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Aerodynamic Roughness Height of Gravel-covered Plains in the Puna of Argentina

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Abstract

Plains covered by gravel-dominated desert pavement in the Puna of Argentina have an aerodynamic roughness height (or length) z_0 of ∼1 cm, likely representing a skimming flow regime above the closely spaced gravel particles. Aerodynamic roughness height locally may transition from that of skimming flow over the gravels to a z_0 that includes the effects of obstacles considerably larger than those of the gravel particles alone. Among large (>60 cm tall) megaripples, z_0 is elevated beyond that of the gravels alone to values of 2–4 cm. These results represent an analog for an improved understanding of the aerodynamics of gravel-dominated desert pavement and megaripples documented by multiple rovers on Mars.

Unified Astronomy Thesaurus concepts: Earth (planet) (439); Surface processes (2116); Geological processes (2289)

1. Introduction

Aerodynamic roughness height (or length) z_0 is the distance above the surface at which the wind velocity is zero, due to momentum loss through interaction with the roughness of the surface. Bagnold plotted wind data as linear velocity versus logarithmic height; on such a plot, the wind data project along a straight line to a common height of zero velocity for multiple wind conditions over the same surface; the slope of each line is dependent on the shear stress, or friction speed, when the wind speeds were measured (Bagnold 1941, pp. 47–49; Greeley & Iversen 1985, pp. 41-45). The semi-logarithmic relationship between height and velocity is called the Prandtl–von Karman equation, or "the Law of the Wall" (Lorenz & Zimbelman 2014, p. 44), quantifying the wind as a function of height within a boundary layer. Measurement of wind velocity with height is important for determining when and where surface particles can be set in motion by the wind.

In planetary geomorphology, a full understanding of the geomorphic work done by wind in modifying planetary surfaces requires accurate knowledge of surface roughness as a necessary boundary condition. Wind-swept desert environments are a common feature of many of the planetary bodies in our Solar System, and such environments are typically characterized by terrain inhomogeneities at small scales (cm to decimeter). Given the uniqueness of each region, surface roughness in these environments is best constrained through well-designed field experiments. Results derived from field measurements will improve our ability to interpret the aeolian implications associated with both coarse-particle-covered megaripples and with gravel plains observed on Mars. They can also help to distinguish mature inactive areas from active areas where particles can be set in motion by the wind.

Field work to determine the aerodynamic roughness height of gravel-covered plains with abundant megaripples was conducted at five locations within the Puna of Argentina, a high altitude (base elevation above 3200 m) cold desert plateau in the Central Andes (de Silva 1989), on 2018 November 19 to 23 (Figure 1). The 2018 profile data were collected at locations chosen to minimize the issues raised by Wieringa (1993) that can affect wind data used in the derivation of z_0 (see Methodology section). Preliminary results from the 2018 effort were reported at the 50th Lunar and Planetary Science Conference (Zimbelman et al. 2019). Here, we present reprocessed 2018 wind profile data (Zimbelman et al. 2022), constrained to time intervals during which the wind profile data were likely to be most useful, providing a robust z_0 value for gravel-covered plains that are common in the Puna. These results should be helpful for increasing the chances of obtaining useful z_0 estimates from diverse settings on other planetary surfaces and planning experiments for future missions (Zimbelman & Diniega 2022).

Wind profiling data can be used to constrain aerodynamic roughness height (z_0) if careful attention is paid to the factors that can limit the usefulness of the wind data. Early wind profiling data (using three anemometers) from the Puna indicated z_0 was in the range of 1–3 cm (Zimbelman et al. 2016). The 2018 field work plan (see Methodology) relied heavily upon the recommendations contained in Wieringa (1993), a remarkable paper brought to our attention during review of the 2010 and 2013 work. Wieringa (1993, p. 325) makes the following important statement: "The popular saying 'z_0 is the height at which the wind speed becomes zero' is true in a purely algebraic sense only, since it implies extrapolation of the equation (logarithmic fit to wind profile data) below its limit of validity." This cogent statement must be kept in mind when interpreting results of field wind profiling data for the initiation of particle movement by the wind.

2. Methodology

Two portable towers ∼2.3 m tall were employed at each location, each outfitted with five data-logging anemometers spaced logarithmically with height along the towers. Tower 1 was built for maximum ease of transport; it was based on combining the interchangeable sections from two Swiffer Sweeper mops. Nine metal sections, each 20 cm long and 2 cm

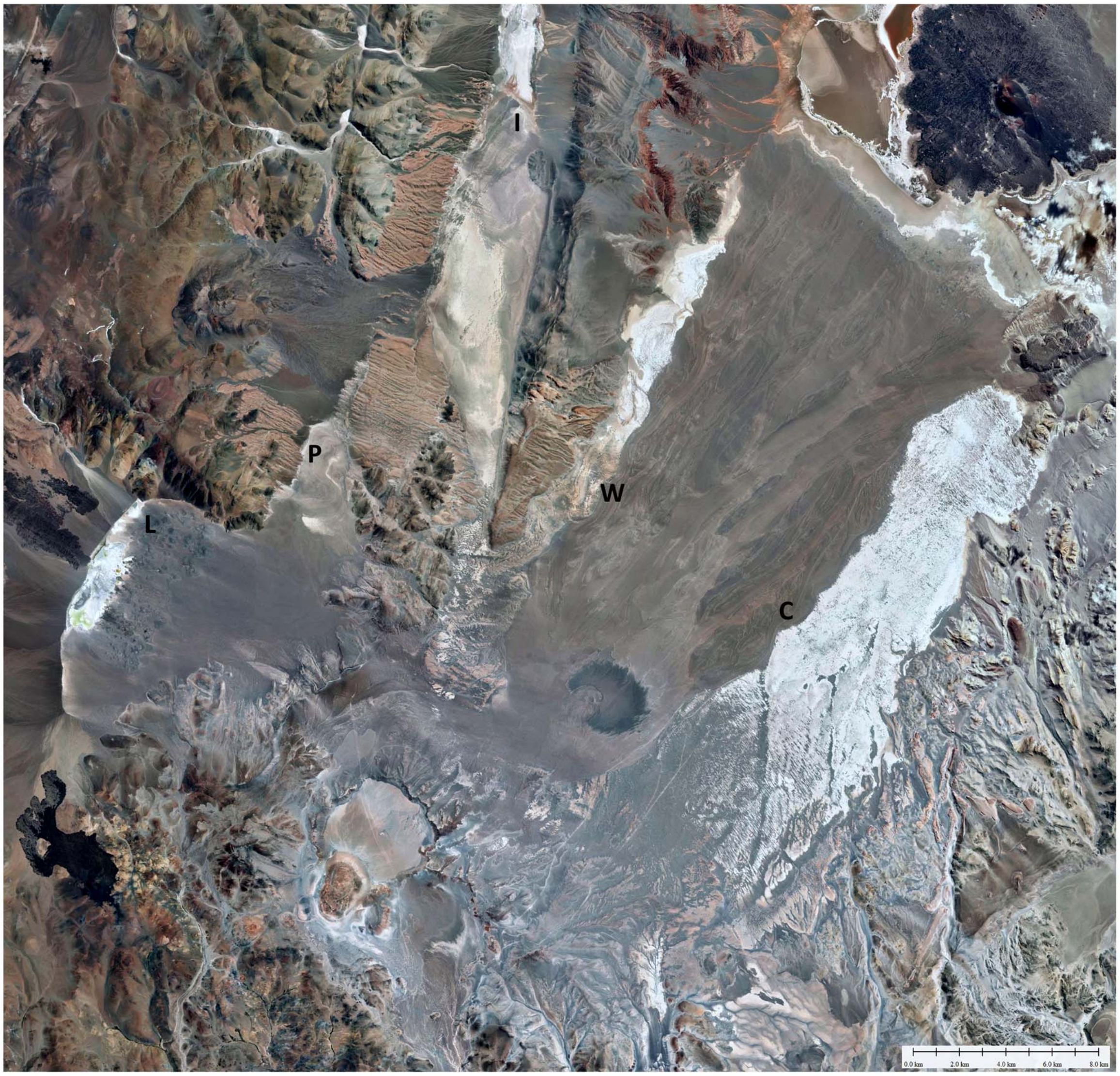

Figure 1. Study areas within the Puna of Argentina on a base image from Bing Maps. C—CPP; W—CPP West; L—Lago Purulla; P—Purulla; I—Incahuasi.

in diameter, were joined with threaded connections between the mop base and handle sections to give a total tower height of >2.2 m, anchored by guy ropes attached to the handle. Anemometers were attached to the tower by binder clamps that could be easily adjusted to the desired height above the surface, measured to the center of the spinning vanes on each sensor. This lightweight tower has been used in a variety of field settings (Zimbelman et al. 2016), but the tower was observed to flex in winds >15 m s^{-1}, requiring someone to hold the tower steady during data collection under such conditions (e.g., the CPP West site). The second tower was built in Argentina by attaching sections of metal tubes (2 cm diameter) commonly used as a paint roller extension pole, mounted on a wooden base and anchored at the top by guy ropes similar to those used with tower 1. Tower 2 remained stable during the strongest winds experienced in 2018.

The anemometers were all General Anemometer model DAF4207SD purchased from General Tools and Instruments, each with an inserted SD card to store data. Each anemometer recorded data until stopped manually or as long as both battery power and storage capacity remained. Wind speeds were stored automatically at intervals ranging upward from 1 s. Tests before going to the field showed that the spinning blades of the anemometer sensor required <2 s to react to a typical change in wind speed, so all measurements collected at the Puna used a 2 s recording interval. Manual starts for each anemometer led to time mismatches between anemometers on one tower, but gusts and lulls in the data were easily matched manually between the anemometers, after which all data were referenced to a single anemometer time.

Measurement sites and anemometer heights were chosen following the recommendations described in Wieringa (1993): the lowest anemometer height was >20 times the estimated z_0 for each study area (based on results from our previous studies; Zimbelman et al. 2016); five recording anemometers were used instead of the three averaging anemometers utilized previously; the towers were sited at a distance downwind of the nearest obstacle (megaripple) that was >15 times the obstacle height; the fetch upwind of the tower had consistent roughness elements for a distance of at least 80 m; and we avoided times near either sunrise or sunset.

Analysis was restricted to time intervals during which the measured wind speeds systematically increased with increasing height. A least-squares log-height versus wind speed fit was

Table 1
Average Wind Speeds during the Time Interval Shown in Parentheses

	An	Ht (cm)	Vave (m s^{-1})	z0	r (cm)	R2
CPP (11-19-18)						
Tower 1 (coincident 20 min)						
	5	200	4.07			
	4	134	3.76			
	3	90	4.86			
	2	60	3.96			
	1	40	3.32			
An 1-5				4.3	.369	.136
An 1-2,4-5				7.6	.718	.516
An 1,4-5				0.02	.983	.967
Tower 2 (coincident 20 min)						
	10	200	3.28			
	9	134	3.04			
	8	90	3.00			
	7	60	2.98			
	6	40	2.92			
An 6-10				1.3	.887	.787
An 6-7,9-10				1.3	.902	.814
CPP West (11-20-18)						
Tower 1 (24 min)						
	5	200	10.38			
	4	134	9.07			
	3	90	8.11			
	2	60	7.56			
	1	40	7.07			
An 1-5				1.4	.976	.954
Tower 2 (7 min)						
10	200	12.61				
9	134	9.67				
8	90	9.21				
7	60	8.97				
6	40	8.5				
An 6-10				1.1	.993	.747
Lago Purulla	(11-21-18)					
Tower 1 (22 min)						
5	200	5.65				
4	134	4.80				
3	90	4.37				
2	60	5.94				
1	40	3.92				
An 1-5				0.02	.431	.186
An 1,3-5				1.0	.946	.895
Tower 2 (27 min)						
	10	200	6.34			
	9	148	5.99			
	8	110	5.73			
	7	81	5.41			
	6	60	5.11			
An 6-10				0.4	.999	.999
Purulla (11-21-18)						
Tower 1 (7 min)						
	5	200	3.74			
	4	160	3.64			
	3	127	2.65			
	2	101	3.22			
	1	80	3.12			
An 1-5				1.4	.598	.358
An 1-2,4-5				1.1	.992	.983
Tower 2 (1 hr 5 min)						
	10	200	4.16			
	9	168	4.11			
	8	141	3.84			
	7	119	3.67			
	6	100	3.51			
An 6-10				3.0	.986	.990
An 6-8,10				2.3	.999	.999
Incahuasi(11-22-18)						
Tower 1 (2 hr 25 min)						
	5	200	1.66			
	4	160	1.56			
	3	127	1.39			
	2	101	1.33			
	1	80	1.28			
An 1-5				4.5	.975	.951
An 1-2,4-5				4.3	.993	.986
Tower 2 (1 hr 56 min)						
	10	210	1.81			
	9	178	1.87			
	8	151	1.81			
	7	129	1.67			
	6	110	1.61			
An 6-10				0.76	.864	.746
An 6-9				6.8	.986	.964

Notes. Log best fits improved when spurious anemometer values were excluded, but a three-anemometer fit has lower confidence than fits using four or five anemometers. Here, z_0 is aerodynamic roughness height, r is the correlation coefficient, R^2 is the coefficient of determination (variance of the data with respect to the fit), An is anemometer number, Ht is the anemometer height above the surface, and V_{ave} is the average wind speed documented during the data recording period.

applied to the average wind speeds obtained during each identified time interval. Fits were considered for interpretation here when the correlation coefficient (r) of the fit was ⩾.90. The least-squares fit was then used to calculate the height at which the wind speed is zero (taken here to represent z_0), bearing in mind the statement from Wieringa (1993) that such extrapolated heights of zero velocity are "true in a purely algebraic sense only." That is, the wind profile close to or between surface roughness elements is almost certainly not following the logarithmic pattern observed at heights greater than 20 times z_0. Here, z_0 is reported to two significant figures, where the first significant figure is the most robust value. Average wind speed is reported to two significant figures beyond the decimal point, but the most robust value is the first of those two figures. Correlation coefficient is reported in the text to two significant figures, but Table 1 lists both correlation coefficient and coefficient of determination values to three figures, so the reader can round/truncate as desired.

Intermittent issues arose with some of the anemometers during most data collection runs, perhaps associated with the blade mechanism of the anemometers when operating at the high elevation of the Puna (above 3000 m). We did not use time intervals during which anemometer issues were apparent, or in some cases we left an anomalous anemometer out of the best-fit procedure. Most likely, these inconsistent problems were not the result of wind flow over megaripple topography, as was clearly the case for some measurements obtained during

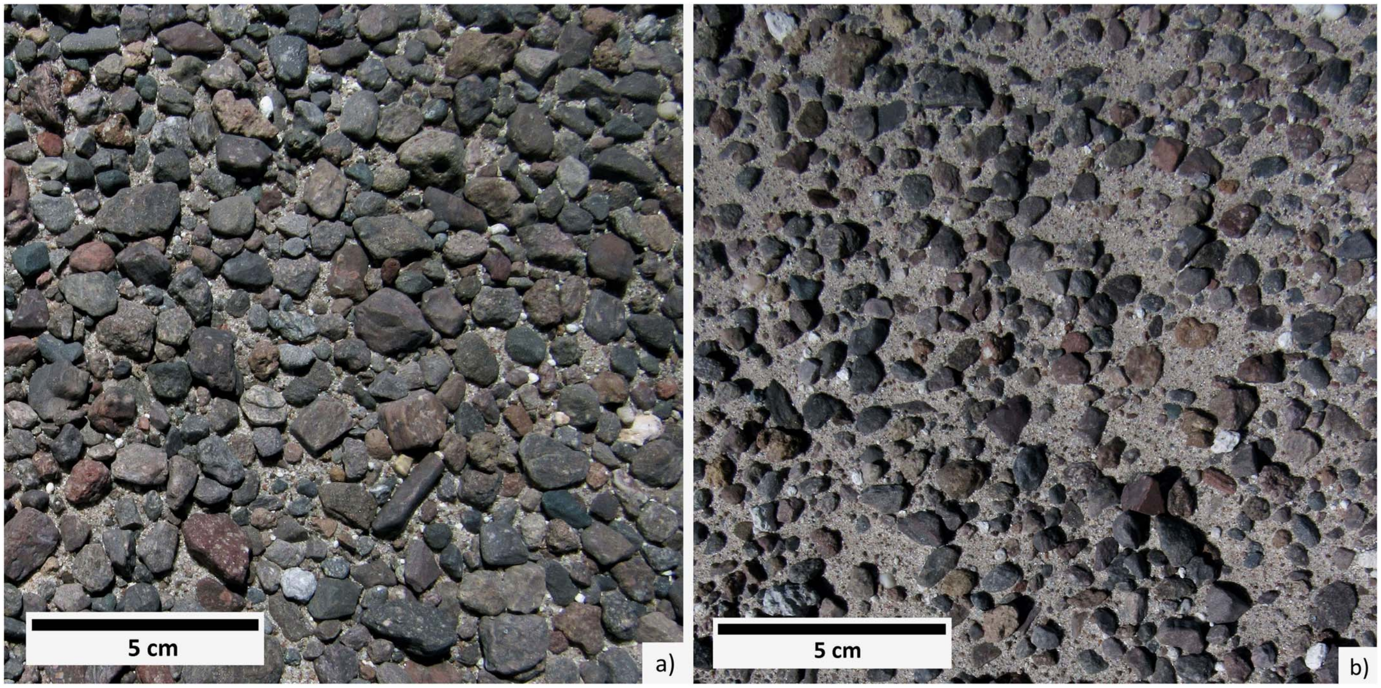

Figure 2. Vertical views of gravel particles at the CPP site. Gravels on the crest of a 30 cm tall megaripple (a), and on the surface between megaripples (b), which is also representative of particles on gravel plains in the Puna. Photos by JRZ on 2018 November 19

2010 and 2013 (Zimbelman et al. 2016). In 2018, the wind measurement towers were consistently positioned well downwind from the nearest upwind megaripple.

3. Results

Results reported below follow the order in which our five field sites were visited during the 2018 work. Overall relief ranges throughout the Puna plains from flat gravel-covered plains to fields of megaripples from 25 to 70 cm in height, as summarized in Zimbelman et al. (2016), which includes measured profiles across multiple megaripples). Additional field photographs from each 2018 site and the original wind data (in an Excel file with tabs for each site) are available at doi:10.5281/zenodo.7574372 (Zimbelman et al. 2023).

3.1. Campo Piedra Pomez (CPP); 2018 November 19; S 26° 35′31.″3; W67°30′16.″7; 3160 m Elevation

Two towers were set up approximately 60 m apart. Tower 1 was located downwind of a field of ∼ 30 cm tall gravel-covered megaripples and tower 2 was downwind of a flat gravel-covered plain. The rounded gravel particles ranged from 1 to 2 cm in their elongated length direction, with larger particles more closely spaced at megaripple crests (Figure 2(a)) than are the gravels between megaripples (Figure 2(b)) or the gravels present on plains lacking megaripples. The wind was consistently within 5° of perpendicular to the anemometers during data collection. No fits for data from either tower using five anemometers had r >.90. However, both towers documented consistent wind events during a 20 minute interval of coincident data collection. Once consistent coincident wind patterns had been documented by the two towers, subsequent data were not forced to follow only coincident times. The best five-anemometer fit at this location came from tower 2, giving a z_0 of 1.3 cm for an r of .89; a four-anemometer fit gave a z_0 of 1.3 cm with an r of .90 after excluding anemometer 8 (Table 1). We are confident this z_0 value is representative of the gravel plain. No reliable fits could be determined for the tower 1 data here, where two anemometers were anomalous. (Table 1).

3.2. CPP West; 2018 November 20; S 26°35′2.″9; W67°36′ 6.″5; 3360 m Elevation

This site was on the downwind side of a large megaripple field, where the bedforms were similar in size to those at the CPP site, and the gravel particles were also comparable to those at the CPP site. The towers were situated about 30 m apart in anticipation of the normal afternoon wind being perpendicular to the megaripple crests, but the actual afternoon wind this day (the strongest experienced during the 2018 field effort) was more closely parallel to the nearest megaripple crests in the area (Figure 3). The strong afternoon wind was consistently within 5° of perpendicular to the anemometers during data collection. At CPP West, pumice fragments were present on the lee (downwind) side of megaripples, consistent with earlier observations at several places throughout the Puna study area (de Silva et al. 2013; Zimbelman et al. 2016).

Given the strong consistent afternoon wind direction, the towers were rotated in place to face the anemometer blades into the wind prior to starting data collection. The strong wind also necessitated a team member holding tower 1 during data collection (Figure 3). No megaripples were within 15 m upwind of either tower in the unanticipated direction; instead, a uniform gravel-covered plain was present surrounding the megaripples. A five-anemometer fit for tower 1 data (Figure 4) gave a z_0 of 1.4 cm with an r of .98, and a five-anemometer fit for tower 2 gave a z_0 of 1.1 cm with an r of .99, both consistent with that for the gravel plain at CPP.

3.3. Lago Purulla; 2018 November 21; S 26°37′55.″0; W67° 50′31.″3; 3800 m Elevation

At this unique site, incipient gravel-covered megaripples ∼25 cm in height were located on top of wind-sculpted

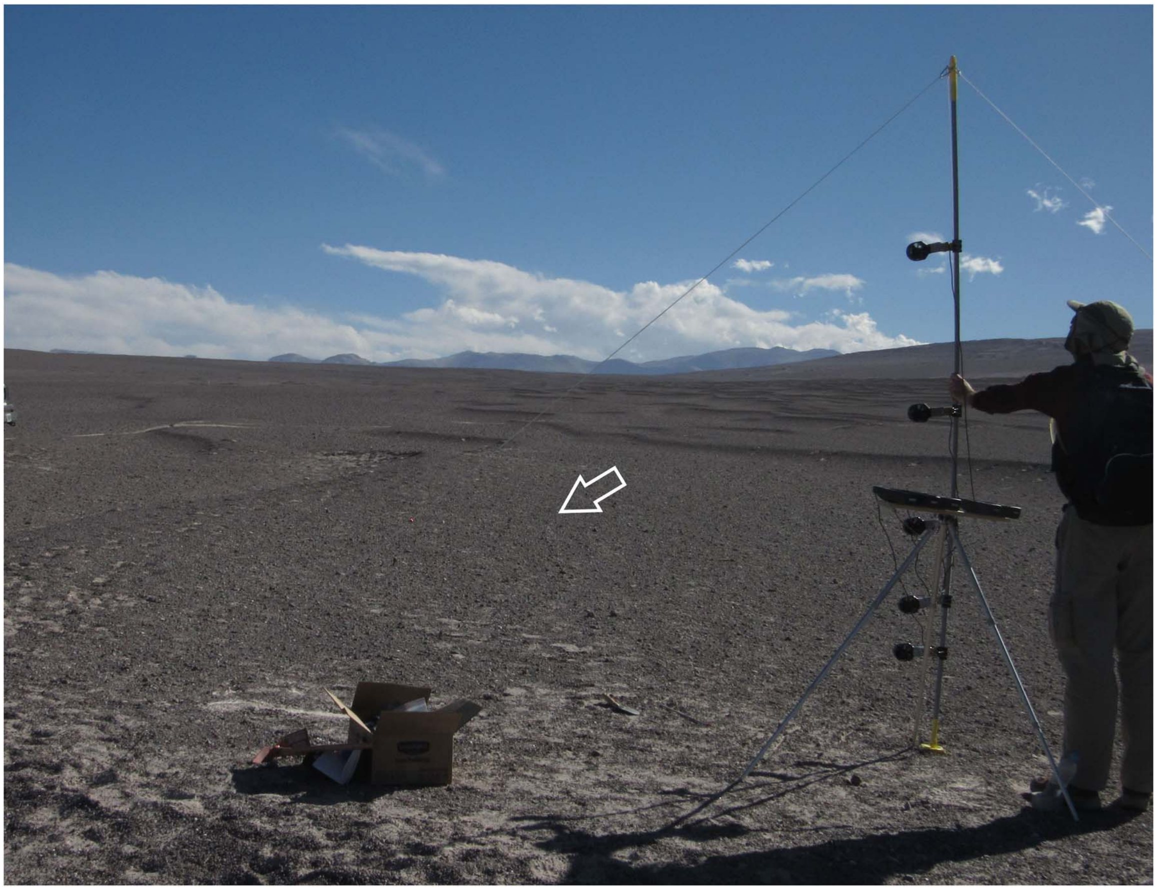

Figure 3. Tower 1 at the CPP West site during data collection. Five recording anemometers are logarithmically spaced with increasing height. Anemometer controllers are mounted on a tripod downwind of the tower. The tower needed to be held in place during data collection because of strong late-afternoon winds blowing almost parallel to the megaripple at left. It is worth noting the flat gravel plain upwind of the tower, continuous to the megaripple approximately 15 m upwind. An arrow indicates the dominant wind direction. Photo by JRZ on 2018 November 20

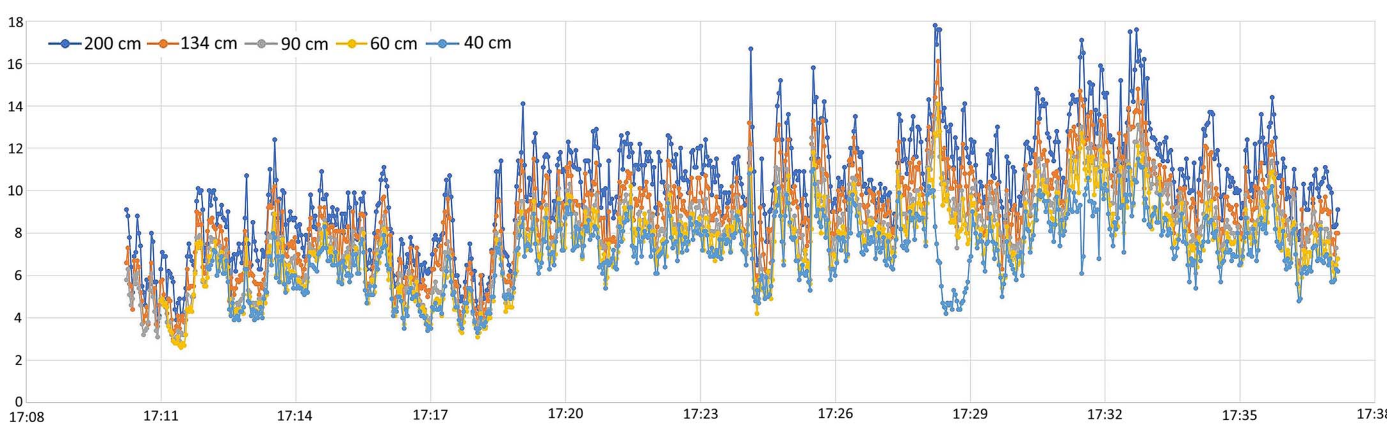

Figure 4. Wind data record from Tower 1 at the CPP West site. Horizontal axis is local time; vertical axis is wind speed (m s^{-1}).

ignimbrite bedrock ridges, also known as Periodic Bedrock Ridges (PBRs; Montgomery et al. 2012; Hugenholtz et al. 2015). This situation likely represents the initiation stage of megaripple development throughout the Puna study area (de Silva et al. 2013). The two towers were separated by about 30 m. The wind was consistently within 5° of perpendicular to the anemometers during data collection. A five-anemometer fit to the tower 1 wind data had an r of only 0.18, but a four-anemometer fit (excluding anemometer 2) gave a z_0 of 1.0 cm with an r of .95 while a five-anemometer fit for tower 2 gave a z_0 of 0.4 cm with an r of 1.0 (Table 1). The slightly lower value for the tower 2 data may be influenced by the wind at all heights at tower 2 being stronger than those at tower 1. We consider both values to be consistent with those obtained at the CPP and CPP West sites.

3.4. Purulla; 2018 November 21; S 26° 36′44.7″; W67°46′ 15.6″; 3900 m Elevation

This site is located within a well-developed gravel-covered megaripple field, where the megaripples are ∼70 cm in height

Figure 5. Large (70 cm tall) gravel-covered megaripples at the Purulla site, the largest observed during the 2018 field work. This site was last visited by a member of our team in 2016 March, at which time a large nail placed on the megaripple crest showed no movement since being placed during 2010 November. Photo includes the nail (center), now located 21 cm south of the current crest (see Discussion). Arrow indicates dominant wind direction. Photo by JRZ on 2018 November 21.

(Figure 5). The two towers were situated about 90 m apart, and the wind was consistently within 5° of perpendicular to the anemometers during data collection. Intermittent anemometer discrepancies were particularly problematic at this location for tower 1. One 7 minute time interval at tower 1 gave a five-anemometer fit with an r of .60, but the same time interval gave a four-anemometer fit with a z_0 of 1.1 cm and an r of .99 by excluding anemometer 3 (Table 1). Tower 2 data, collected over more than one hour, gave a five-anemometer fit with a z_0 of 3.0 cm and an r of .99, and a four-anemometer fit with a z_0 of 2.3 cm and an r of 1.0 by excluding anemometer 9 (Table 1). The increased z_0 at tower 2 should be real, given the high correlation coefficients, so it is possible that the large size of the megaripples at Purulla began to influence the roughness from the gravel particles alone. This possibility is strengthened by the results obtained at Incahuasi below.

3.5. Incahuasi; 2018 November 22; S 26° 29′2.1″; W67° 41′ 0.7″; 3290 m Elevation

The towers were located deep within a well-developed gravel-coated megaripple field with typical megaripple heights of ∼60 cm. The two towers were separated by about 90 m. Gravel particles here are consistent with those observed on and between other Puna megaripples. Some 15–25 cm diameter blocks were scattered over the surface between the megaripples at Incahuasi, but the towers were situated sufficiently removed from any blocks that they should not have significantly altered the surface roughness.

Wind direction was highly variable at Incahuasi (±50° from perpendicular during data collection), but a gentle breeze blew almost continuously during a 2.4 hr period for tower 1 and nearly 2 hr of recording for tower 2, the longest recording sessions obtained during the 2018 work. The wind speeds at all heights for both towers were the lowest of any documented during the 2018 study (Table 1), a fact that might skew the results toward larger z_0 values.

A five-anemometer fit for the tower 1 data gave a z_0 of 4.5 cm and an r of .98, and a four-anemometer fit to the same data (excluding anemometer 3) gave a z_0 of 4.3 cm with an r of .99 (Table 1). Tower 2 data produced a five-anemometer fit with a z_0 of 0.8 cm for an r of .86, and a four-anemometer fit to the same data (excluding anemometer 10) gave a z_0 of 6.8 cm for an r of .99 (Table 1). Considering the results from both towers, it is possible that, as at Purulla, the large megaripples along with some scattered blocks may have increased z_0 above that of the gravel plains alone.

4. Discussion

Gravel plains at CPP (without megaripples) and CPP West (with megaripples well upwind) have comparable z_0 values of ∼1 cm. This z_0 likely reflects "skimming flow" occurred above the closely spaced gravel particles present on gravel plains; Wieringa (1993, p. 327) says "skimming flow occurs when the surface is so closely covered with obstacles that flow in the interspaces between obstacles has a regime quite separate from the bulk flow above," which he defines as being when the distance between obstacles is less than five times the height of the obstacles. This condition most likely occurs when the distance between "nonerodible" obstacles is less than four times the height of the obstacle/particle (Chepil 1950). Roughness height becomes less a result of the size of individual particles than it is the cumulative effect of the gaps in between the many closely spaced particles. Wind speeds between gravel particles almost certainly do not follow the log-height relationship observed well above the surface. When Reynolds number approaches unity, viscosity becomes dominant and damps out turbulent fluctuations, creating a viscous sublayer in which airflow is laminar (Lorenz & Zimbelman 2014, pp. 44–45); this could be the case between gravel particles. We conclude that a z_0 value of approximately 1 cm represents the aerodynamic roughness to be expected for gravel-covered plains throughout the Puna. This result is consistent with (but more robust than) previous Puna work using three anemometers (Zimbelman et al. 2016), and it is also consistent with z_0 results reported from field studies obtained in a variety of settings (Wieringa 1993; Zimbelman 2022).

Previous wind profiling by our team (Zimbelman et al. 2016) gave z_0 results for the Puna that are essentially the same as the results presented here, even though the earlier work used only three anemometers on a single tower. The consistency of both efforts is supportive of the interpretation that the z_0 values provide a reasonable representation of the gravel-covered plains and features in the Puna. The consistent results also strengthen the inferences made earlier in comparing z_0 from the Puna with published results from several desert environments (Zimbelman et al. 2016). Form flow resulting from the wind flowing over bedforms (Walker & Nickling 2002), given the size and aerodynamic shape of the megaripples in the Puna, alters the local wind profile much like flow above the airfoil of a wing, a situation encountered during the 2010 and 2013 wind profiling measurements (Zimbelman et al. 2016). The 2018 wind profiling avoided locations where "wake-interference flow" was likely, which occurs where the spacing between obstacles (megaripples instead of gravel particles) is roughly ten times the height of the obstacles (Wieringa 1993).

Results from Purulla and Incahuasi suggest that when megaripples are large (>60 cm in height), even where outside the "wake-flow interference" zone, roughness height may begin to be affected by a field of large megaripples, with z_0 increasing to 2 to 4 cm, once again consistent with earlier three-anemometer results (Zimbelman et al. 2016). Rather than roughness height being "controlled" by megaripples, we hypothesize that large megaripples may disrupt the overall wind flow through increased local turbulence not tied to the wake zone downwind of any single megaripple. This hypothesis deserves additional testing, in particular in the central portion of the Purulla field where megaripples exceed 1 m in height.

The scattered blocks between megaripples at Incahuasi could also contribute to elevated z_0 values relative to what would be expected in a megaripple field lacking blocks. However, the wide spacing between blocks lead us to conclude that the potential increase in z_0 due to the blocks should account for only a minimal increase relative to the gravels at the other four sites. The low wind speeds experienced during the prolonged time interval of recording at this site may be a greater contributor to the elevated z_0 value obtained at this site.

Wieringa's words that the extrapolated height at which wind speed reaches zero holds only in a "purely algebraic sense" means that z_0 values derived from a fit of log-height to wind speed must be interpreted with caution. Even so, it is still important to obtain field estimates of z_0 from diverse desert locations. The more wind profiling data collected, in particular when careful attention is paid to factors that could limit the validity of those data, the better will be our understanding of the utility of z_0 estimates from diverse settings on other planetary surfaces (Zimbelman & Diniega 2022). In spite of Bagnold's assertion that wind speed at two heights can constrain the average particle size of the surface (Bagnold 1941, p. 50), such an approach involves many unstated assumptions, given the complexity of potential particle size distributions produced by diverse geological processes.

A serendipitous observation at the Purulla site requires elaboration. During our initial work among the Puna megaripples in 2010 November, we placed a large nail on the crest of a megaripple in the Purulla field. Subsequent visits by one or more of our team to the area revealed no crest movement through the visit in 2016 March. Figure 5 includes that nail, now 21 cm south of the current ripple crest. The height of the nail is at the same level as the current crest of the megaripple, so the megaripple moved north without displacing the long nail. Clearly a large wind event took place during the 2+ yr between these visits, perhaps along the lines of exceptionally strong wind events in the Puna proposed by Milana (2009). The observed shift in the megaripple crest confirms that Puna megaripples are mobile on timescales approaching a decade, depending on the occurrence of strong wind events.

The literature regarding z_0 is extensive (see references in Wieringa 1993 and Zimbelman et al. 2016). The results from the Puna are similar to results from previous studies involving diverse settings. Gravel plains in the Puna (z_0 of 1 cm) have aerodynamic roughness comparable to "sand sheet with salt grass" (z_0 of 0.2–1.3 cm; Lancaster & Baas 1998), "short grass and moss" (z_0 of 0.8–3 cm; Wieringa 1993), and "vegetated stony pasture" (0.4–1.5 cm; Marticorena et al. 2006). Fields of large gravel-covered megaripples in the Puna (z_0 of 2–4 cm) have aerodynamic roughness comparable to "gravelly sand sheets to boulder-covered moraines" (z_0 of 0.1–3 cm; Lancaster 2004) and "short grass and moss" (Wieringa 1993; see above). Thus, a given z_0 value can be obtained from multiple aeolian settings. An interesting wind tunnel study by Dong et al. (2002) explored the relationship between gravel particles and z_0; the roughness effect is fully developed when gravel coverage exceeds 15%, the ratio of z_0 to gravel height increases with gravel coverage, and maximum z_0 occurs at gravel coverage ranging from 40% to 75% (values consistent with the gravel coverage in the Puna; Figure 2).

The widely accepted "rule of thumb" that z_0 often is 1/30 the height of typical relief elements (Bagnold 1941) has many complicating factors when the surface includes an assortment of gravels (Lancaster 1991; Dong et al. 2002). For surfaces with a mix of gravel sizes, the mean gravel size is not a good measure of surface roughness (Lancaster 1991). Dong et al. (2002) concluded that the Bagnold (1941) assumption of expressing z_0 as a percentage of roughness element height is "out of scope" for gravel surfaces, as demonstrated in their wind tunnel experiments. Caution should be exerted when using the assumption of any constant relationship between roughness element height and z_0.

There is extensive literature about Transverse Aeolian Ridges on Mars, many of which may be coarse-grain-covered megaripples like the Dingo Gap bedform traversed by the Curiosity rover (Day & Kocurek 2016; Zimbelman & Foroutan 2020 and references therein). Understanding gained from Earth analogs can be invaluable in interpreting these features on Mars. The Puna represents a useful analog for aeolian features observed on Mars, including PBRs (Hugenholtz et al. 2015) and megaripples covered by coarse-grained particles (Milana 2009; de Silva et al. 2013; Bridges et al. 2015; Zimbelman et al. 2016). Different Earth locations other than the Puna that have been proposed as analogs for megaripples on Mars include Israel (Yizhaq 2005; Yizhaq et al. 2009), Iran (Foroutan & Zimbelman 2016; Hugenholtz & Barchyn 2017), and Libya (Foroutan et al. 2019). The utility of any analog site, including the Puna, is enhanced considerably by conducting field studies at the site that can provide insight and critical data valuable for better understanding aeolian processes on Mars and other planetary surfaces (Lorenz & Zimbelman 2014).

5. Conclusions

Plains covered by gravel-dominated desert pavement in the Puna of Argentina (consisting of both lithics and pumice) have an aerodynamic roughness height z_0 of ∼1 cm, likely representing a skimming flow regime above the closely spaced gravel particles. Aerodynamic roughness height locally may transition from that of skimming flow over the gravels to a z_0 that includes the effects of obstacles considerably larger than those of the gravel particles alone. Among large (>60 cm tall) megaripples, z_0 is elevated beyond that of the gravels alone to values of 2–4 cm. The complex nature of the transition in aerodynamic roughness from that of closely spaced gravels to situations when upwind bedforms or obstacles becomes important is not intuitively obvious from visual inspection of a site. This lack of a close correlation between the visual appearance of a site and the actual wind flow over the terrain is why field measurements such as those reported here are important, to constrain the best estimate possible using the downward extrapolation of the Law of the Wall. These results provide important analog information for an improved understanding of megaripples and desert pavement documented by multiple rovers on Mars.

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