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Field Evaluation of Two Traps for High-Resolution Aeolian Transport Measurements

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ABSTRACT

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Two traps were developed to provide short-duration, high-resolution measurements of vertical and horizontal variability in aeolian mass flux. One trap is oriented vertically to monitor variation in mass flux with elevation above the bed, and the other is oriented horizontally to record the variation in mass flux with distance from an upwind boundary. Both traps are partitioned into multiple compartments, each equipped with a separate electronic weighing system that provides a 1-Hz record of transport into that compartment. Data from an experiment conducted at Oceano Dunes, CA were used to compare trap performance. It was found that the average transport rates measured during nine runs spread over three days differed by only about 4%, and the grain size-distributions of the trapped samples were found to be virtually identical, indicating the traps had comparable relative efficiencies, despite their different physical configurations. Larger differences in measured transport existed at the shorter time scales of individual runs and portions of runs. However, detailed examination of the transport records revealed that these differences were attributable to small-scale spatial variability in the transport field. It was concluded that the traps performed well and have comparable efficiencies, however, small-scale variability in the transport field was identified as a significant issue for short-term measurements of aeolian transport.

ADDITIONAL INDEX WORDS: *Aeolian transport, sediment trap, mass flux.*

INTRODUCTION

The movement of sand by wind has long been an issue of concern in coastal environments (SHERMAN and NORDSTROM 1994). Interest in understanding and quantifying this process has increased with recognition of the role of dunes and aeolian transport as a component of the larger coastal sediment budget (*e.g.,* PSUTY 1988, SHERMAN and BAUER 1993). The purpose of the present paper is to present the results of a field assessment of two recently developed aeolian sediment traps. These traps represent examples of the two major trap categories identified by WANG and KRAUS (1999)—horizontally-oriented trench type traps, and vertically-oriented interception shells. However, the present traps differ from earlier devices in that they are designed to provide both high temporal and high spatial resolution measurements of the transport field. The traps are subdivided into multiple compartments that funnel trapped sediment to individual electronic weighing assemblies, providing a 1-Hz record of transport at discrete elevations above the bed, and with distance from an upwind boundary. The traps are intended to provide a record of vertical and horizontal variability in aeolian mass flux suitable for evaluating numerical representations of the saltation process (*e.g.,* ANDERSON and HAFF, 1991; MCEWAN and WILLETTS, 1993).

Concern regarding the relative efficiency of vertical and horizontal trap styles has been raised by several workers (*e.g.* JACKSON, 1996; HOTTA, 1988; WANG and KRAUS, 1999). Because horizontal traps do not impede the wind flow, it has been suggested that their efficiency should approach 100%, assuming that the trap extends farther downwind than the maximum saltation hop-length and that sediment is not remobilized once it enters the trap (WANG and KRAUS, 1999). Wind tunnel studies have shown that some styles of vertical collector can be quite efficient, although performance varies significantly with the specifics of trap design. For example, SHAO *et al.* (1993) found efficiencies of 85–102% for several samplers, whereas RASMUSSEN and MIKKELSEN (1998) measured efficiencies of 50–80%, and NICKLING and MCKENNA NEUMAN (1997) reported an efficiency of >90% for their wedge-type vertical trap. In field tests, however, results have been more discouraging. KUBOTA *et al.* (1982) found that conventional vertical traps captured only about two-thirds of the sediment load collected at an adjacent horizontal trench-type trap, and GREELEY *et al.* (1996) reported that several types of vertical trap typically collected only about 30% of the sediment load measured by a nearby trench-type trap.

The traps described in this report are intended to provide contemporaneous measurements of two aspects of the same process (*i.e.,* vertical and horizontal variability within the saltation field). Clearly, the relative efficiency of the two designs is critical to the utility of the measurements for this purpose, and it is the primary consideration in the present evaluation.

Previous Work

A wide variety of devices have been employed to collect data regarding various aspects of aeolian transport, including

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adhesive plates or tape (WALKER and SOUTHARD, 1984; MATHEWS *et al.,* 1998), tagged tracers (BERG, 1983; WILLETTS and RICE, 1985; BARNDORFF-NIELSEN *et al.,* 1986; SHERMAN, 1990), acoustic and impact sensors (STOCKON and GILLETTE, 1990; SPAAN and ABEELE, 1991), optical instruments (NICKLING 1988; BUTTERFIELD, 1999) and a wide variety of vertically- or horizontally-oriented traps (O'BRIEN and RINDLAUB, 1936; BAGNOLD, 1941; HORIKAWA and SHEN, 1960; LEATHERMAN, 1978; HORIKAWA *et al.,* 1984; SHAO *et al.,* 1993; ARENS and VAN DER LEE, 1995; MCDONALD and ANDERSON, 1995; GREELEY *et al.,* 1996; JACKSON and MCCLOSKEY, 1997; NICKLING and MCKENNA NEUMAN, 1997; RASMUSSEN and MIKKELSEN, 1998). Each of these approaches has both advantages and limitations. Although a comprehensive review of trapping technology and methodology is beyond the scope of the present paper, examination of previous work reveals several considerations that are fundamental to trap design. Of greatest concern are the spatial and temporal measurement resolution required for a given project, and the efficiency of the trapping approach.

In part, the variety of devices that has been employed for measuring aeolian transport reflects the range of temporal and spatial scales over which the process varies, and the specific focus of individual studies. For organizational purposes, three (somewhat overlapping) scales of interest are distinguished here: low-resolution studies, in which the parameter of interest is generally the total transport rate and/or associated topographic change, and time scales typically range from hours to weeks or longer (DINGLER *et al.,* 1992; BENNETT and OLYPHANT, 1998); high-resolution studies, which tend to focus on internal variability within the transport field (such as variations in mass flux with elevation, *etc.*), at time scales of seconds to tens of seconds (BUTTERFIELD, 1990, 1999); and intermediate-scale studies, which deal with time periods ranging from tens of seconds to tens of minutes and may be concerned with total transport (SHERMAN *et al.,* 1998), internal variability (MCDONALD and ANDERSON, 1995), or both (NAMIKAS, 1999).

The most widely used approach to measuring the rate of transport involves intercepting some portion of the sediment in motion and periodically weighing the captured material, either by closing the trap and manually retrieving samples, or through an integrated electronic weighing system. Given the range of time scales across which aeolian transport is of interest, the mass of sediment involved potentially ranges across *nine* orders of magnitude, from milligrams (BUTTERFIELD, 1993) to hundreds of kilograms (WANG and KRAUS, 1998). It seems unlikely a single device could be developed that would be suitable for all purposes, and a need is apparent for specialized approaches focused on more limited scale ranges. The traps described herein were designed for use at relatively short time scales (seconds to tens of minutes) and to obtain information regarding both total transport rates and the internal structure of the transport field—specifically, the vertical and horizontal distributions of mass flux. The intent was to bridge the gap between high-resolution work typically restricted to the controlled environment of wind tunnels and the lower resolution approaches typical of the majority of field studies.

Trap Efficiency

It should be recognized that all measuring devices exert some degree of influence on the transport field (with the exception of tracers). This influence is usually considered in the context of trap efficiency, which can be defined as the ratio of the measured transport rate to the actual or true rate. Quantification of trap efficiency is clearly desirable since it provides a basis for confidence in both the data obtained from a trap and conclusions derived from those data. However, establishing the absolute efficiency of a trap is problematic since it requires knowledge of the 'actual' transport rate, the parameter that the trap is supposed to measure in the first place. In effect, it pre-supposes the existence of a perfectly efficient trap (which would potentially obviate the need for new trap designs). In practice, efficiency cannot be determined in an absolute sense, it can only be determined relative to some standard. However, if the standard is close to reality (*i.e.,* provides accurate measurements of the transport rate) then estimated efficiency will be close to the true efficiency. Isokinetic traps, which employ vacuum systems to draw air through the trap and thereby compensate for the influence of the trap shell, have been used as a standard in some wind tunnel studies to evaluate efficiency (SHAO *et al.,* 1993; RASMUSSEN and MIKKELSEN, 1998). However, the relative variability of natural wind fields makes this approach untenable in the field.

Attempts at determining the efficiency of traps in the field have generally focused on relative assessments, obtained through comparison of measurements from multiple trap styles installed at adjacent locations (*e.g.,* KUBOTA *et al.* 1983, GREELEY *et al.* 1996). While this represents the most feasible approach currently available, the complication introduced by small-scale variability in transport rates should not be overlooked. KUBOTA *et al.* (1982), for example, have reported significant variation in transport rates obtained by adjacent traps of the *same* design, despite apparent uniformity in average wind conditions. Relatively subtle variations in topography and vegetation cover were thought to represent the source of the discrepancies in that case. Others authors have noted obvious visual indications of small-scale spatial variability, in the form of sand 'streamers' or 'snakes' (MCEWAN and WILLETTS, 1993; GARES *et al.* 1996). The significance of such variability to assessments of relative efficiency is simply that it represents a potential source of departures in transport measurements, even when traps are located quite close together.

TRAP DESIGNS

Vertical Trap (VTRAP)

A vertically segmented trap (VTRAP) was developed to record variations in mass flux with elevation above the bed (Figure 1). The VTRAP consists of a set of 15 wedge-shaped sampling heads that intercept sediment at discrete elevations and funnel it to individual weighing devices, providing a near-continuous record of transport at each elevation. The wedge-shaped sampling heads were constructed of galvanized sheet metal, and the rear exit ports were screened with pre-

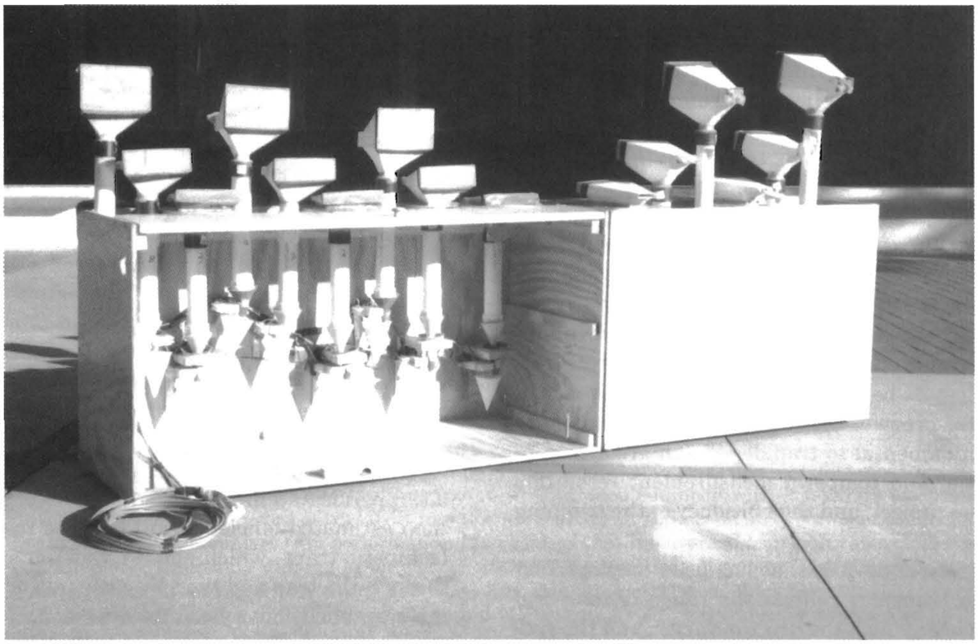

Figure 1. The vertical sand trap (VTRAP). Rear view of housing box on left, with back removed to show funnels and weighing cups. The back side of the trap heads are covered with fine wire mesh. Front view of housing box on right, trap mouths are plugged with foam stoppers.

cision mesh wire-cloth (45% porosity, 0.08 mm openings). The horizontal dimension of the trap mouths was 0.06 m. Three sets of five heads were constructed with vertical mouth dimensions of 0.01, 0.02, and 0.04 m, respectively, providing coverage from the bed to an elevation of 0.35 m. Although it was expected that some sediment would move at elevations above 0.35 m, it is widely recognized that most aeolian transport actually takes place relatively close to the bed (WILLIAMS, 1964; RASSMUSSEN *et al.,* 1985). Post-experiment extrapolations from the measured vertical profiles of mass flux and from numerical simulations of the saltation process indicated that more than 99% of the transport typically occurred within the monitored elevation range during these experiments (NAMIKAS, 1999).

The trap heads were mounted in necks constructed of 1.5″ PVC pipe that were in turn mounted in two buried housing boxes, with a total alongshore spread of about 2.5 m. Ideally, it would be desirable to stack the heads vertically so that the data more nearly represented a two-dimensional profile of the transport field. With such a configuration, however, funneling trapped sediment to weighing mechanisms would require multiple layers of mesh over the exit port (one per compartment) which would likely increase friction to the point that substantial back pressure (and a reduced trapping efficiency) was generated. Staggering the trap heads alongshore to preclude this problem introduces a potential complication in the form of small scale spatial variability in transport, but the trade-off was considered worthwhile.

The lower end of each neck terminated just above a small funnel, which directed sediment into a weighing cup hanging from a load cell. Paper drink cones worked well for this purpose (Figure 2). A small plexiglass brace was glued across each cup mouth to prevent the cup from flexing and thereby taking up part of the weight force of the accumulating particles. Most fine, light threads tend to stretch under tension and thereby take up a part of the applied weight force, a problem noted in BAUER and NAMIKAS (1998). A thread made of 'Spectra' (a competitor of Kevlar), available commercially as high-end fishing line, was found to eliminate this problem and was used here. The cup assemblies weighed only about 4 g (an important consideration as the total weight capacity of the load cells is small), and proved quite durable—only two of fifty-four needed to be replaced during the experiments. The load cells used in this trap (Futek FR1020) have a capacity of 30 g and a combined error of 0.25% full scale (~0.075 g). About 30–40% of this error is due to hysteresis (differences in output for a given weight depending on whether the load is increasing or decreasing). Because the load cells were used to measure in one direction only (increasing weight), somewhat better repeatability is possible.

Horizontal (HTRAP)

Horizontal variations in mass flux were monitored using a multi-compartment trough-type trap (HTRAP). The design is similar to that tested by HORIKAWA and SHEN (1960), with the major differences being an increased (downwind) length in the present trap, and the inclusion of load cell based weighing mechanisms for each compartment (Figure 3). The trap opening is 2.11 m long (downwind) by 0.15 m wide (cross-stream), and is sub-divided along the long axis into 35 compartments of varying downwind length (1 × 2.0 cm, 8 × 2.6 cm, 6 × 3.8

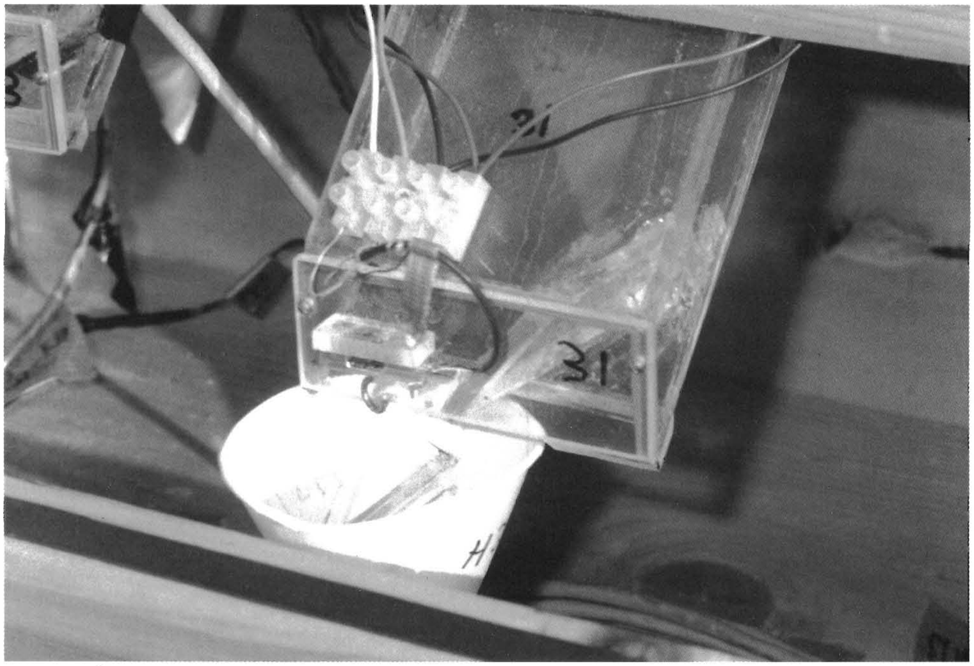

Figure 2. A weighing-cup assembly suspended from a thin-beam load cell mounted on one of the HTRAP chutes.

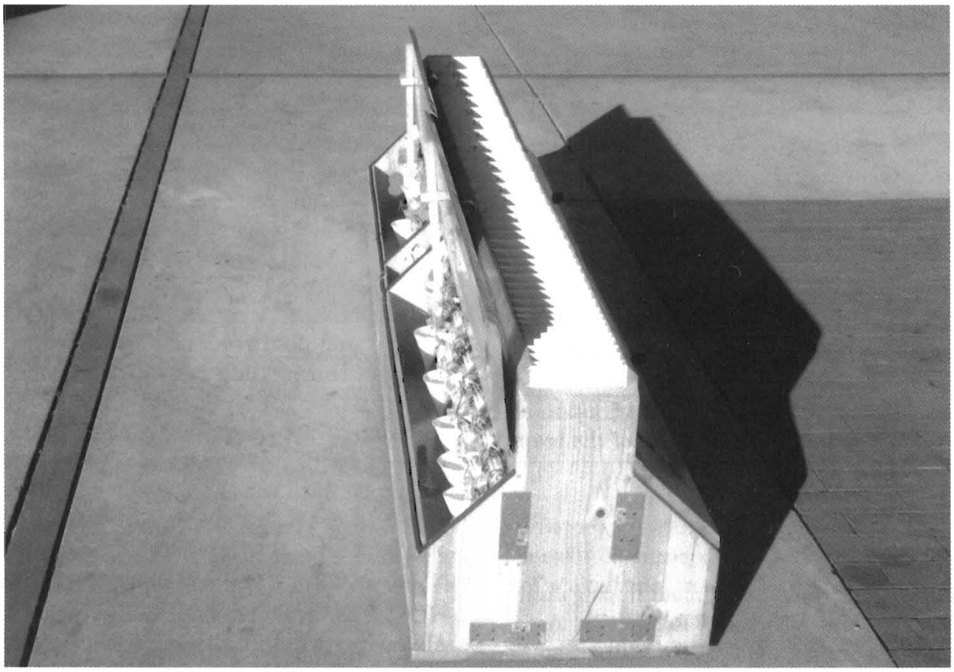

Figure 3. The horizontal trap (HTRAP). Each compartment funnels sand through a plexiglass chute to a separate weighing cup on alternating sides of the unit.

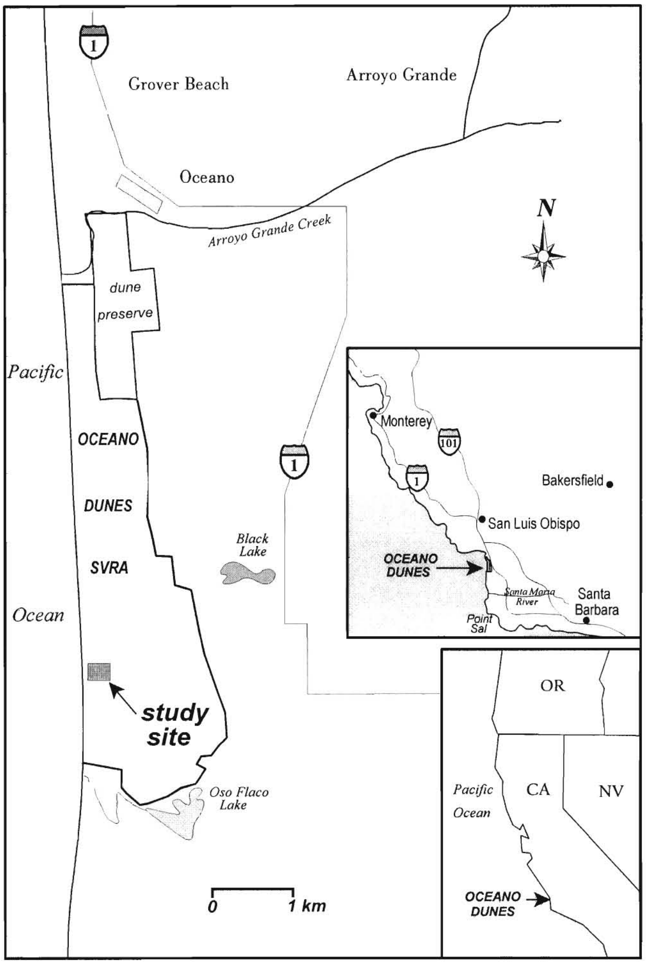

Figure 4. Location of the field site.

cm, 6 × 5.2 cm, 6 × 7.7 cm, 7 × 10.3 cm, 1 × 16 cm). Each compartment directs sand through a plexiglass chute to a separate weighing cup (Figure 2). The cup assemblies and load cells were identical to those used in the vertical trap.

In the field, the HTRAP is installed along the centerline of a larger, plywood-lined pit (2.5 m cross-shore by 6 m alongshore, by 0.5 to 0.75 m deep). The purpose of the pit is to exclude entry of grains from the sides of the trap (*cf.* GREELEY *et al.,* 1996), so that the measured distribution of trapped sediment will directly reflect the path length distribution of saltating grains launched from positions upwind of the trap.

FIELD TEST

Study Site

The traps were deployed in a field experiment during June 1997, at Oceano Dunes State Vehicular Recreation Area (SVRA) on the central California coast (Figure 4). At this location a broad, relatively flat and unvegetated sand sheet extends inland from the high-tide berm for a distance of about 250 m. The instruments were installed near the midpoint of this sand sheet, along a shore-parallel transect about 100 m landward of the berm crest (Figure 5).

Local topography was minimal, composed primarily of ripples on the order of a few centimeters in height. Larger ripples (10–15 cm in height) were present at adjacent locations, and small barchans were found within about 100 m of the site. The mean slope from the berm crest to the instrument array was less than 1.0°, and flattened to about 0.25° from 20 m seaward to 20 m landward of the deployment. The local sediments are predominately well-sorted, fine to medium quartz sands, although coarser surface lags were present, particularly in association with the larger ripples. GREELEY *et al.* (1996) reported a mean grain size of 0.23 mm at this site, whereas samples taken during the present study were slightly coarser, averaging about 0.25 mm.

The reliability of wind direction was a particular concern in the present study, because the HTRAP orientation can be adjusted only by about ± 10° after installation. This site consistently experiences strong, onshore winds during the spring and early summer months, so it was considered nearly ideal.

Deployment

The traps were arrayed along a transect about 18 m in length and oriented parallel to the shoreline (Figure 5). In addition to the VTRAP and HTRAP, four Guelph traps (NICKLING and MCKENNA NEUMANN, 1997) fitted with tipping-bucket weighing mechanisms (BAUER and NAMIKAS 1998) were deployed. The latter traps are not included in the analyses below, because damage to the load cells during the experiments prevented establishment of reliable calibrations.

Wind speed and temperature profiles were monitored at the midpoint of the transect using a mast of eight anemometers mounted at logarithmically-spaced elevations (0.1 to 2.5 m), and four solid-state temperature sensors (co-located with every second anemometer). A wind vane on the mast and four additional wind vanes mounted on the Guelph traps were used to monitor wind direction. All sensors were cabled back to a PC-based data acquisition system housed in a small trailer.

For each data run, voltage outputs were initially recorded with the traps covered to establish baseline voltage outputs. The traps were then opened, and data collection continued until the maximum safe capacity of any load cell (typically 150% of rated capacity) was approached. The traps were then covered and data recording continued to verify final output voltages. During the runs, all 75 sensors were burst-sampled at 100 Hz for 0.1 seconds at 1 second intervals, generating 10 readings per second per sensor. These ten measurements were subsequently averaged to produce one measurement per second for each sensor. The advantage of the burst-sampling approach is that random electrical noise is largely averaged out, increasing the signal-to-noise ratio. Following completion of a data run, the trapped samples were retrieved and bagged for subsequent analyses.

RESULTS

A summary of the data collected is given in Table 1. A total of nine usable data runs were obtained, over a period of three

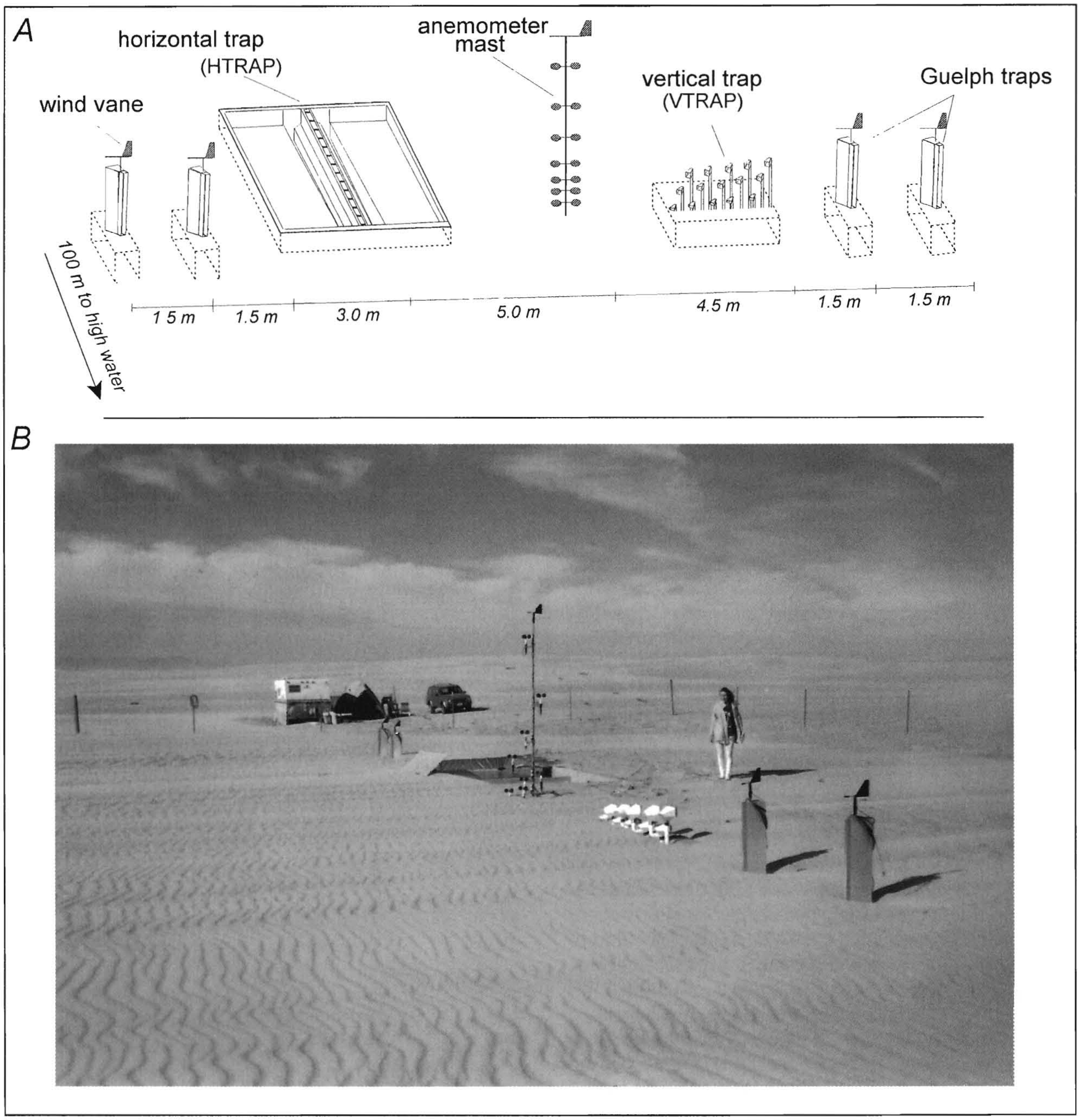

Figure 5. Experiment layout. A) Schematic of the instrument transect. Dotted lines indicate buried plywood housings. B) Photo of the deployment. One of several plywood 'shields' (used to minimize deposition of sand in the pit surrounding the HTRAP between data runs) is present in front of the HTRAP pit. Additional traps are discussed in NAMIKAS (1999).

consecutive days. Run duration was limited by load cell capacity, so that individual runs ranged in length from 76 s during heavy, sustained transport (run P14) to as long as 2640 s during light, intermittent transport events (P3). Average shear velocities calculated from the wind speed profiles ranged from 0.27 ms^{-1} to 0.63 ms^{-1}, and 95% confidence limits averaged about ±9% of the estimated values. Wind direction departed from due onshore by less than 10° in all cases, which was within the adjustment range of the traps. The measured transport rates ranged across nearly three orders of magnitude, from $6x10^{-5}$ $kgm^{-1}s^{-1}$ to 4×10^{-2} $kgm^{-1}s^{-1}$.

Load Cell Calibrations

Most of the load cells used in the traps were calibrated in the field both before and after the main sequence of experi-

Table 1. *Key characteristics of data runs*

Data Runs				Wind Field Characteristics					Vtrap		Htrap		Relative Efficiency
Run	Date	Start Time	Duration (s)	Uz z = 1m (m/s)	U. (m/s)	Confidence Limits (95%) (±m/s)	Zo (m)	Direction (deg.)	Total Transport (kg)	Transport Rate (kg/m/s)	Total Transport (kg)	Transport Rate (kg/m/s)	Htrap / Vtrap
P3	6/20	16:40	2640	5.98	0.27	0.019	1.27E-04	5	0.049	0.00031	0.302	0.00076	2.45
P4		18:39	804	6.37	0.32	0.025	3.20E-04	−9	0.071	0.00146	0.329	0.00273	1.87
P5		19:31	1448	6.27	0.32	0.019	3.96E-04	−9	0.005	0.00006	0.076	0.00035	6.27
P6	6/21	13:20	417	7.29	0.37	0.031	3.51E-04	0	0.164	0.00656	0.367	0.00586	0.89
P8		14:58	685	6.69	0.30	0.035	1.44E-04	9	0.060	0.00147	0.218	0.00212	1.45
P9		15:59	262	7.08	0.38	0.026	5.66E-04	0	0.142	0.00905	0.219	0.00557	0.62
P10		17:57	262	7.13	0.38	0.025	5.24E-04	−5	0.106	0.00674	0.220	0.00561	0.83
P13	6/22	12:16	158	7.62	0.47	0.031	1.26E-03	−6	0.110	0.01157	0.280	0.01180	1.02
P14		14:24	76	9.31	0.63	0.117	2.70E-03	−1	0.185	0.04054	0.332	0.02911	0.72
Total:									0.89	0.00220	2.34	0.00231	1.04

ments (a few were damaged and replaced during the project so that only one calibration was available). A typical example of the calibration results is shown in Figure 6. Of 100 calibrations, the R^2 value was less than 0.999 in only 7 cases, and it was never less than 0.995. The slopes of the calibration relations were also robust, with an average variation of about 0.8% between the pre- and post-experiment calibrations. The standard error averaged about 0.1 (g) and was also consistent between calibrations in most instances. Overall, the performance of the sensors is considered good and the measurements are considered reliable.

Assessment of Relative Efficiency

Grain Size Distributions

Trap efficiency is most often considered in the context of rates or total amounts of sediment transport. However, because finer grains are more susceptible to fluctuations in the wind field (as might be generated by the presence of a trap), efficiency may vary with grain size and may therefore influence the size distribution of trapped sediments (SHAO *et al.,* 1993; ARENS and VAN DER LEE, 1995). Further, scour around the base of vertical traps is a commonly cited problem (RASMUSSEN and MIKKELSEN 1998). The divergence of the wind field around the trap which generates scour may also divert a portion of transported grains around, rather than into, the trap mouth. Because the coarser particles in a mixed population tend to travel closer to the ground (*e.g.,* GILLETTE *et al.,* 1997), trapped samples could be deficient in coarse materials relative to the parent population. It was therefore considered worthwhile to compare the grain size distributions of the trapped samples.

Samples collected in the upper/downwind trap compartments were too small for grain-size analysis using standard sieving techniques, making it necessary to combine some samples. As it was also desired to examine vertical and horizontal variations in sediment size-characteristics, samples from given elevation or distance intervals were amalgamated for several runs rather than simply combining all of the compartments for a given run. Because shear velocity generally increased from one day to the next over the three main days of data collection (Table 1), it was decided to combine samples from all runs on a given day. For example, samples from a given compartment during runs P3, P4, and P5 were combined into a single sample (designated P3-P5). In addition, samples from the fifteen VTRAP compartments were amalgamated into six elevation intervals (0–1 cm, 1–2 cm, 2–4 cm, 4–7 cm, 7–13 cm, and 13–35 cm), and the HTRAP samples were similarly combined into seventeen distance intervals. Daily composite distributions (representing the total sediment population collected by a given trap on a given day) were constructed by summing size-class weights across all compartment intervals for each day. An overall composite distribution was for each trap was generated by summing the composites for all three days (Figure 7).

The daily composite samples collected in the vertical and horizontal traps are virtually indistinguishable (Table 2).

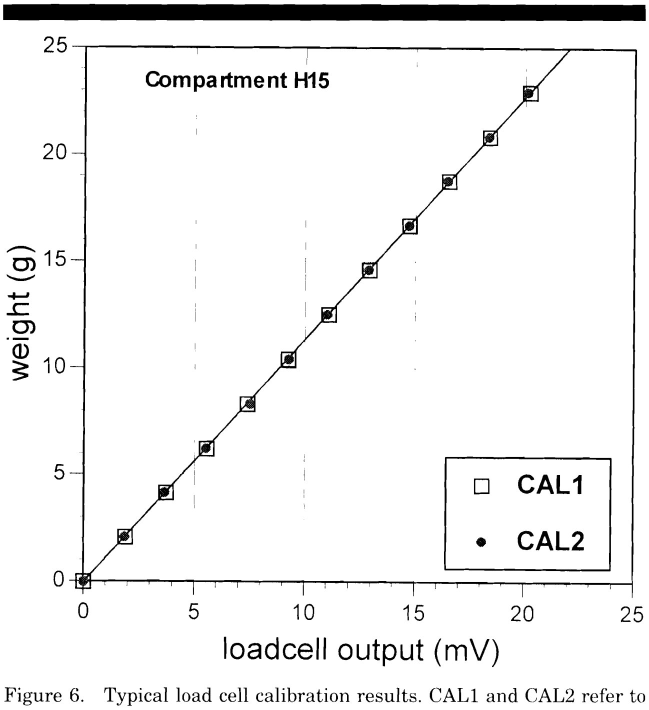

Figure 6. Typical load cell calibration results. CAL1 and CAL2 refer to pre- and post-experiment calibrations, respectively.

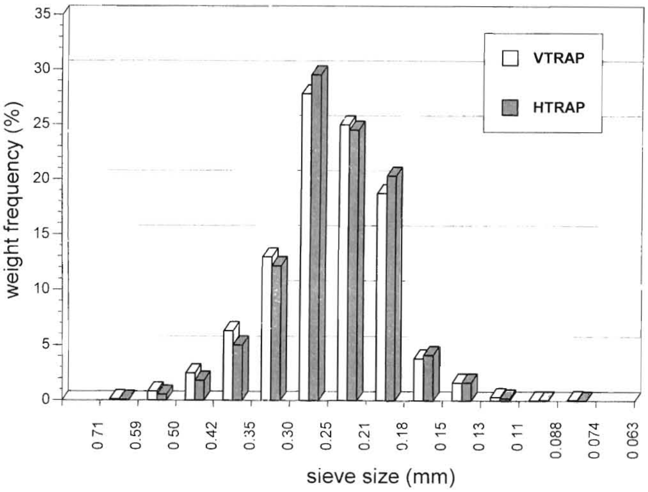

Figure 7. Grain size distributions for the overall composite samples. These distributions represent the total sediment load trapped during all runs.

Mean grain size averages 0.25 mm for both traps, with little variation between individual samples. All samples are well-sorted and only slight variations in the standard deviation are apparent. The overall averages show that samples from both traps are skewed towards the coarse end of the distribution to about the same degree. However, the HTRAP composites consistently show a coarse skew (−0.1 to −0.3) for all three daily composites while the individual VTRAP composites range from nearly symmetrical (+0.1 to −0.1) to strongly coarse-skewed (<−0.30). Only one daily composite VTRAP sample, P6-10, shows similar skew to the HTRAP composites.

An examination of the class-weight data revealed that most of the differences in skewness for the other two VTRAP composites was generated by small absolute differences (a few tenths of a gram) in the quantity of material present in the coarsest and finest size-classes, amounting to less than 0.4% of the total sample. Because the sieve fractions were weighed only to the nearest 0.1 g, it is possible that truncation of the distribution tails due to the measurement resolution contributed to the variability in skewness values. Further, the VTRAP skewness values fall on both sides of the HTRAP values, so there is no indication of a consistent bias for or against particular size fractions in either trap. Given the strong similarities between the two trap types in mean grain size and sorting, it is felt that the minor differences in skewness do not reflect a fundamental difference in trapping efficiency.

Transport Measurements

Some degree of variation in the transport rates measured by the two traps was expected. The trap openings were offset in the alongshore direction, and therefore exposed to different portions of the saltation field. Although the study site was intentionally selected to provide (as nearly as possible) spatially uniform conditions, many workers have reported small-scale variability in measured transport rates, and noted obvious visual indications of spatial variability in the transport field on beaches, such as sand streamers or sand snakes (KUBOTA *et al.*, 1983; MCEWAN and WILLETTS, 1993; GARES *et al.*, 1996). This variability complicates the assessment of trap efficiency in that it provides another possible cause for differences in measured transport rates. It is not known to what degree (if any) such variations average to spatially uniform transport rates over longer time scales (or what the appropriate time scales might be). However, the persistence of a uniformly flat sand surface at this site suggests that long-term transport rates must be relatively constant in space. Differential transport rates would yield differential erosion/deposition rates and, hence, changes in local topography.

Table 2. *Grain size statistics for trapped sediments*

Trap	Run	Mean (mm)	Mode (mm)	Stdev	Skew	Kurtosis
HTRAP	P3–P5	0.25	0.25	0.35	−0.18	3.56
HTRAP	P6–P10	0.25	0.25	0.36	−0.14	3.48
HTRAP	P13–P14	0.25	0.25	0.37	−0.25	3.61
HTRAP	mean	0.25	0.25	0.36	−0.19	3.55
VTRAP	P3–P5	0.25	0.25	0.38	0.05	4.04
VTRAP	P6–P10	0.25	0.25	0.38	−0.21	3.41
VTRAP	P13–P14	0.26	0.25	0.38	−0.38	3.46
VTRAP	mean	0.25	0.25	0.38	−0.18	3.64

Relative efficiency is defined here as the ratio of the transport measured by the HTRAP to that measured by the VTRAP. Hence, an efficiency of 1.0 indicates the measured transport rates were identical, and values greater or less than 1.0 indicate that the HTRAP or VTRAP intercepted more sand, respectively. The average relative efficiency over all nine runs (adjusted for the difference in trap mouth width) is 1.04, indicating that the HTRAP captured only about 4% more sediment per unit width than the VTRAP (Table 1). This level of agreement is considered excellent. However, examination of the relative efficiencies for the shorter time scales represented by individual runs reveals more substantial differences. The extreme case occurred during run P5, in which the transport measured by the HTRAP exceeded that at the VTRAP by more than a factor of six, prompting further examination.

Transport during Run P5 was light and intermittent, with brief episodes of transport separated by quiescent periods (Figure 8). The cumulative transport measured by the traps would be identical if the efficiencies of the two traps were identical, and the transport field spatially uniform. If only the trapping efficiencies differed, then the traces would show increases in accumulated sediment at the same time(s) (indicating a transport event), but the increase would be consistently smaller for the trap with lower efficiency. Alternatively, if the difference in measured transport were due only to spatial variation in the transport field, the timing of sediment accumulations would differ between the two traces and/or differences in the rate of accumulation would be variable, rather than consistently smaller for one trap.

At first examination, the timing of transport events during P5 appears to be roughly the same at both traps (Figure 8). Most of the transport recorded by the VTRAP (about 81%)

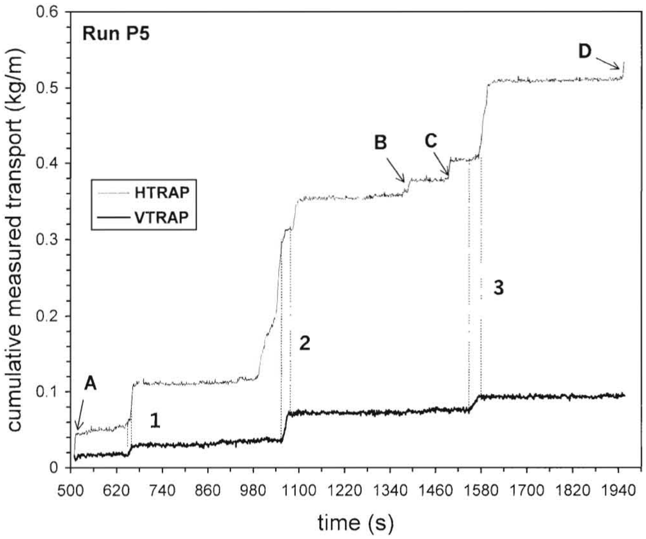

Figure 8. Cumulative transport traces for run P5.

occurred during three discrete 10 to 25 second transport events, beginning at about 650s, 1056s, and 1550s (labeled 1 through 3 on Figure 8). Similarly, most of the transport intercepted by the HTRAP (about 77%) occurred during three events at about the same times. However, closer examination reveals that the timing is offset. The vertical dashed lines on Figure 8 delineate the temporal extent of the VTRAP transport events. Events 1 and 3 can be seen to terminate at the VTRAP just prior to the occurrence of substantial transport at the HTRAP. This suggests spatial variation in the transport field is the underlying factor rather than differences in efficiency. The record immediately after event 3 shows that the VTRAP was not simply intercepting a smaller quantity of sediment at the same time that the HTRAP received large amounts (as would be expected if their efficiencies differed). Rather, the VTRAP intercepted *no* detectable transport at all. This is clearly indicative of spatial variability in the transport process rather than a difference in trap efficiency. Event 2 shows even clearer indications of the influence of spatial variability, in that substantial quantities of sediment were supplied to the HTRAP more than one minute before any measurable amount of sand began to accumulate in the VTRAP. Further, much of the accumulation recorded by the VTRAP during this event occurred at the same time that the HTRAP was experiencing a lull in transport. Accumulation at the VTRAP again terminated well before the HTRAP stopped registering additional sediment inputs. So, even though these major transport events roughly correspond in terms of timing, the detailed nature of the differences in measured transport indicates that spatial variation in the transport field exerts a more significant influence on the records than any difference in trap efficiency.

Several additional observations support the conclusion that the differences in measured transport reflect spatial variation in transport rather than a difference in efficiency. Four periods of significant accumulation at the HTRAP can be identified during which the VTRAP measured *no* corresponding transport (Figure 8, events A through D). This seems clearly indicative of spatial variability. Further, when only those portions of the record during which both traps show accumulation are considered (the events identified as 1 to 3), the calculated relative efficiency of the HTRAP to the VTRAP is 1.08. This is in good agreement with the value determined from the entire data set, suggesting minimal efficiency differences, at worst. As well, when the major transport events (1 to 3, and A to D) are excluded from consideration, the relative efficiency determined from the remaining 'background' accumulations (which took place during numerous transport events too minor to register individually) is 1.04, again indicating little difference in trap efficiency. Finally, it is apparent that the variations in relative efficiency calculated for individual runs are not consistent in direction (Table 1). For some events the VTRAP recorded larger transport rates, and during others it recorded smaller rates. If efficiency was the major factor controlling differences in the transport measurements, it would be expected that one trap would *consistently* measure smaller rates of transport. Thus, the conclusion is that spatial variability exerts a much stronger influence on the measured transport rates over short time intervals than any difference in trap efficiency.

The question remains as to why run P5 showed such a large difference between traps, in comparison to the other runs. Consideration of the environmental conditions at the site during this run suggests a possible explanation. Run P5 was conducted during and shortly after sunset, and condensation was noticeably moistening the beach surface during this period. It is widely acknowledged that even small amounts of surficial moisture can reduce transport significantly (HOTTA *et al.,* 1984; MCKENNA NEUMAN and NICKLING, 1989; NAMIKAS and SHERMAN, 1995). Hence, spatial variation in surficial moisture content (due to differences in surface temperature, evaporation rates, micro topography, sediment porosity, packing, size distributions, etc.) could generate spatial variation in the transport rate (in addition to those factors otherwise present). Put simply, if the sand surface was moister in front of the VTRAP than in front of the HTRAP, substantially lower transport rates would likely have resulted. Although speculative, this interpretation is supported by the fact that transport rates at both traps during P5 were roughly an order of magnitude smaller than those measured during comparable shear velocities and dry conditions in runs P4 and P8, indicating that surficial moisture was indeed influencing transport during P5.

Run P8 was conducted during conditions of intermittent transport and small average shear velocity, similar to P5. However, P8 was conducted during mid-afternoon when the beach surface was not subject to condensation. Although the HTRAP again recorded a larger transport rate, the relative efficiency is much closer than was the case for P5 (Table 1). Strong similarities are evident in the transport records from the two traps during P8 (Figure 9). Cumulative measured mass transport is nearly identical for the first 100 seconds of the run. Although the traces diverge at that point, superimposition of several segments of the VTRAP trace (by adding the difference in cumulative weight at the start of each seg-

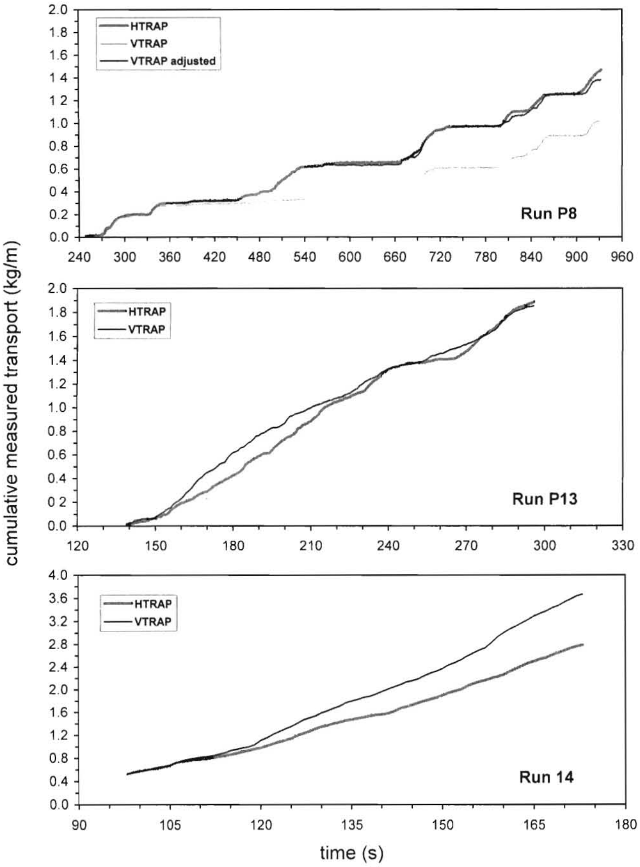

Figure 9. Cumulative transport traces for runs P8, P13, and P14.

ment to the VTRAP values) shows that this divergence was largely restricted to three relatively brief time intervals. For close to 80% of the run duration, the rates of sediment accumulation agree well. Thus, it appears that under the dry surface conditions experienced during P8 (and all other runs), spatial variability in transport is much more sporadic and limited than was indicated by P5.

Of the individual runs, P13 produced the calculated relative efficiency (1.02) closest to unity (Table 1). The traces for this run indicate that this result was somewhat fortuitous (Figure 9). For about 80% of the record, the total accumulation in the HTRAP was less than that in the VTRAP, and had the run been terminated during these periods, the calculated relative efficiency would have differed from unity more substantially. If the run had been terminated during the period of maximum absolute difference in trapped weights (around 185–195s), for example, a calculated efficiency of about 0.7–0.8 would have resulted. However, for about half of the record the relative efficiency ranged within 5% of unity (*i.e.,* 0.95–1.05), so that the probability of obtaining a close match in efficiency for this run was fairly high. These traces also provide evidence that short term spatial variations in the transport rate can generate comparable average transport rates over longer time periods.

In run P14 the transport records are comparable for the first 15–20 seconds, then diverge in a relatively consistent manner for the remainder of the record (Figure 9). Of all the runs, P14 most closely approximates the type of result expected from different trap efficiencies—both traps experience transport at the same time, but one trap consistently intercepts smaller quantities. If this run were examined in isolation, it would be difficult not to conclude that a significant difference in trap efficiency existed. However, comparison of the P14 traces with the initial 60 seconds of run P13 shows that a similar pattern is present. In the longer run P13, the period of divergence is followed by a similar period of convergence that resulted in the total amounts of accumulation coming back into agreement, as suggested in the earlier discussion regarding the expectation that transport should be relatively uniform over time at this site. It may be that run P14 was simply too brief to capture an eventual convergence of the traces.

Influence of Transport Magnitude

Examination of the individual run efficiency values (Table 1) reveals one other feature that needs to be addressed. In the low shear velocity runs, the VTRAP consistently catches less sediment per unit width than the HTRAP, but in the high shear velocity runs it consistently catches more. This observation suggests that the relative efficiency may vary as a function of shear velocity and/or transport rate. The high and low shear velocity runs were largely collected on different days, but it seems unlikely that changing site conditions were responsible for the efficiency differences, because run P8 ($U_* = 0.30$ ms^{-1}, relative efficiency = 1.45) was conducted between two higher shear velocity, lower efficiency runs.

Individual run efficiencies were plotted against shear velocity to examine this issue (Figure 10a). Although there is a suggestion of a decrease in the relative efficiency of the HTRAP with increasing shear velocity, linear regression analysis indicates that the trend is not statistically significant ($R^2 = 0.16$, $p = 0.28$). Given that only nine data points are available, this finding cannot be considered conclusive. However, it was possible to extend the analysis by subdividing each of the data runs into smaller blocks.

The data runs were divided into a total of 442 blocks of 15 seconds in duration, and transport rates and shear velocity values were determined for each block. The block duration was chosen to produce the largest number of observations, while keeping the blocks of sufficient duration that transport levels were detectable and shear velocity estimates remained reasonably reliable (see NAMIKAS (1999) for discussions of these issues). The analyses outlined below were also conducted using a 30-second block length, and no substantive differences were found.

During 62 of the blocks, no transport was measured at either trap, and these were eliminated from further consideration. During an additional 128 blocks, transport was measured at one trap but not the other. Because this must be due to spatial variability in the transport field, these blocks were also eliminated leaving a data set of 252 blocks. Partitioning of the data set in this fashion assumes that the 15-second

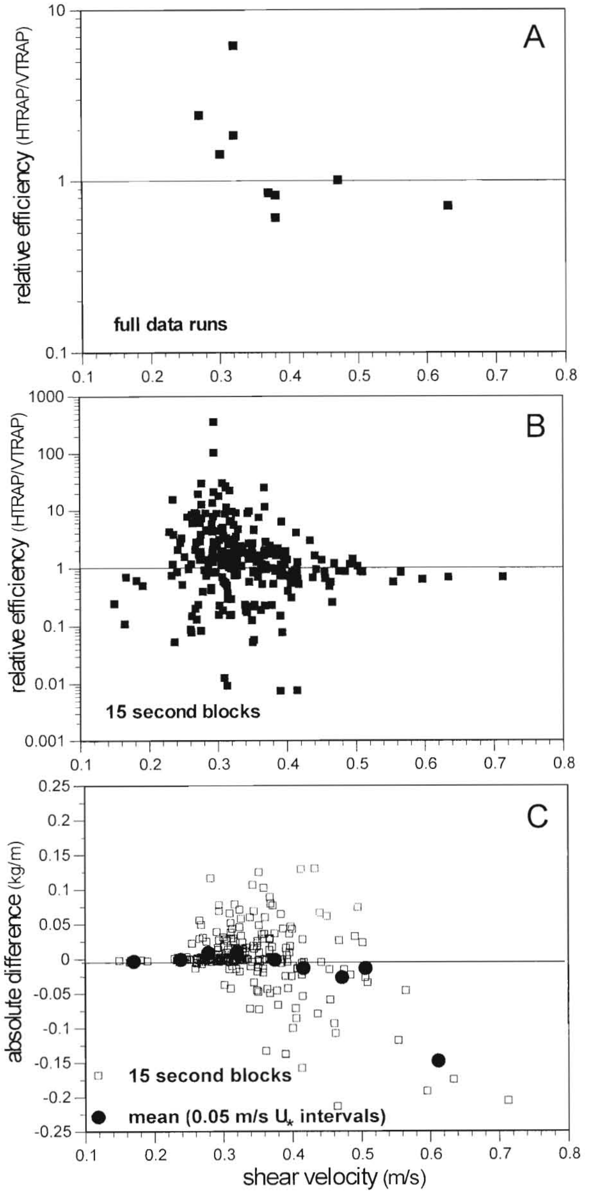

Figure 10. Comparison of HTRAP and VTRAP measurements. A) Relative efficiency for the full data runs. B) Relative efficiency for 15 second blocks. C) Absolute difference in measured transport for individual 15 second blocks (open symbols) and averaged over $0.05 ms^{-1}$ shear velocity intervals (solid symbols).

blocks can, in effect, be considered to be independent observations (*i.e.,* not autocorrelated). This assumption seems reasonable because most of the blocks were quite widely separated in time. They were drawn from nine runs, which were separated by an hour or more on any given day, and spread out over three days. Only about 1/3 to 2/3 of the blocks from the low-intensity runs met the criteria for inclusion, and these were quite discontinuous in time—only rarely were as many as four or five adjacent blocks included. Further, blocks at any given shear velocity tended to be spread between several runs. For example, the 18 blocks with a shear velocity between $0.36 ms^{-1}$ and $0.37 ms^{-1}$ were distributed between eight different runs over three days, and in no case did two temporally-adjacent blocks fall into this range. Thus, from a physical standpoint the assumption of independence seems reasonable. Most blocks from the higher-intensity runs were retained, and because these were temporally adjacent to a much greater degree a more rigorous examination was conducted. The HTRAP, VTRAP, and shear velocity records for each run were individually tested for autocorrelation (P14 was omitted due to the small number of observations). In none of the 15 cases was statistically significant autocorrelation found with a lag interval of two or more blocks. With a lag interval of one block, nine of the records showed no autocorrelation and three had only weak autocorrelation. Run P10 proved to be the exception, with all three records (HTRAP, VTRAP, and shear velocity) for this run showing moderately-strong autocorrelation (R^2 = 0.57, 0.51, 0.47, and p = 0.001, 0.002, 0.003, for the HTRAP, VTRAP, and U_*, respectively). However, in the analysis below the individual blocks from P10 are largely compared with blocks from other runs, so it is felt that the results can be considered robust.

Relative efficiency was plotted against shear velocity for the 15-second blocks (Figure 10b). No clear trend is evident, except for a decrease in the scatter about unity with increasing shear velocity. The latter is likely due, at least in part, to the small number of observations at the largest shear velocities. However, it may also reflect the decreasing effect on calculated relative efficiency of a given absolute difference in measured transport at larger transport rates (and thus larger shear velocities). Regression analysis confirmed the lack of a significant relationship between relative efficiency and shear velocity (R^2 = 0.01, p = 0.18).

The *absolute* differences in measured transport for the 15-second blocks show considerable variability (Figure 10c). However, when the mean values for $0.05 ms^{-1}$ shear velocity increments are considered, it is apparent that the between-trap differences in measured transport tend to balance over the three days of measurements. The result is that the mean measured transport in any given shear velocity interval is about the same for both traps (and the relative efficiency is approximately unity). This finding strengthens the conclusion that relative efficiency did not vary systematically with increasing shear velocity, at least up to the 0.50–0.55 ms^{-1} class. Blocks in the latter class consistently showed large negative differences in measured transport. This could be taken to indicate that the HTRAP became significantly less efficient than the VTRAP at the highest shear velocities. However, given that this class included only 5 blocks (primarily from the short-duration run P14), it seems just as plausible that the differences resulted from spatial variation in the transport field, and may have been reduced had more observations been available in this shear velocity range. In addition, despite the large absolute differences in measured transport at high shear velocities, the relative efficiencies for the highest shear velocity blocks are actually relatively close to unity (Figure 10b).

CONCLUSIONS

Several conclusions emerge from this investigation. Over the total duration of the experiment, both the grain-size characteristics of trapped samples and the average measured transport rates were nearly identical for the two traps. It is concluded that the relative efficiency of the two traps is similar, and that measurements obtained from them are comparable at the relatively long time scale represented by the entire data set.

However, it is clear that the measured transport rates did differ at shorter time scales, despite the proximity of the traps and the relatively uniform characteristics of the site. Detailed examination of the transport records indicated that the differences in sediment accumulation were primarily associated with variations in the timing of transport events (*i.e.*, transport occurred at one trap but not the other). Further, measured transport was not found to be consistently larger or smaller for either trap. It is concluded that the major cause of the differences in transport measurements over shorter time scales was spatial variability in the transport rate rather than a difference in trap efficiency.

The existence of significant spatial variation in transport over small distances has implications for the many field studies in which a single trap was used to monitor transport at a location. There was, however, some indication that the short term variations in measured transport may average to a uniform mean transport rate for higher intensity events (*e.g.*, P13), and low-intensity events when enough observations are available (Figure 10c), so that for longer-duration measurements small scale spatial variability is probably less significant. The absolute magnitude of the transport differences measured in the present study increased with shear velocity, although the relative differences tended to decrease. It is concluded, therefore, that spatial variability is especially significant during intermittent, low-intensity transport and for short duration measurements.

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