Linear scaling of wind-driven sand flux with shear stress

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ABSTRACT:

- Uncertainty about the relationship between aeolian saltation flux and wind shear stress hinders understanding of earth and planetary geomorphology and atmospheric dust generation.
- Here, we investigate the saltation flux law based on data from three field campaigns yielding comprehensive data of unprecedented scope.
- Our observations show that mean saltation layer height remains constant with changes in shear velocity, indicating constant mean particle speeds.
- Based on this, we predict a linear relationship between saltation flux and shear stress scaled by the typical duration of saltation hops.
- Direct stress-flux comparison strongly supports inference of flux law with saltation flux increasing linearly with excess shear stress.
- We expect a linear relationship to hold in other environments (e.g. Mars) with large particle-fluid density ratios.

SALTATION FLUX LAW DEBATE (LINEAR VS. NONLINEAR 3/2):

- $\boldsymbol{Q}$ (g m^{-1} s^{-1}) – saltation mass flux
- $\boldsymbol{\tau}$ (Pa) – shear stress
    - $\tau = \rho_f u_*^2$, where ρ_f is air density and u_* is shear velocity

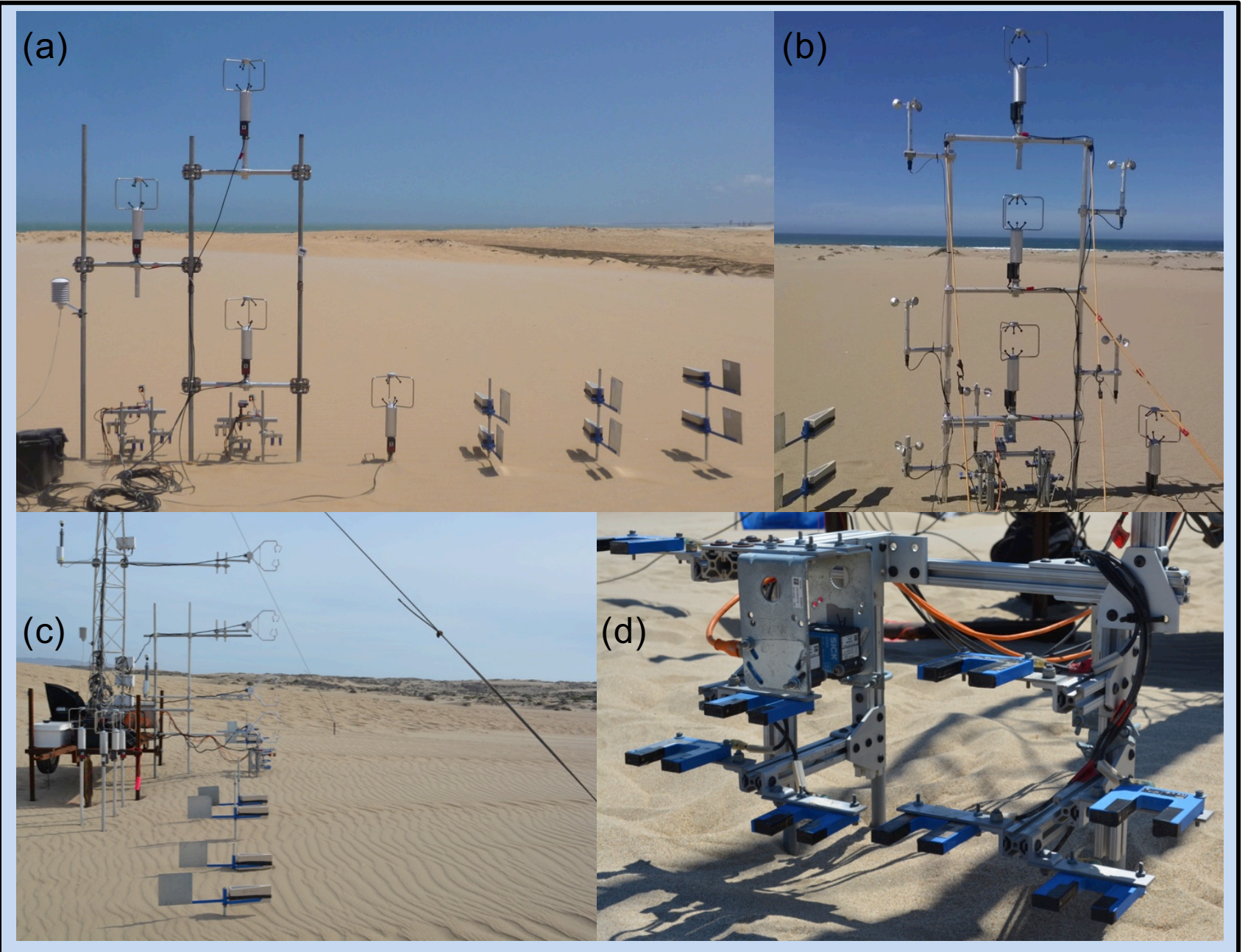
$Q = \Phi V$ (Particle concentration * Particle speed)

- Mean **particle concentration $\boldsymbol{\Phi}$ scales linearly with excess stress $\boldsymbol{\tau_{ex}}$, $\boldsymbol{\tau_{ex} = \tau - \tau_{it}}$** (e.g., Ho et al., 2011)
- Mean **particle speed $\boldsymbol{V}$** is controversial:
    - Most existing flux laws (e.g., Bagnold, 1941; Owen, 1964) **assume $\boldsymbol{V \sim u_*}$** and therefore predict $Q \sim \tau^{3/2}$ $(Q \sim u_*^3)$
    - Recent theory (e.g. Ungar and Haff, 1987) and experiments (e.g. Ho et al., 2011) alternatively support **$\boldsymbol{V}$ constant with $\boldsymbol{u_*}$** and therefore predict $Q \sim \tau$ $(Q \sim u_*^2)$
- Further, $\boldsymbol{V}$ is related to **saltation layer height $\boldsymbol{z_q}$** as: $V \sim \sqrt{z_q}$ (Owen, 1964)
- **Therefore, determining z_q versus u_* should resolve Q vs. τ scaling**

FIELD CAMPAIGNS

	Jericoacoara (Ceara, Brazil)	Rancho Guadalupe (California, USA)	Oceano (California, USA)
# saltation days	3	2	12
surface d_{50}	0.55 ± 0.04	0.53 ± 0.03	0.40 ± 0.07

- Saltation flux, $\boldsymbol{Q}$, calculated from exponential fit to 30 minute avg flux profile of Wenglors ($z \approx$ 2-47 cm), shown on right, calibrated from ~hourly BSNE sand trap collections.
- Shear stress, $\boldsymbol{\tau}$, computed as Reynolds stress ($\tau = -\rho_f \overline{u'w'}$) over 30-minute windows from sonic anemometer mounted at $z \approx$ 0.5 m.

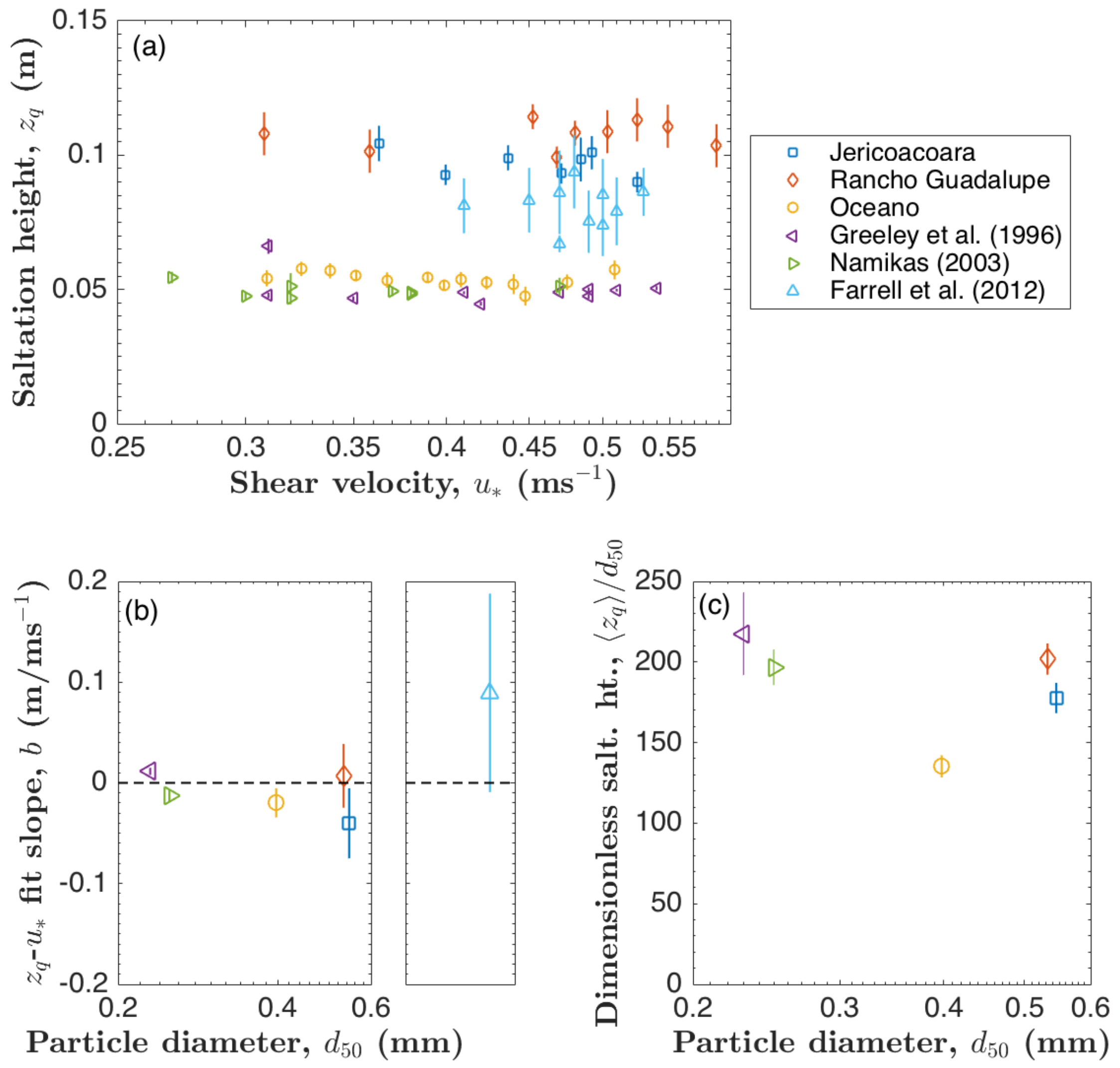


(a) Jericoacoara, looking upwind (b) Rancho Guadalupe, looking upwind. (c) Oceano, looking from the side. (d) Close-up of Wenglor array at Oceano, looking downwind.

SALTATION HEIGHT VERSUS SHEAR VELOCITY:

Saltation height, z_q, is e-folding height for flux profile:

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



- Observations mostly suggest **little to no change in saltation height $\boldsymbol{z_q}$ with shear velocity ($\boldsymbol{u_*}$).**
- **Using median surface grain diameter, $\boldsymbol{d_{50}}$, to nondimensionalize** saltation height, z_q, explains most variability among sites.

CONSTANT SALTATION HEIGHT => LINEAR FLUX LAW:

$Q = \Phi V$ (Particle concentration * Particle speed). [1]

Excess stress ($\tau_{ex} = \tau - \tau_{it}$) is balanced by particle momentum dissipation at bed:

$$\boldsymbol{\tau_{ex} = \tau_p = MV(1-e)}. \text{ [2]}$$

M = mass collision rate and e = restitution coefficient. Resulting concentration is:

$$\boldsymbol{\Phi = Mt_{hop}}. \text{ [3]}$$

Hop time t_{hop} scales with square root of saltation height z_q: $\boldsymbol{t_{hop} \sim \sqrt{z_q}}$. [4]

$\boldsymbol{z_q \sim d_{50}}$ **[5] from our measurements (constant saltation layer height).**

$u_{*,it} \sim \sqrt{g d_{50}}$ **[6]** (Bagnold, 1941).

Combining [1-6], we get $Q = C_Q \frac{u_{*,it}}{g} \tau_{ex}$, i.e. flux ~ excess stress.

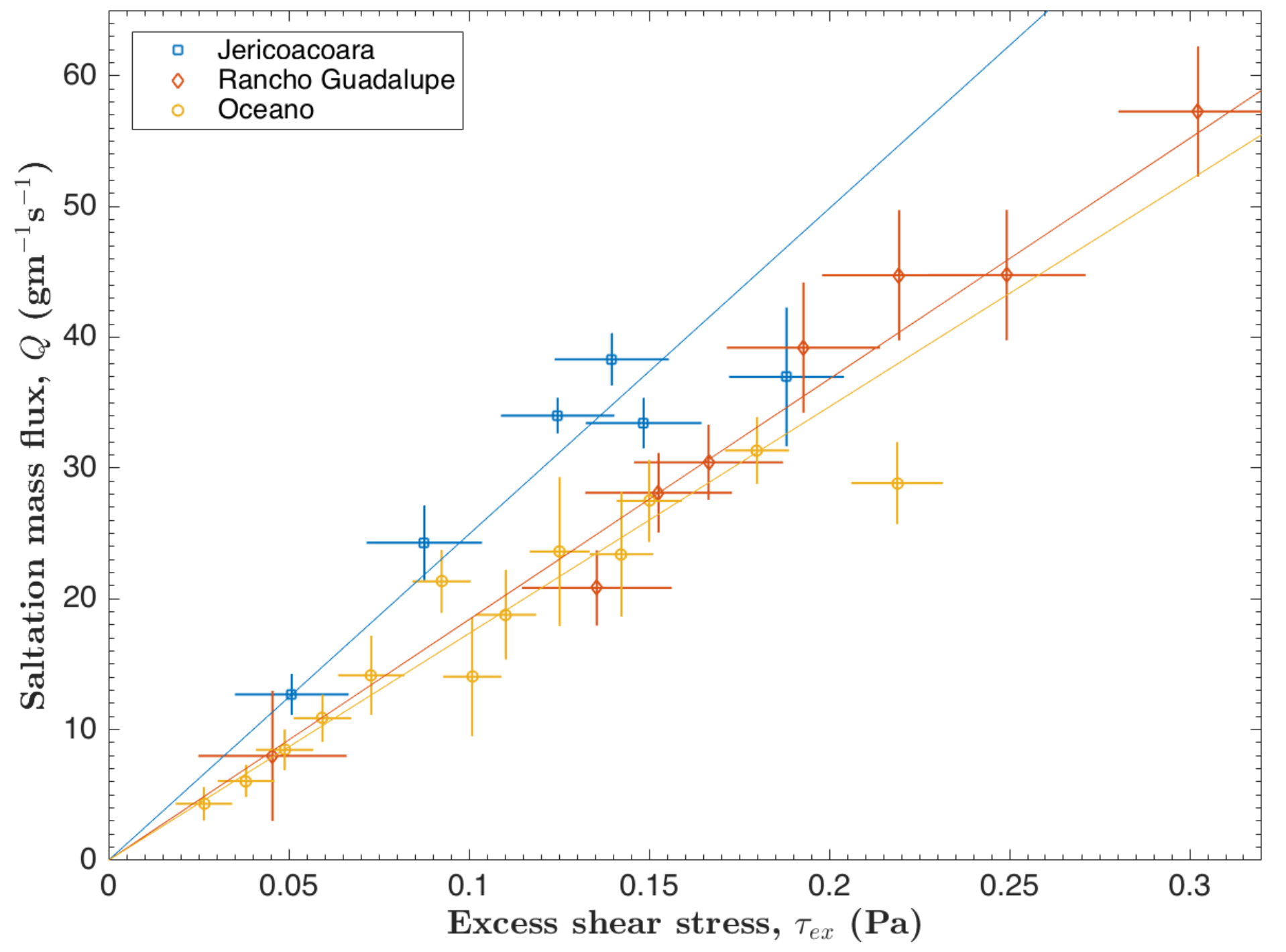
LINEAR SALTATION FLUX LAW:

$$Q = \underbrace{C_Q \frac{u_{*,it}}{g}}_{\text{Constant mean hop time}} \underbrace{\tau_{ex}}_{\text{Represents rate of particle momentum dissipation through collisions with bed}}$$

“Excess stress”

$$\tau_{ex} = \tau - \tau_{it} = \rho_f (u_*^2 - u_{*,it}^2)$$

Determined from zero-intercept of Q vs τ

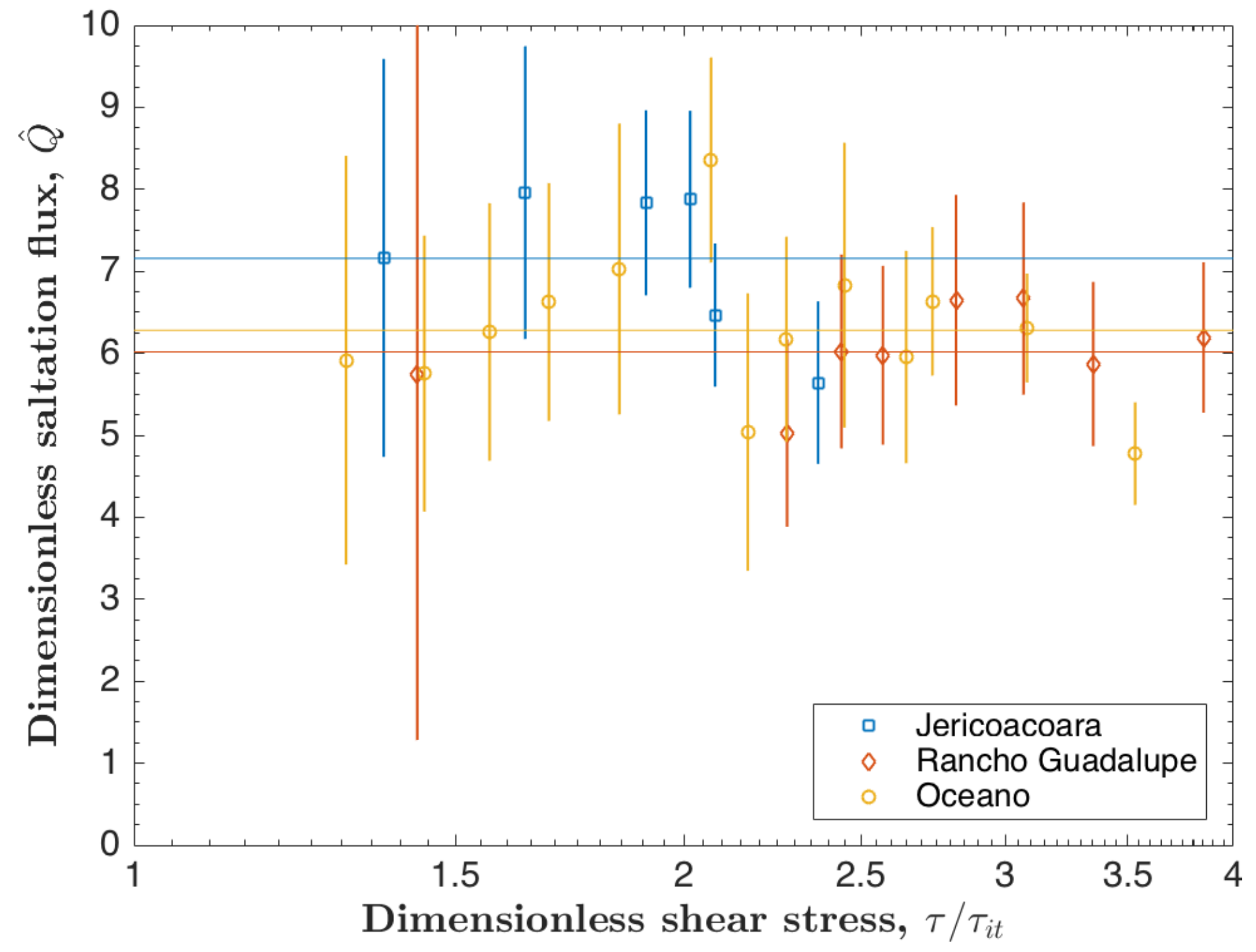


Dimensionless saltation flux, $\hat{Q}$, normalizes flux by excess stress, τ_{ex}, and characteristic saltation hop time, $u_{*,it}/g$:

$$\hat{Q} = \frac{g}{u_{*,it}} \frac{Q}{\tau_{ex}}$$

Calculate scaling parameter, $\boldsymbol{C_Q}$, based on mean value of $\hat{Q}$.

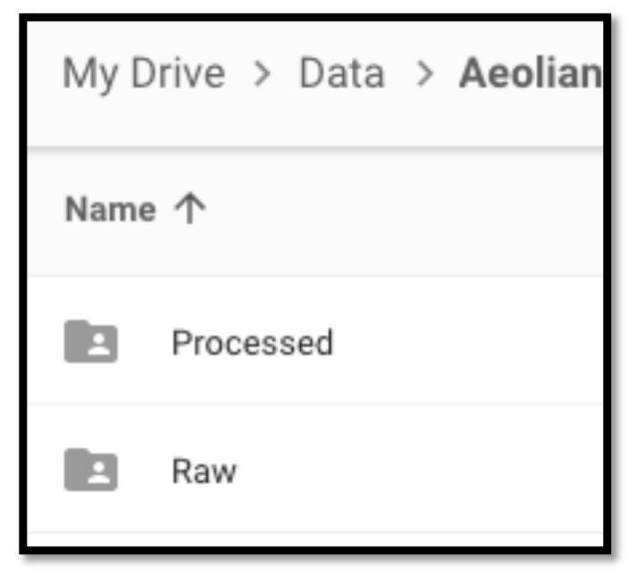
Source	Scaling value for flux law, C_Q
Jericoacoara	7.2 ± 0.9
Rancho Guad.	6.0 ± 0.5
Oceano	6.3 ± 0.9
Kok et al. (2012)	5



DATA MANAGEMENT

“Raw” data (Google Drive)

- Instrumental records (.dat)
- Field notes
- Sand sample collection weights and grain sizes
- Site photos



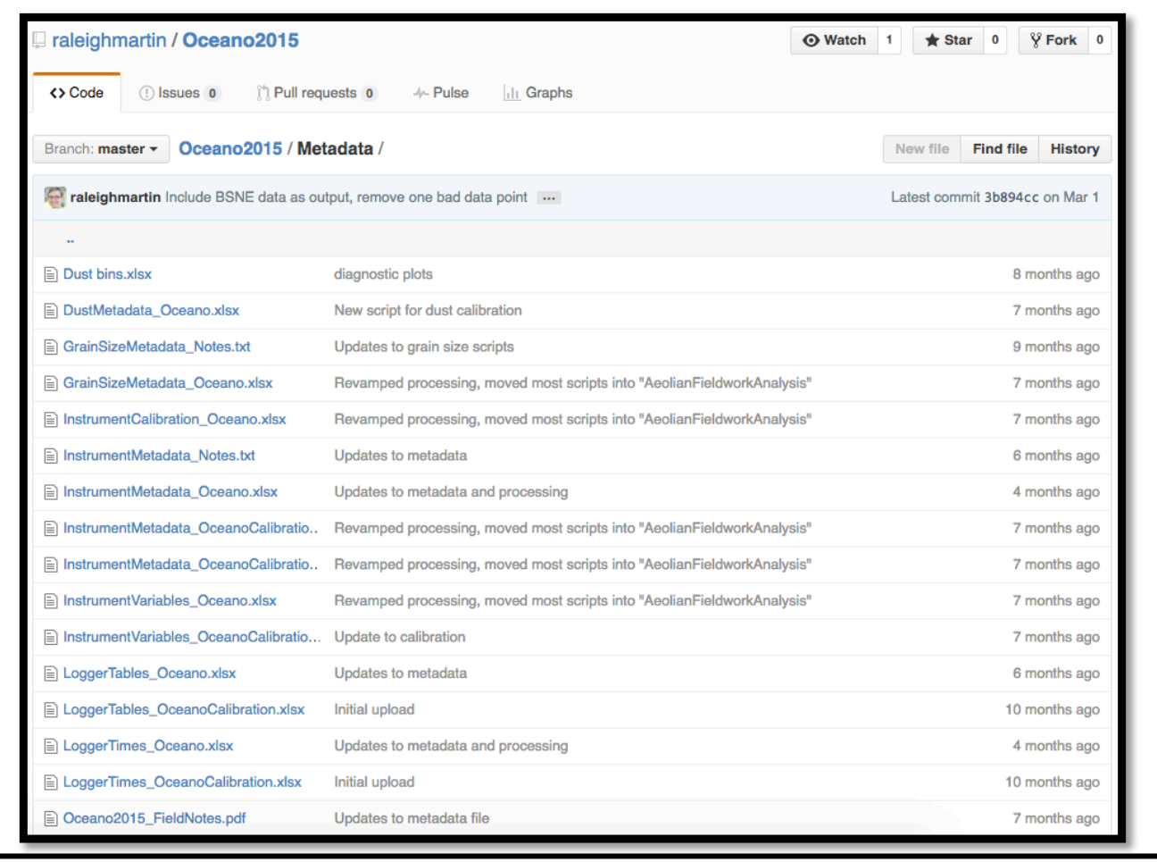
MATLAB scripts (Github)

“Processed” data (Google Drive)

- Limit data to specific time intervals.
- Interpolate error flagged points.
- Calibration of saltation flux counts (digital) from trap data (analog).

“Metadata” (Github, SEN-KB)

- Excel spreadsheets containing:
    - Instrument names, positions and unique identifiers
    - Time intervals of useful data
    - Measurement uncertainties
    - Relationships among datasets
- Workflows / discovery info on SEN-KB



Oceano2015 / Metadata /

raleighmartin Include BSNE data as output, remove one bad data point … Latest commit 3b894cc on Mar 1

..		
Dust bins.xlsx	diagnostic plots	8 months ago
DustMetadata_Oceano.xlsx	New script for dust calibration	7 months ago
GrainSizeMetadata_Notes.txt	Updates to grain size scripts	9 months ago
GrainSizeMetadata_Oceano.xlsx	Revamped processing, moved most scripts into "AeolianFieldworkAnalysis"	7 months ago
InstrumentCalibration_Oceano.xlsx	Revamped processing, moved most scripts into "AeolianFieldworkAnalysis"	7 months ago
InstrumentMetadata_Notes.txt	Updates to metadata	6 months ago
InstrumentMetadata_Oceano.xlsx	Updates to metadata and processing	4 months ago
InstrumentMetadata_OceanoCalibratio..	Revamped processing, moved most scripts into "AeolianFieldworkAnalysis"	7 months ago
InstrumentMetadata_OceanoCalibratio..	Revamped processing, moved most scripts into "AeolianFieldworkAnalysis"	7 months ago
InstrumentVariables_Oceano.xlsx	Revamped processing, moved most scripts into "AeolianFieldworkAnalysis"	7 months ago
InstrumentVariables_OceanoCalibratio...	Update to calibration	7 months ago
LoggerTables_Oceano.xlsx	Updates to metadata	6 months ago
LoggerTables_OceanoCalibration.xlsx	Initial upload	10 months ago
LoggerTimes_Oceano.xlsx	Updates to metadata and processing	4 months ago
LoggerTimes_OceanoCalibration.xlsx	Initial upload	10 months ago
Oceano2015_FieldNotes.pdf	Updates to metadata file	7 months ago

MATLAB scripts (Github)

“Analysis” data (Github)

- Data analyzed in 30-minute intervals to estimate:
    - Saltation flux
    - Wind shear stress
- Further data binning for analyses and uncertainty estimation

Questions

1. Where to host long term?
2. How to capture relationships among data and uncertainties?
3. What should get DOIs and when?
4. What should be included with paper supplementary info?
5. What is useful for modelers?

INTERPRETING THE LINEAR FLUX LAW

- Our observations provide the first strong field-based evidence for a linear (as opposed to 3/2) flux law.
    - *Past field work:* Insufficient data to resolve flux law (e.g., Sherman and Li, 2012)
    - *Past experiments:* Insufficient development of saturated flux (e.g., Rasmussen et al., 2015) or suppression of saltator hops (e.g., Li and McKenna Neuman, 2012).
- Constant saltation height / particle velocity arises from **dominance of splash entrainment mechanism** which requires constant near-surface particle speeds at steady-state
- Therefore, expect constant saltator heights and linear flux law for all cases with particle entrainment dominated by splash:
    - In aeolian case, splash entrainment dominates and **$\boldsymbol{V}$ is constant and $\boldsymbol{Q \sim \tau}$** $(Q \sim u_*^2)$.
    - However, In fluvial case (e.g., Lajeunesse et al., 2010), fluid entrainment and $\boldsymbol{V \sim u_*}$ and $\boldsymbol{Q \sim \tau^{3/2}}$ $(Q \sim u_*^3)$.
    - ***Hypothesis*: Contrast is set by particle-fluid density ratio, $\boldsymbol{s = \rho_p/\rho_f}$**
- Extension to planetary surfaces (e.g., Pahtz and Duran, 2016)

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

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