Development of Wind Tunnel Techniques for the Solution of Problems in Planetary Aeolian Processes

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Aeolian processes (wind/surface interactions resulting in sediment erosion, transport, and deposition) dominate current surface activity on Mars and are suspected to be active on Venus (Greeley and Iversen, 1985). In the absence of returned comprehensive meteorological data, reliable wind tunnel simulations become necessary for increasing understanding of aeolian processes on other planets. Key to determining the character of any wind/surface interaction is U_* (the wind friction speed). Obtaining U_* values for the surface of Mars, for instance, requires complete velocity-vs.-height wind profiles, but the Viking Lander wind velocity data are only applicable to the spot elevations (1.6 m) of the meteorology booms. An infinite number of wind profile curves can be drawn through each 1.6 m elevation. Determination of the proper wind profile requires the Viking wind velocity data to be coupled with a knowledge of z_0, the surface roughness parameter. The problem can be solved with sufficiently sophisticated wind tunnel simulations of the Viking Lander sites. However, the degree to which scale model wind tunnel experiments accurately reflect field conditions has never been tested directly. The objective of this study is to evaluate wind tunnel experiments in predicting full-scale field results. Such a direct comparison between wind tunnel scale models and full-scale field results can identify working guidelines for a broad range of boundary layer geological modelling applications on Earth, but is especially relevant and critical for the planetary context.

The field study of Kutzbach (1961) is a good candidate for a wind tunnel simulation because the experiment is carefully specified and the results have been utilized in other studies (e.g. Lettau, 1969). Kutzbach (1961) reports wind profiles over a series of roughness elements on a frozen lake and how the wind profile changed as the surface roughness was varied. The approach of the current study is to duplicate Kutzbach's roughness arrays in the wind tunnel at 1/20 and 1/40 scales, and to compare the wind profiles over these scale models to those derived by Kutzbach at full scale in the field. Kutzbach measured U_* and z_0 for ten roughness element arrays ranging in basket density from 1 per 48.5 m^2 to 1 per 0.4 m^2. Wind velocities were measured by cup anemometers on a mast located within the basket array close to its downwind end. Depending on the run, six to eleven cup anemometers were arrayed at heights ranging from ten to 340 cm above the ice.

For the wind tunnel simulation, 3/8- and 3/4-inch dowel cut to the proper lengths conveniently produces reasonably accurate 1/40 and 1/20 scale roughness element models. The matrix of runs was as follows: 2 scales (1/40 and 1/20) X 10 arrays (specified by Kutzbach) X 3 tunnel freestream velocities (approx. 9.3, 16.0, and 20.7 m/sec) X 2 repeats for each scale, each array, and each freestream velocity = 120 runs. In practice the number of repeats often exceeded 2 (especially for 9 m/sec freestream runs) to improve overall consistency of the data. The data were collected by a pitot tube rake located within each scaled roughness array in a relative position identical to that of Kutzbach's anemometer mast. Kutzbach, using a fixed number of roughness elements, was forced to decrease his roughness fetch (upwind distance of the roughness array) from 80 m for the low density runs down to 18 m for the high density runs, and discussed the possibility that for the short fetch, high density runs the boundary layer might not have been fully developed. This possibility poses no liability for this study, whose concern is the simulation of real field conditions in a wind tunnel, whether real field conditions are represented by fully developed boundary layers or not. While this represents a severe test of reality for a wind tunnel simulation, it remains relevant, for in nature many surfaces do not possess enough fetch to support a fully turbulent boundary layer.

Kutzbach reduced his field data by using the computer program of Robinson (1961, 1962), which was based on the method outlined by Lettau (1957). In this method the log-law wind profile is assumed correct over the range of heights measured, and values of z_0, U_*, and D (zero-plane displacement) are adjusted until the sum of error squares between the data points and the fitted log curve is a minimum. The method simultaneously finds the best fit log curve and locates the true zero reference level.

However, the same technique is apparently not valid for the reduction of data taken over very rough surfaces in wind tunnels. Several workers (e.g. Kawatani and Meroney, 1970; Mulhearn and Finnegan, 1978; Raupach et al., 1980) have reported a transition zone below 2-3.5 times the height of the roughness elements in which U_* is not constant and the wind log-law is invalid. The data for this study were reduced according to transition zone restrictions specified by Raupach et al. (1980), who used roughness elements very similar in size and shape to those of this study. The zero reference plane was taken to be the floor of the tunnel, and the qualified data were reduced according to

$$U_z = (U_*'/0.4) \ln (z/z_0)$$

where U_z is the velocity at height z and 0.4 is the von Karman constant. Here z_0 represents merely the height at which the average wind velocity = 0, and not necessarily the "effective roughness height" as discussed, for instance, by Greeley and Iversen (1985 pp. 42-43). This simplification expresses the wind profile in a convenient form for future comparison. U_*' represents the modified value of U_* required by the z_0 simplification.

Before comparing the wind tunnel data of this study with the field results obtained by Kutzbach, some comparisons can be made beween the 1/40 scale and 1/20 scale results. These comparisons are summarized in Table 1.

Table 1. Evaluation of scaling relations

		1/40 scale z_0 : 1/20 scale z_0 ratios		
		predicted	actual	std. dev.
	all velocities	1:2.0	1:3.2	1.3
Distance scaling only	9.3 m/sec	1:2.0	1:3.2	1.6
	16.0 m/sec	1:2.0	1:3.3	1.2
	20.7 m/sec	1:2.0	1:3.3	1.7
Distance scaling with Re scaling	20.6 m/sec 1/40: 9.3 m/sec 1/20	1:2 - 1:3.2	1:4.8	2.9
Distance scaling with velocity scaling	9.3 m/sec 1/40: 20.7 m/sec 1/20	1:2.2	1:2.3	1.0

Length scaling alone predicts a 1:2 ratio between values of 1/40 scale z_0 and 1/20 scale z_0, but the actual ratio is found to be 1:3.2. If the data are partitioned by freestream velocity each freestream velocity subset returns essentially the same 1/40 to 1/20 scale z_0 ratio : 1:3.2. Combining length scaling with Reynolds number scaling predicts a lower 1/40 scale:1/20 scale z_0 ratio, although a precise value between 1:2 and 1:3.2 is not indicated. Reynolds numbers (and thus turbulence characteristics) are most closely matched by comparing high freestream smaller scale runs (20.63 m/sec 1/40 scale z_0 results) with low freestream larger scale runs (9.30 m/sec 1/20 scale z_0 results). However, the actual 1/40 scale to 1/20 scale z_0 ratio is found to be 1:4.8 - a relatively less accurate prediction than for length scaling alone. The final prediction to be considered was that of length scaling combined with velocity scaling. Velocity scaling seems appropriate, considering that for the purposes of this study z_0 has been defined as the height where the average velocity = 0. According to velocity scaling the wind should move across the same scale distance - the upwind fetch of an array, for example - in the same time interval at both scales. Thus, comparison of the 1/40 scale 9.29 m/sec freesteam z_0 values with the 1/20 scale 20.65 m/sec freestream z_0 values should yield a 1:2.2 ratio. The actual ratio is found to be 1:2.3. The wind tunnel simulation apparently was performed under a flow regime in which Re scaling is dominated by the effects of simple velocity scaling. The threshold Re below which Re scaling becomes significant was not probed for in this study.

Comparing the wind tunnel data to Kutzbach's field results proved extremely difficult in practice. The main problem lies in differences in data reduction techniques. Kutzbach derived his z_0 and U_* values for each roughness array by applying a log-law fit over his entire height range of data. Raupach et al. (1980) and other workers have shown this to be an invalid procedure for very rough surfaces in the wind tunnel environment. Whether the procedure is invalid for very rough surfaces in the field environment remains unresolved. Test examples showed that the two reduction techniques give widely divergent results when applied to the same data, requiring that a single reduction technique be applied to both raw data sets for a meaningful comparison. Unfortunately, the raw data of Kutzbach (1961) are unavailable, and transfering the raw data from Kutzbach's published figures proved unsatisfactory. (Data points from different runs were often difficult to tell apart, and running even the clearer points through the original Fortran program of Robinson (1961) gave an unsatisfactorily inaccurate reproduction of Kutzbach's results.)

The best comparison that can be made involves reconstructing Kutzbach's best-fit profile curves (from his final results) and re-reducing a set of hypothesized data points from each curve in a manner identical to that used for the wind tunnel data. Dividing the results by 40 and by 20 provides a set of values that can be readily compared with the wind tunnel results. (Unfortunately, Kutzbach's results for the four densest arrays were reduced in a slightly different manner than the others, disabling them from the comparison.) Before a comparison can be made, however, velocity scaling must be taken into account. Kutzbach's reference anemometer wind speeds correspond to a scaled velocity of approximately only 0.3 m/sec in the wind tunnel at 1/20 scale. The trend of results suggests that if it were possible to measure values of z_0 at this freestream, they might range from 1.5 to 2.5 times the z_0 values measured for the same roughness arrays at 16.0 m/sec freestream. In any case the necessary extrapolation is somewhat extended; a factor of 1.1 times the 16.0 m/sec z_0 results turns out to match Kutzbach's field results (divided by 40 and 20) the best.

Although this study suggests that wind tunnel scale models can predict the values of important wind profile parameters measured in the field, the development of more definitive guidelines requires a field experiment designed specifically to be compared in detail with wind tunnel results. Such an experiment is currently in the advanced planning stages.

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