: (e.g., Ho et al., 2011)

$$\Phi \propto \tau_{ex}$$

Excess wind stress = Total wind stress minus threshold stress (Owen, 1964): $\tau_{ex} = \tau - \tau_{it}$

Particle speed (V)	**Saltation flux (Q)**
scales with shear velocity →	scales with **3/2 power** of stress
$V \propto u_* = \tau^{1/2}$ (e.g., Bagnold, 1941; Owen, 1964)	$Q \sim \tau^{3/2}$ $(Q \sim u_*^3)$ *"3/2 scaling"*
OR is invariant with shear velocity →	scales **linearly** with stress
$V \neq f(u_*)$ (e.g., Ungar and Haff, 1987; Ho et al., 2011)	$Q \sim \tau$ $(Q \sim u_*^2)$ *"linear scaling"*

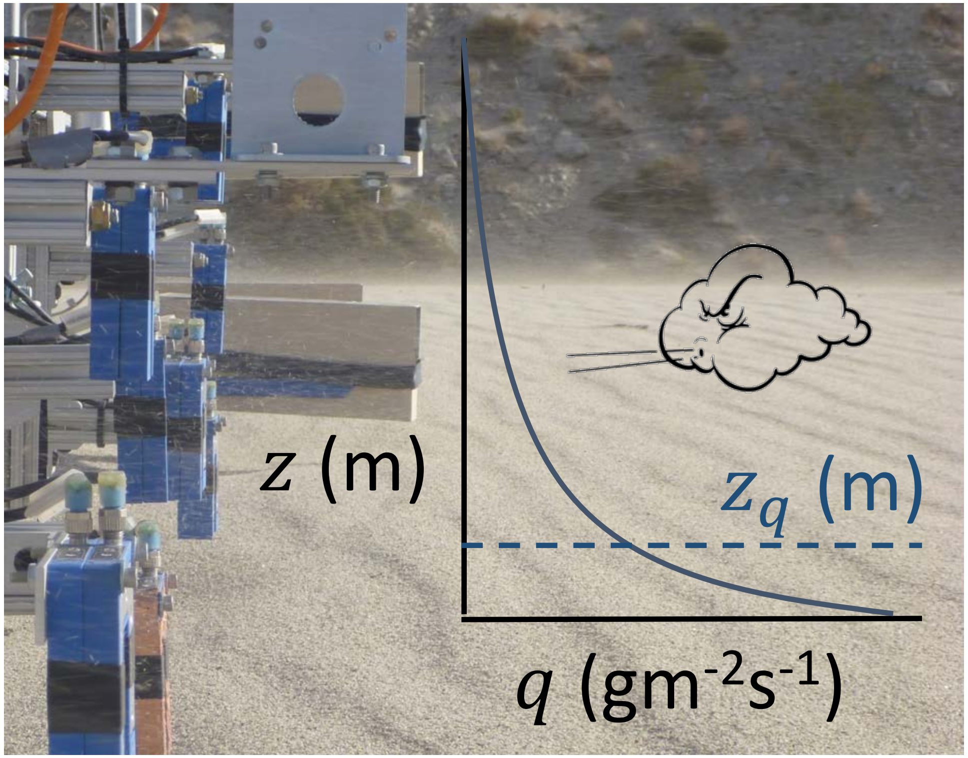
We need to know **particle speed scaling** to resolve **flux law scaling**!

Saltation layer height: Insight into particle speed

Saltation height z_q =
e-folding height of flux profile:

$$q(z) = q_0 \exp\left(-\frac{z}{z_q}\right)$$

Saltation height scales with **particle speed** squared:
$z_q \propto V^2$ (Owen, 1964)



So, how does saltation height vary with shear velocity? $z_q = f(u_*)$?

Methods: Field deployments

BSNE traps: flux calibration

Sonic anemometers: high-freq. wind

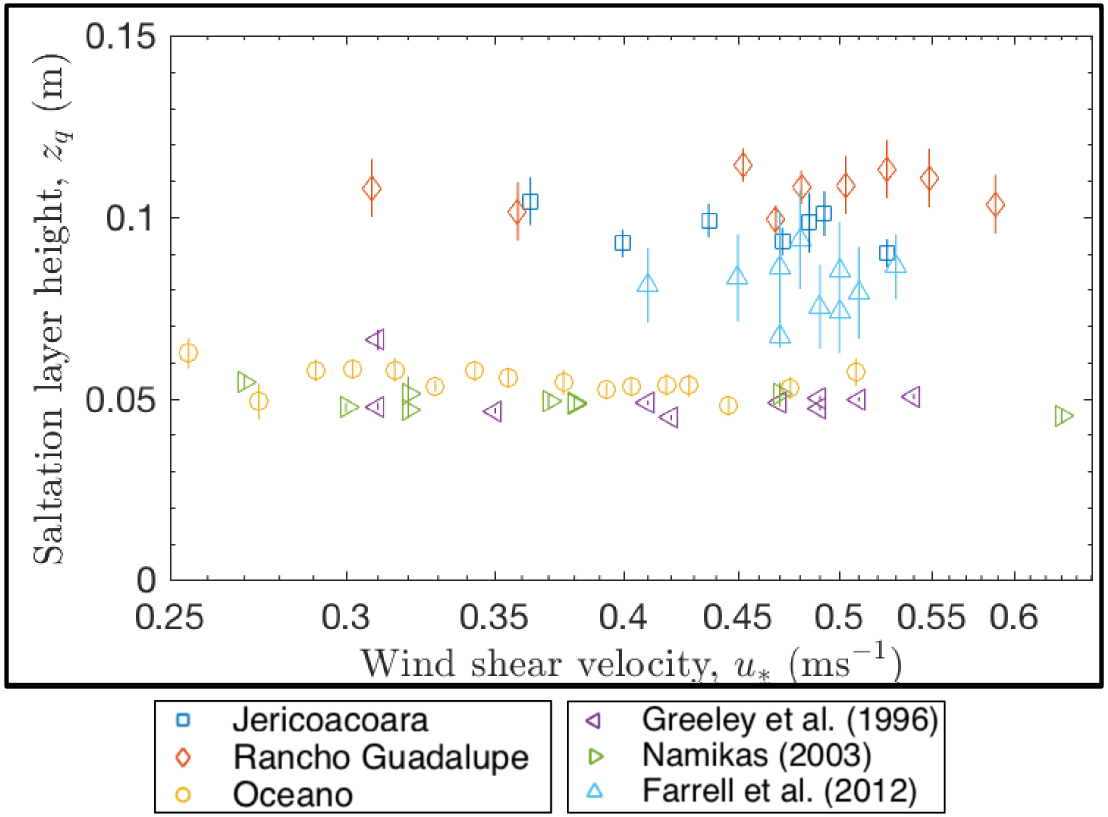
- $\boldsymbol{u_*}$: shear velocity
- $\boldsymbol{\tau}$: shear stress

Wenglors: saltation flux profile, $q(z)$

- $\boldsymbol{z_q}$: saltation height
- $\boldsymbol{Q}$: total flux

Video: June 2, 2015, Oceano Dunes, CA
Time-lapse @ 600x (1 second = 10 minutes). Image width ≈ 3 m

Saltation height is invariant with shear velocity



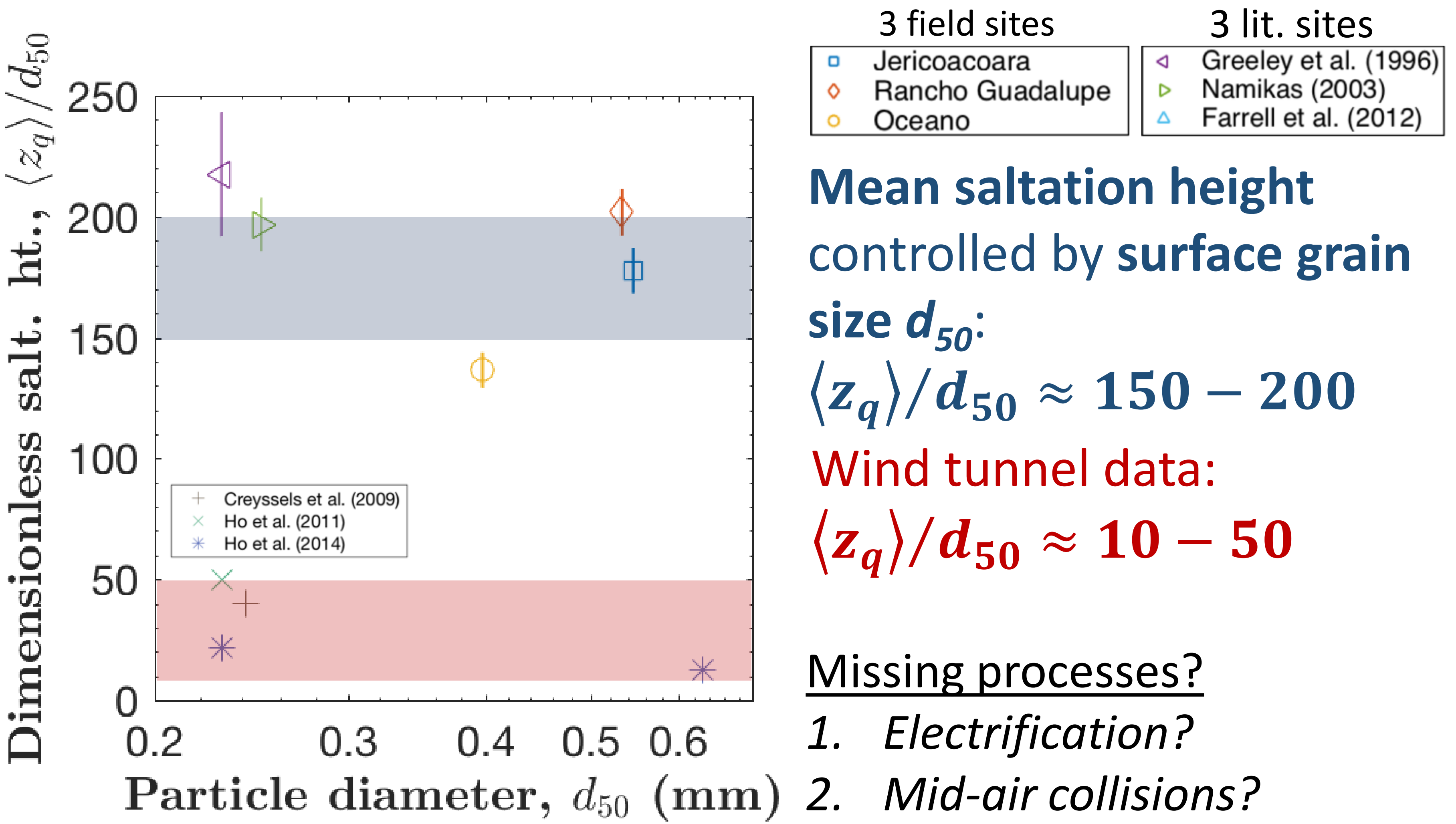
Constant saltation heights: $z_q \neq f(u_*)$

→ **constant particle speeds: $\boldsymbol{V \neq f(u_*)}$**

(because $z_q \propto V^2$)

(Martin and Kok, in press, *Science Advances, Preprint: arXiv:1609.09458v2*)

Soil particle size controls saltation height



Mean saltation height controlled by **surface grain size *d_{50}***:

$$\langle z_q \rangle / d_{50} \approx \mathbf{150 - 200}$$

Wind tunnel data:

$$\langle z_q \rangle / d_{50} \approx \mathbf{10 - 50}$$

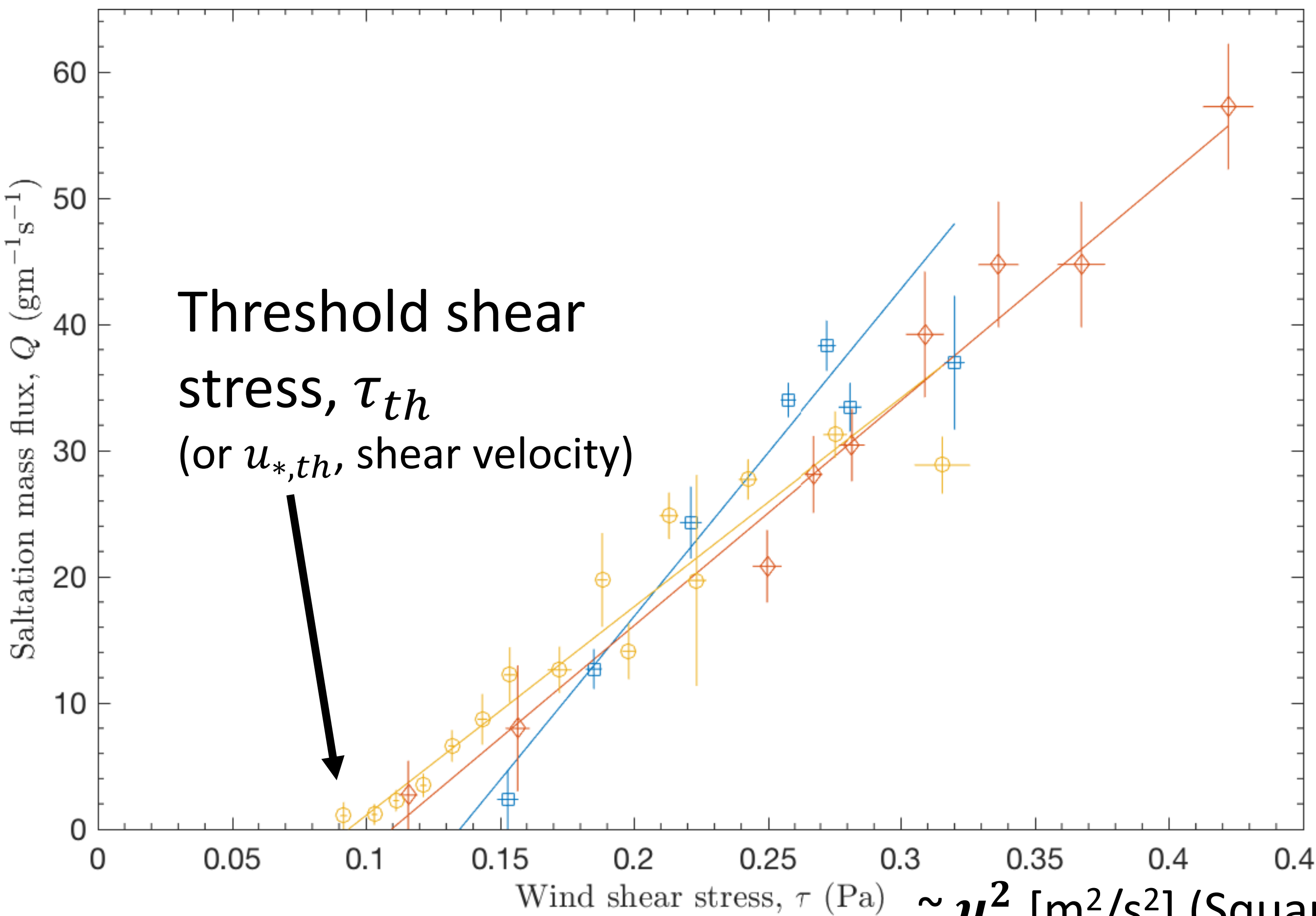
Missing processes?

1. *Electrification?*
2. *Mid-air collisions?*
3. *Turbulence?*

Constant z_q → linear flux scaling: $\boldsymbol{Q} \propto \boldsymbol{\tau}$

Constant saltation layer height, $z_q \neq f(u_*)$
→ Constant particle speed, $V \neq f(u_*)$
→ Linear flux scaling, $Q \sim \tau$ ($Q \sim u_*^2$)

Does this agree with measurements?



$\sim u_*^2$ [m²/s²] (Squared shear velocity)

Yes: $Q \propto \tau$

Best-fit threshold (τ_{th}) corresponds to impact threshold (τ_{it}) (Martin and Kok 2017, in review, *GRL*)

(Martin and Kok, in press, *Science Advances, Preprint: arXiv:1609.09458v2*)

Saltation heights ∝ particle diameter → linear flux law

$$Q \propto \frac{u_{*,it}}{g}(\tau - \tau_{it})$$

Confirms recent theoretical (Duran et al., 2011; Kok et al., 2012) and wind tunnel studies (e.g., Ho et al., 2011)

Q Saltation flux

=

V particle speed

*

Φ particle conc.

(ballistic trajectory) (our observations) (Bagnold, 1941)

$\propto \sqrt{\text{hop height}} \propto \sqrt{\text{surface grain diameter}} \propto$ threshold shear vel.

$\propto \sqrt{z_q * g}$ $\propto \sqrt{d_{50} * g}$

$V \propto u_{*,it}$

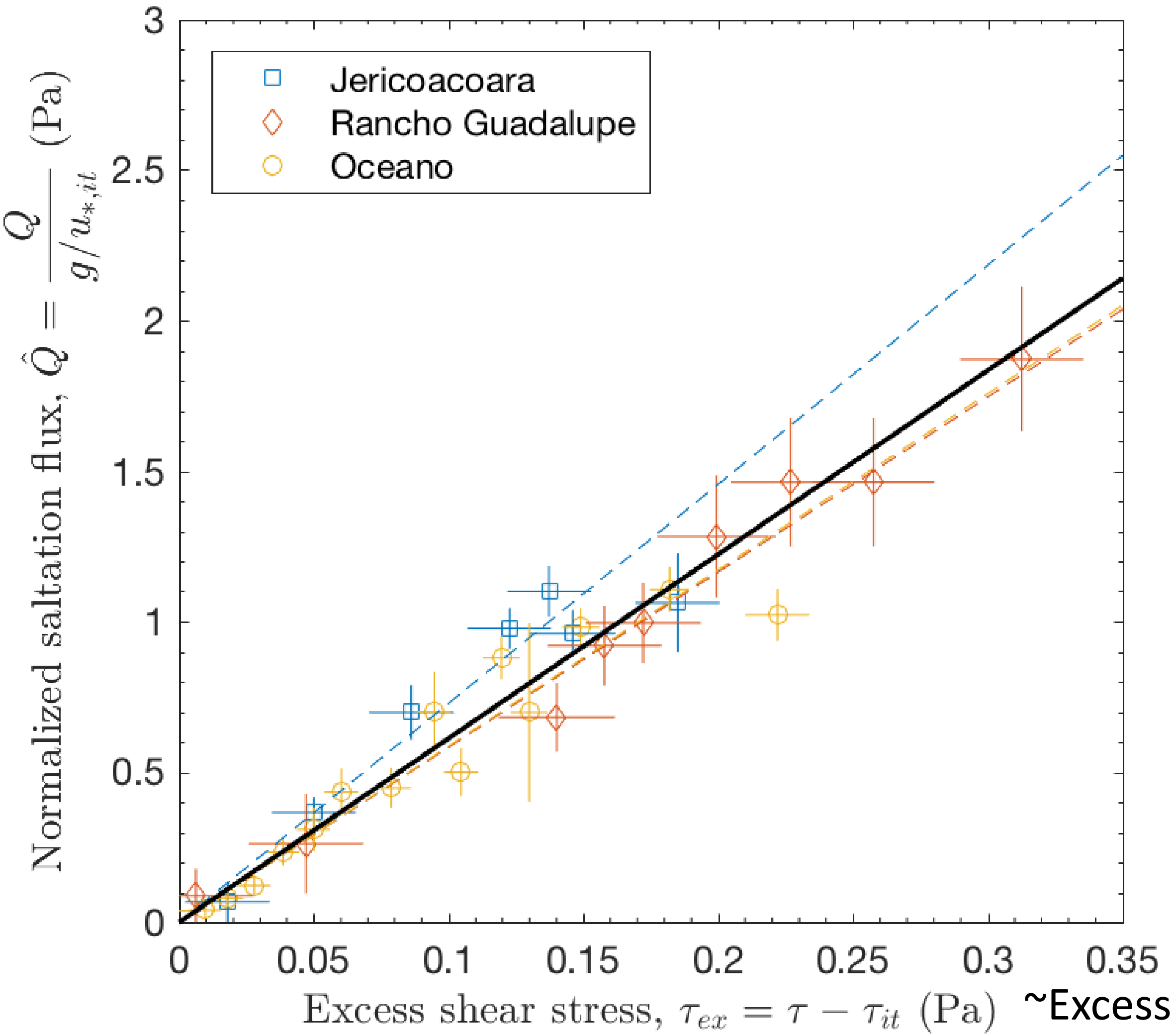
$\Phi \propto (\tau - \tau_{it})/\mathrm{g}$

(stress above threshold)

Parameterization factor for flux law

$$Q \propto \frac{u_{*,th}}{g}(\tau - \tau_{it}) \rightarrow Q = C_Q \frac{u_{*,it}}{g}(\tau - \tau_{it})$$

what is C_Q?



~Excess shear velocity, $u_*^2 - u_{*,it}^2$ (m²/s²)

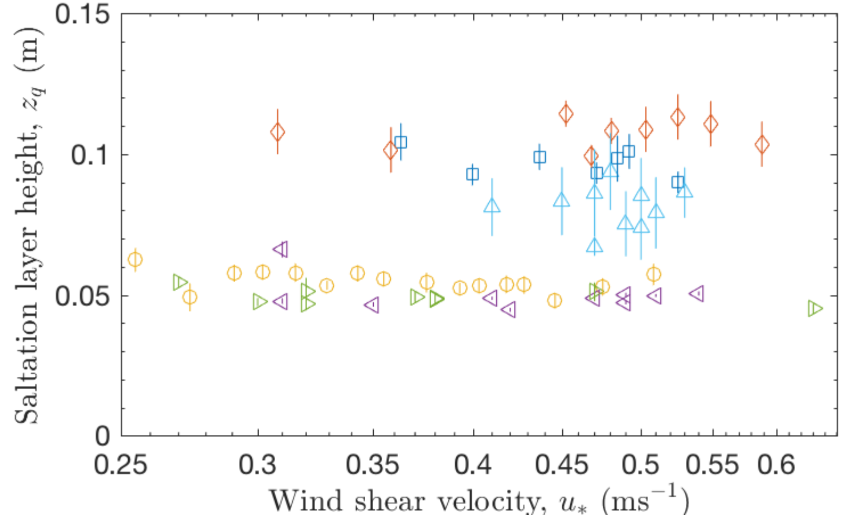
Source	C_Q
Jericoacoara	7.3 ± 0.9
Rancho Guad.	5.8 ± 0.5
Oceano	5.9 ± 1.0

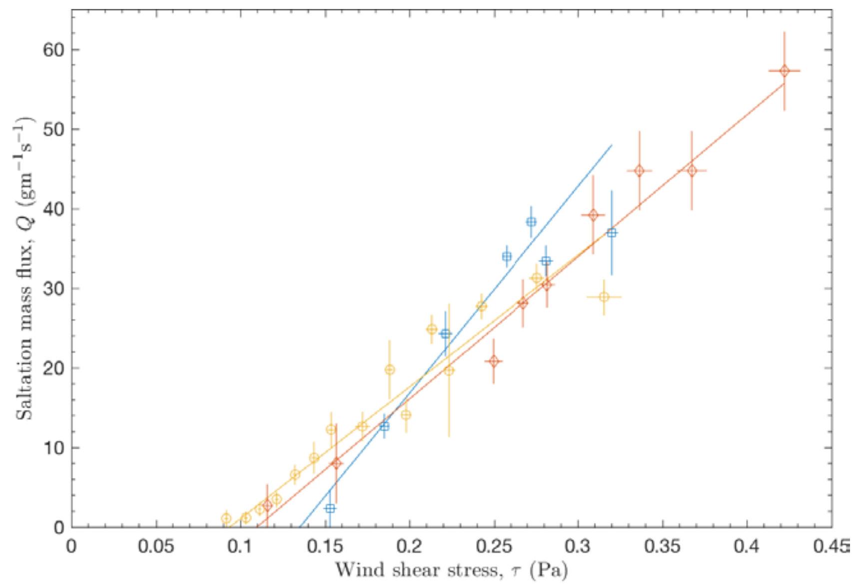
$$C_Q = 6.1 \pm 0.4$$

Kok et al. (2012): $C_Q = 5$

Conclusions

- We present the **first field-based evidence** for a linear saltation flux law ($Q = C_Q \frac{u_{*,it}}{g} \tau_{ex}$)
    - *Indirect evidence:* Constant saltation heights
    - *Direct evidence:* Stress vs. flux comparison
- Saltation heights are much larger than predicted: z_q/d_{50} = 150-200 (field) vs 10-50 (wind tunnel, numerical)
    - One or more important processes are not accounted for in numerical and wind tunnel studies
- Our findings suggest a **linear saltation flux law** on Mars, Triton, Pluto, Io, and comets with dilute atmospheres





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Saltation flux law in other environments

Aeolian: **Large** particle-fluid density ratio ($\boldsymbol{s = \rho_p/\rho_f} \approx 2000$)
→ Dominance of splash entrainment
→ Constant particle speeds
→ Linear flux law: $\boldsymbol{Q \sim \tau}$ ($Q \sim u_*^2$)

Fluvial: **Small** particle-fluid density ratio ($\boldsymbol{s = \rho_p/\rho_f} \approx 2.65$)
→ Dominance of fluid entrainment
→ Particle speeds increase with shear velocity → 3/2 flux law: $\boldsymbol{Q \sim \tau^{3/2}}$ ($Q \sim u_*^3$)

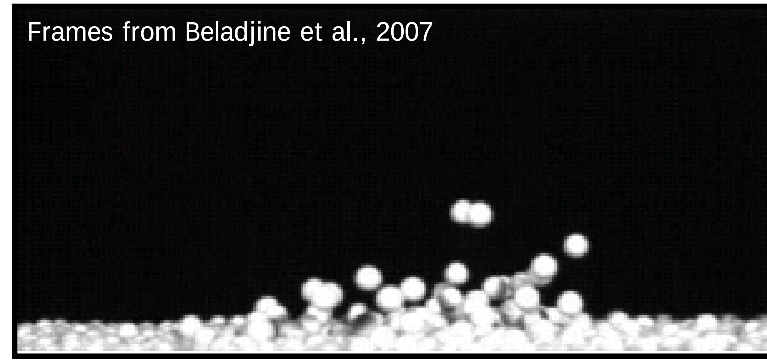
Hypothesis: **Particle-fluid density ratio governs linear versus 3/2 flux law**
(Pahtz and Duran, 2016 x 2)

Environment	Particle-fluid density ratio: $s = \rho_p/\rho_f$	Flux law type
Earth fluvial	**2.65**	**Nonlinear 3/2**
Venus	40	?
Titan	190	?
Earth aeolian	**2000**	**Linear**
Mars	2.5×10^5	Linear predicted
Triton	10^7	Linear predicted
Pluto	10^7	Linear predicted
Io	10^{12}	Linear predicted
Comets	e.g., 10^{12}	Linear predicted

Saltation particle speed at surface is constant with wind speed

- Particle speeds at surface **constrained by splash**
  - Steady state: **constant particle concentration**

  → One particle leaving the soil for each particle impacting it



- Rebound of impacting particle and splashing of surface particle(s) **depends on impact speed** (not on wind speed!)
  - **Impact speed ~constant with wind speed!** (e.g., Kok et al. 2012)
  - Measurements show this clearly
  - **Model and theory accounting for splash** reproduces this