Characterizing aerodynamic roughness length (z0) for a debris-covered glacier: aerodynamic inversion and SfM-derived microtopographic approaches

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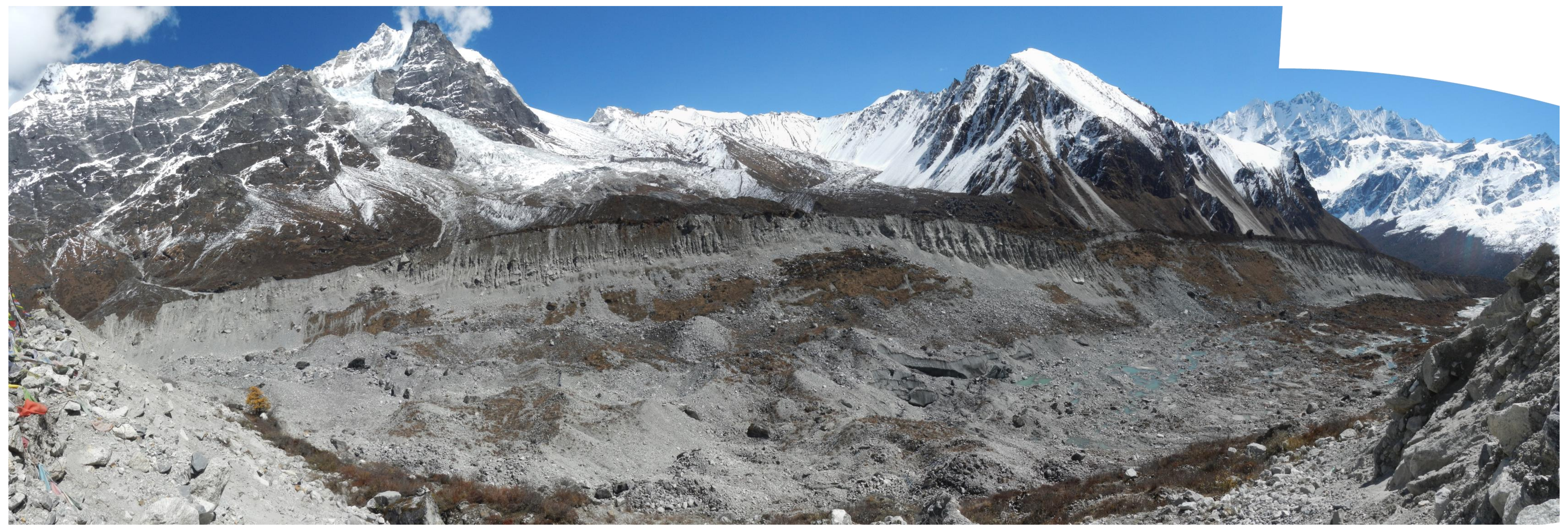
1. 'Surface Roughness' on a debris-covered glacier

'Surface roughness' has many meanings in geosciences; here we discuss the aerodynamic roughness length (**z0**) is an essential parameter in surface energy balance studies. While aerodynamic inversion measurements on bare ice glaciers are relatively rare, a wide range of **literature values** exist for ice and snow surfaces. There are very few values suggested for debris covered glaciers and actual measurements are even scarcer. The increased use of SfM photogrammetry on glaciers provides an opportunity to characterize the range of z0 values **meaningful for debris-covered glaciers**.

Study	Method	Surface	z0 (m)	Site
Dabski 2012	Electronic profilometer	Surface of a boulder	4.03-8.54 x10-6	glacier forefields
Han et al 2014	Eddy covariance, wind profile	Snow-covered moraine	0.00075	Koxcar Glacier
Nield et al 2012	Wind profile	Volcanic tephra	0.0008-0.003	Iceland
Brock et al 2007	Sensitivity testing	Volcanic tephra	0.0005-0.005	Volcan Villarica
Dong et al 2002	Wind tunnel	Gravels of varying size	0.00214-0.0106	Wind tunnel
Rounce et al 2015	Photog., Munro 1989	Debris-covered glacier	0.0022-0.0091	Imja-Lhotse Star Glacier
Inuoe & Yoshida 1980	Wind profile	Small debris with bare ice	0.0035	Khumbu Glacier
Takeuchi 2010	Wind profile	Debris-covered glacier	0.0063	Khumbu Glacier
Rounce et al 2015	Photog., Modified Lettau	Debris-covered glacier	0.007-0.03	Imja-Lhotse Star Glacier
Brock et al 2010	Wind profile	Debris-covered glacier	0.016	Miage Glacier
Inuoe & Yoshida 1980	Wind profile	Large debris	0.06	Khumbu Glacier
Han et al 2014	Eddy covariance, wind profile	Moraine	0.093-0.098	Koxcar Glacier

Relevant values for z0 found in literature. Most modelling studies use a fixed value of 0.01-0.016m.

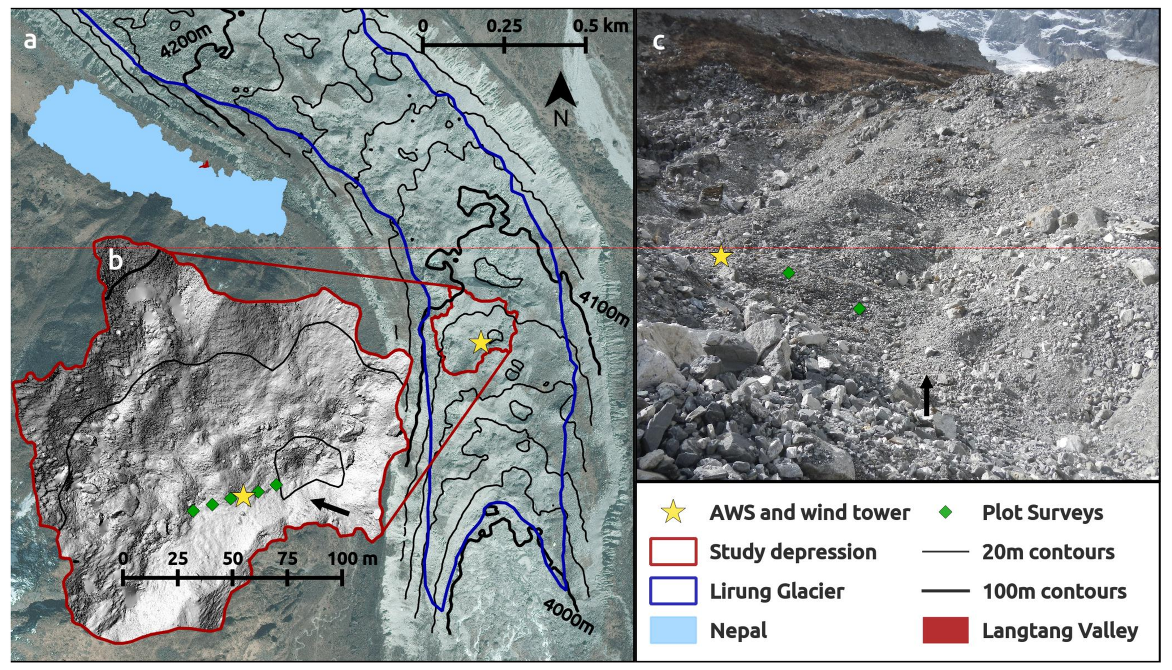


The study site: Lirung Glacier, Nepal

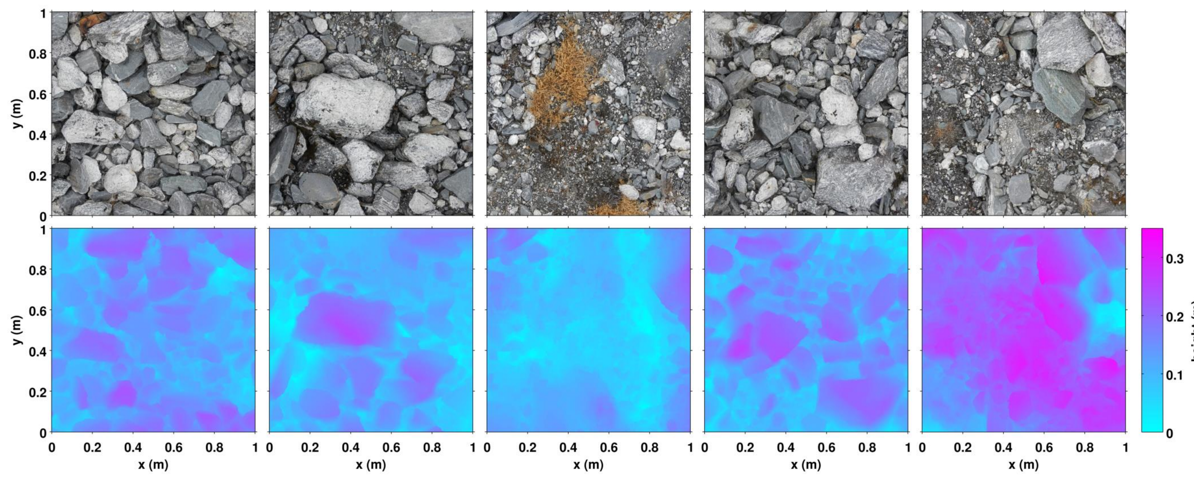
Some of the challenges

1. z0 integrates topographic and atmospheric boundary layer effects
2. Heterogeneous surface at multiple scales:
   - Hummocky rises and depressions, ponds, cliffs
   - Grain sizes from sand to house-sized boulders
3. Glacier/valley wind interactions with variable forcing
4. Met. measurement normally requires long self-similar fetch for stable boundary layer

2. Methods



Observations on Lirung Glacier, with a hillshade (b) and oblique view of the study depression (c).



The five study plots encompass a range of debris-cover grain-size distributions.

We apply a **Structure-from-Motion** (SfM) process chain to produce high resolution DEMs for **five 1m² plots** (at 1mm resolution; 5 photos each), as well as a large **21,300m² depression** (5cm resolution; 173 photos) surrounding an AWS and wind tower.

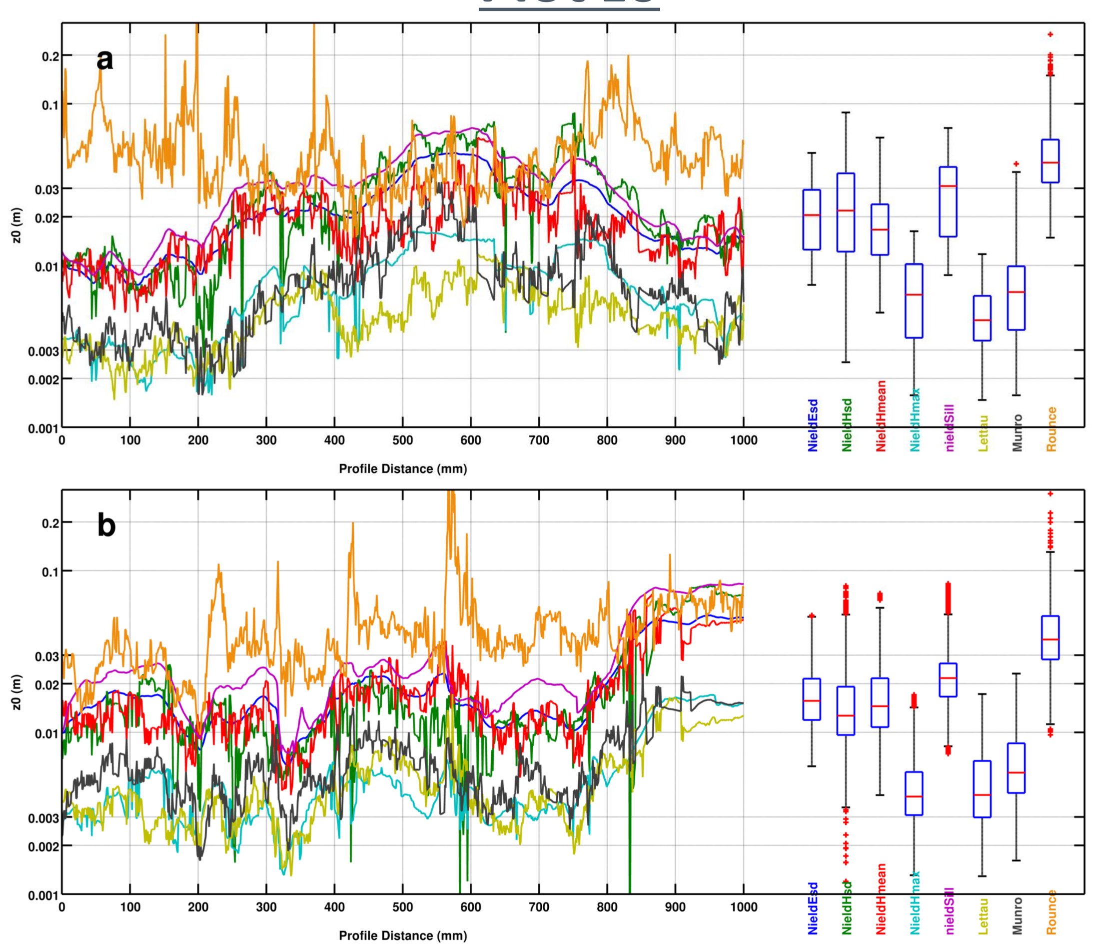
For each plot, we calculate z0 according to **7 transect-based microtopographic parameterisations** (see Lettau 1969, Munro 1989, Nield 2013, Rounce 2015). We compare individual-transect z0 estimates based on profile position and direction, as each plot produces **1000 distinct profiles** in the x- and y- directions. We also use BASEGRAIN software to assess the grain-size distribution at each plot.

We then develop a '**grid**' version of the z0 algorithms aggregating obstacle data from all bidirectional transects. The larger depression DEM is subdivided into **36m²** and **144m²** segments, and the grid approach is applied to our larger DEM to characterize the **variability** of z0 **across** the site.

Last, a **tower** of wind and temperature sensors was installed in the depression in October 2014, measuring wind speed and temperature at 0.5m, 1m, and 2m above the surface.

3. Results from microtopographic and aerodynamic approaches

Plot z0



Profile results in the cross-glacier (a) and down-glacier (b) directions for Plot 5.

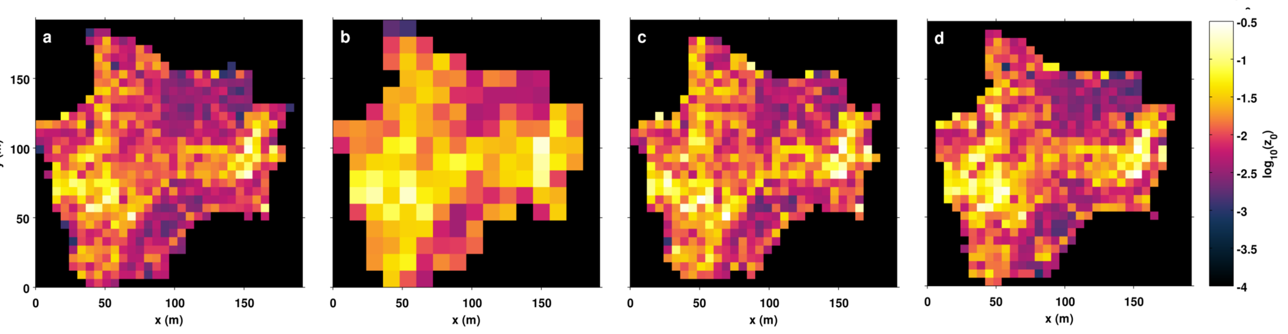
- Results for any algorithm **vary by 10x** based on precise transect position (all within 1m laterally!)
- Algorithms reproduce the **same variability** among transects and plots, some highly sensitive
- Estimates **vary by up to 10x** between algorithms given the same exact profile
- For any algorithm, **minimal difference** between cross- and down-glacier profile results.
- 'Grid' approach closely **reproduces central values**

	NieldEstd	NieldHstd	NieldHmean	NieldHmax	Lettau	Munro	Rounce
Plot1	0.0213	0.0147	0.0161	0.0115	0.0048	0.00631	0.0497
Plot2	0.0255	0.0198	0.0176	0.0131	0.0047	0.00741	0.0418
Plot3	0.0206	0.0144	0.0104	0.0090	0.0027	0.00533	0.0294
Plot4	0.0261	0.0166	0.0191	0.0131	0.0063	0.00752	0.0540
Plot5	0.0351	0.0232	0.0154	0.0171	0.0044	0.0096	0.0438

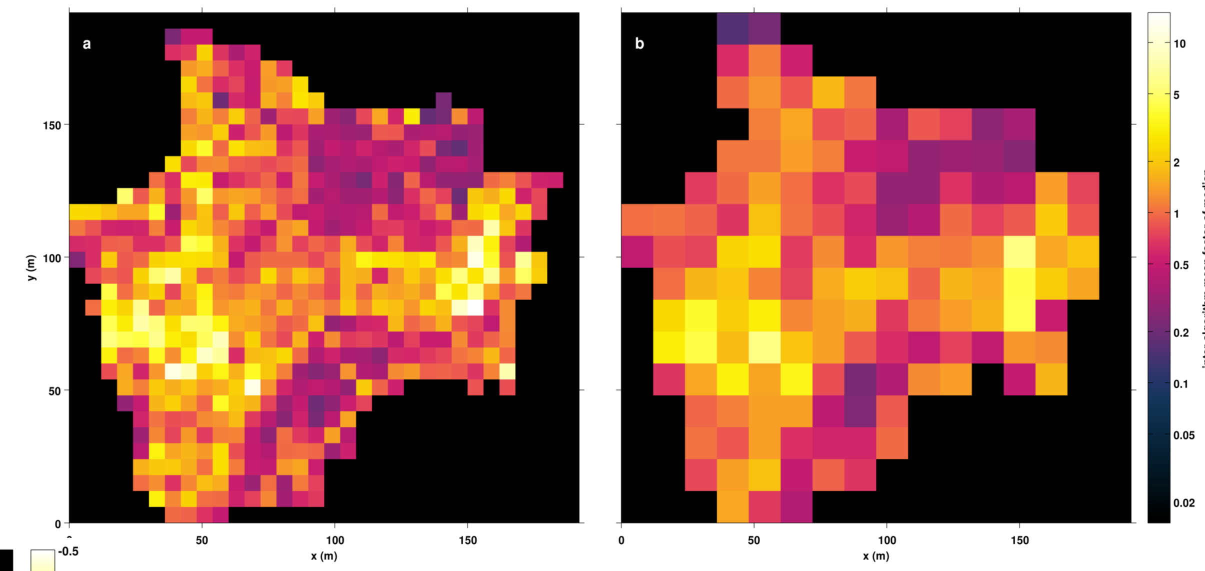
Summary of grid results for each algorithm and plot. All units are [m].

Depression z0

- Results from different algorithms are **strongly correlated**, values are more **closely clustered** than at plot scale
- Any algorithm's estimates **range by 100x** across the area
- Lettau and Munro methods produced lowest values
- Some **scale-dependence** although 6m and 12m normalized deviations are in agreement
- Position of high and low values is sensible with respect to terrain: boulders vs cobbles; smooth slopes vs gullies

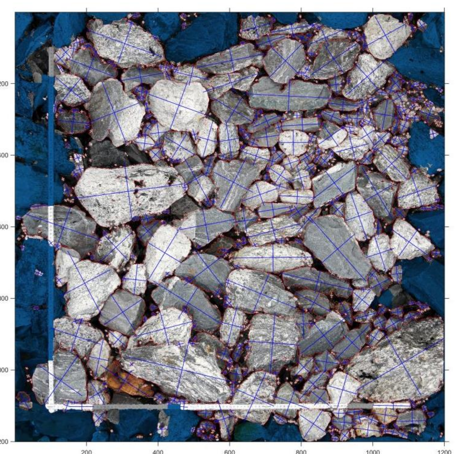


Lettau method grid results across the basin using 6m (a) and 12m (b) subdivisions, compared to the means of cross- (c) and down-glacier (d) transects.

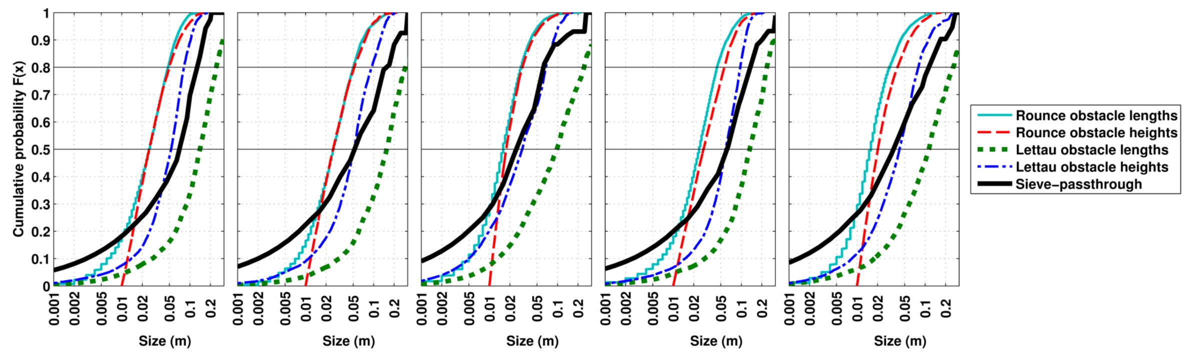


Normalized grid results across the basin using 6m (a) and 12m (b) subdivisions.

Grain-sizes



- Microtopographic z0 should represent physical geometry
- BASEGRAIN gravelometry and profile obstacles are of the **same scale**
- The 50th-percentile grain diameter (d50) closely matches the 50th-percentile Lettau obstacle height
- d80 preserves plot roughness order



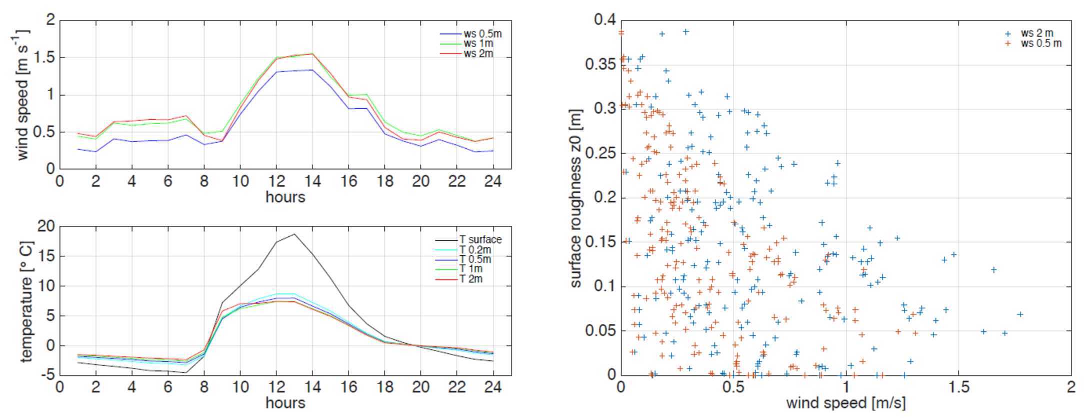
Grain-size and obstacle distributions for the 5 plots.

Wind tower z0

Using an iterative method to derive friction velocity and temperature scale, we derived the **Monin-Obukov length** and surface roughness values for each data pair (e.g. Brock 2006).

- With stability correction, mean **z0 = 0.0023m**
- BUT the profile is **rarely stable** (small fetch?)
- Without stability correction, z0 values range from **0.01 to 0.2m** over the observation period for this single location

It's hard to say what setup and values are meaningful for this type of surface!



Wind and temperature profiles (left) and corresponding z0 values (right).

4. Summary and Outlook

Some interesting outcomes:

1. z0 is highly variable in **both space and time**.
2. Each algorithm produced very **consistent results** with profile, grid, and basin uses.
3. Algorithms produced **similar patterns** of z0, but very **different magnitudes**.
4. Values across the depression **varied by 100x** for any single algorithm.
5. On Lirung Glacier z0 varies between 0.004m (smooth cobbles) to 0.5m (large boulders), and that **0.015m is a reasonable central value**.
6. **Grain sizes** may be promising: d50 from the zero-up-crossing method closely reproduced d50 from the grain-size distributions, and d80 preserves the plot ranking of z0 magnitudes.

BUT, many open questions remain:

- Do any of the diverse algorithms accurately represent z0?
  - To consider: sensitivities to profile resolution and length (not shown)
- Based on setup requirements for aerodynamic inversion (via wind profile), can we **validate z0 on the heterogeneous surface**?
- Are wind profile measurements biased to lower values due to setup?
- The surface of debris-covered glaciers is extremely variable spatially (and temporally), so **what should be used in models**? A single value? A range?
- How much of an effect does a 100x range of z0 have for surface heat exchange?

5. Select Literature

- Brock et al (2006), Measurement and parameterization of aerodynamic roughness length variations at Haut Glacier d'Arolla, *J.Glac*.
- Brock et al (2010), Meteorology and surface energy fluxes in the 2005-2007 ablation seasons at Miage Glacier, *JGR:A*.
- Detert & Weitbrecht (2012), Automatic object detection to analyze the geometry of gravel grains, *River Flow 2012.*
- Irvine-Fynn et al (2014), Measuring glacier surface roughness using plot-scale, close-range digital photogrammetry, *J.Glac.*
- Lettau & Stearns (1969), Studies of effects of boundary modification in problems of small area meteorology, *USACE Tech. Report*.
- Munro (1989), Surface Roughness and Bulk Heat Transfer on a Glacier: Comparison with Eddy Correlation, *J.Glac.*
- Nield et al (2013), Estimating aerodynamic roughness over complex surface terrain, *JGR:A*.
- Rounce et al (2015), Debris-covered glacier energy balance model for Imja-Lhotse Shar Glacier, *The Cryosphere.*
- Smith et al (2015), Structure-from-motion photogrammetry in physical geography, *Progress in Physical Geography.*
- Smith (2014), Roughness in the Earth Sciences, *Earth-Science Reviews*.