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The utility of an omni-directional photoelectronic sensor device to measure meso-scale variability in aeolian sediment transport activity

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ABSTRACT

Electronic sensors (i.e., acoustic, piezoelectric, and photoelectric) have been utilized extensively and effectively in recent years for measuring aeolian transport intensity. The bulk of these studies, however, position the devices in stationary, fixed orientation during field experiments. These practices work fine for shorter, micro-scale field studies; yet, during longer experiments lasting months or even years, a fixed directional orientation is unrealistic due to shifts in wind direction. This issue has ultimately limited the use of electronic sensors for meso-scale aeolian research. In light of this constraint, this paper presents a device to measure aeolian transport activity across a 360-degree azimuthal range. The Rotating Wenglor Device (RWD) was deployed on Santa Rosa Island, Florida for a three-month field study. The data reveal that the prevailing transport activity did not align with the dominant wind direction. The implications of this finding can be further elucidated when analyzing our data using the Fryberger drift potential model. Our findings indicate that the traditional Fryberger method, constructed using our wind data, produced a resultant transport drift towards the northwest; however, the RWD illustrated a resultant transport direction towards the northeast and at a rate three times slower. These finding highlights a major benefit of the RWD as it would produce a more accurate measure of meso-scale transport activity and therefore dune development than models derived strictly from meteorological station data, such as the Fryberger method. An additional advantage of the RWD is that the device operates unattended for extended periods, yet can provide high-resolution data regarding micro-scale transport dynamics.

1. Introduction

In recent years, a variety of electronic devices, such as the Safire, Sensit, and buzzer piezoelectric sensors (Baas, 2004; Udo et al., 2008; Udo, 2009; Barchyn and Hugenholtz, 2010; Swann and Sherman, 2013; Raygosa-Barahona et al., 2016); Saltiphone and Miniphone acoustic sensors (Spaan and Van den Abele, 1991; Schönfeldt and von Lowis, 2003; Ellis et al., 2009; Schönfeldt, 2012; Poortinga et al., 2013, 2015; Yurk et al., 2013); and Wenglor and SPC photoelectronic sensors (Jackson and McCloskey, 1997; Mikami et al., 2005; Redmond et al., 2010; Hugenholtz and Barchyn, 2011; Barchyn et al., 2014) have been employed in both field and laboratory experiments to measure aeolian saltation. A major benefit to these electronic devices is that they are nonintrusive and can measure transport activity at extremely fast measurement intervals thus allowing researchers to assess near-bed instantaneous saltation dynamics (Barchyn et al., 2011; Sherman et al., 2011; Sherman et al., 2013).

While these devices offer significant advantages in their ability to quantify transport activity at the micro-scale (i.e., seconds to sub-seconds measurement intervals) there are a number of shortcomings to their use at the meso-scale. The majority of studies utilizing these devices to measure aeolian transport position the devices in a stationary, fixed directional space, due to the near unidirectional winds these studies analyze. At the meso-scale, however, aeolian transport processes and dune development are a function of the directional fluxes of the wind, resulting in considerable spatial and temporal variability in aeolian sediment transport activity. Therefore, instruments not only need to measure saltation activity at micro-scale processes, but they must also account for the full azimuthal directional range at which transport activity may occur. Unfortunately, these devices struggle to do the latter. For example, Baas (2004) and Barchyn and Hugenholtz (2010) noted substantial variability in sensor sensitivity in recorded saltation around the circumference of the sensing unit for a variety of piezoelectric devices. To minimize the error associated to this variability, Baas (2004) continuously adjusted the sensor manually during shifts in wind direction so that only one side of the sensor recorded

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sediment transport, what the author deemed the 'sweet spot.' Continuous manual adjustments to the sensors may be possible for short-term experiments; however, for longer unattended field experiments over weeks or even months, shifts in wind direction will produce transport occurring from a variety of directions. Thus, as Baas (2004) denoted, accurate measurement of transport activity is greatly reduced.

This constraint has ultimately limited the use of electronic sensors in longer temporal aeolian studies (Stout 2014). A few researchers have attempted to directly address this issue by incorporating electronic devices into apparatuses that pivot with changes in wind direction (e.g.: Spaan and Van den Abele, 1991; Mikami et al., 2005; Webb et al., 2016); however, the design of these devices is still limiting as they focus sensor rotation across only a narrow azimuthal range.

This paper seeks to address this issue by illustrating the capability of a device, constructed by the authors, to measure omni-directional aeolian transport activity. The instrument incorporates the well-documented photoelectronic Wenglor particle counter into a wind-vane style device. The paper also demonstrates the devices ability to encapsulate transport activity across multiple temporal scales, micro and meso.

2. Methods

2.1. Rotating Wenglor Device (RWD) design

The design configuration for the Rotating Wenglor Device (RWD) utilizes a single Wenglor photoelectric sensor (model YH08PCT08, 80 mm fork width) incorporated into a wind vane style device capable of rotating fully across the 360-degree azimuthal range (Fig. 1). The main structure of the device is constructed of PVC. A central shaft (60 cm length) sits over and rotates freely upon a partially buried 1.5 m metal rod (90 cm buried). The base of the central shaft sits on a thin metal plate (10 cm × 10 cm × 1 cm) in which a hole is cut through the center for the metal rod to pass. The metal plate, installed flush with the bed level and paired with the vertical metal rod, provides a solid base for the central shaft of the device to rotate upon. Near the base of the central shaft extends the sensor shaft (25 cm length) in which the Wenglor sensor is attached horizontally at the end. For this study, the height of the sensor shaft/Wenglor was positioned 3 cm above the bed; however, this height can be adjusted depending upon the experiment's objectives. A wind vane shaft was positioned 10 cm below the top of the central shaft. The shaft length and vane were 50 cm and 30 cm × 15 cm, respectively.

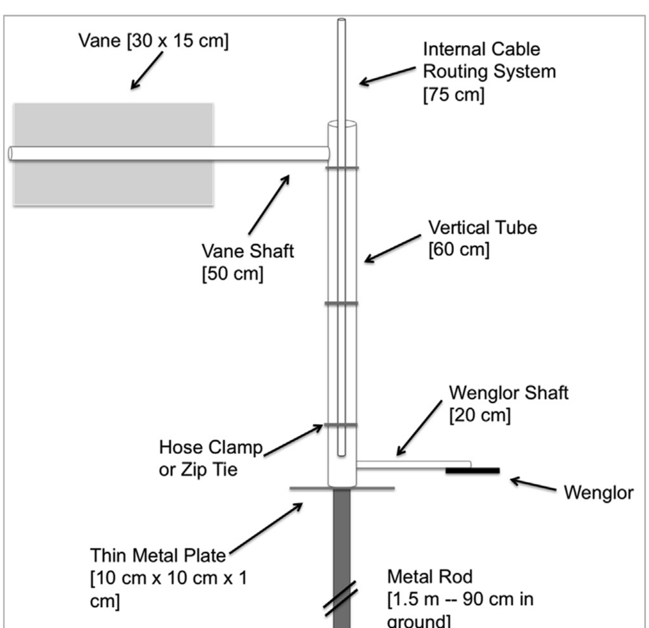

Fig. 1. Schematic illustration of the Rotating Wenglor Device (RWD).

During trial field deployments, we encountered an issue with the Wenglor sensor cable entangling around the central rod as the device rotated. This issue was resolved by attaching an internal cable housing pipe to the vertical central shaft. The pipe extended 15 cm above the end of the central shaft in order to elevate the sensor cable above the structure as a whole. An additional PVC pipe was installed approximately 5 m from the rotating device in the direction of the data logger to elevate the remaining sensor cable above the vane (see Fig. 3). The combination of the internal cable housing and extra pipe eliminated cable entanglement allowing free rotation. We did not experience any twisting, kinking, or crimping of the cable during the duration of the field deployment.

We provide the design specs for our device to offer the reader the context for which we used the RWD. The specific design, dimensions, and construction materials of the RWD outlined within this paper, however, can be modified by other researchers to fit their specific needs. For example, a series of Wenglor sensors can be stacked vertically along the central shaft to measure the vertical flux in transport activity. Additionally, a researcher aiming to measure transport at sec or sub-sec intervals may need to shorten the Wenglor shaft to decrease the inertial swing of the device as well as install sealed ball-bearings into the rotating shaft to decrease frictional drag.

2.2. Study site

The study site for this project was located on Santa Rosa Island in northwest Florida at the University of West Florida's beach property (Fig. 2). Santa Rosa Island stretches 77 km east to west from Destin Pass to the terminus at Fort Pickens and is part of a larger, micro-tidal wave-dominated, barrier island/spit system in the central Gulf of Mexico. Sediment composition is 99% quartz with a mean grain size of 0.33 mm (Houser and Barrett, 2009; Claudino-Sales et al., 2010).

The University of West Florida's beach property covers 70-hectares and contains a well-defined foredune and sets of disorganized dune hummocks, shrub forest, and wetland grasses throughout the interior and backside of the island. The study plot was subsequently located in a topographically flat area (approximately one hectare) in the central portion of the island. Concentrations of asphalt and gravel debris are present throughout the interior of the island where sections of County Road 399 were destroyed during hurricanes Ivan in 2004 and Dennis in 2005 (Houser et al., 2008; Houser, 2009). The RWD was located in the central portion of a 100 m^2 area that had been cleared of all lag debris (Fig. 3). The closest dunes to the RWD were approximately 35–40 m

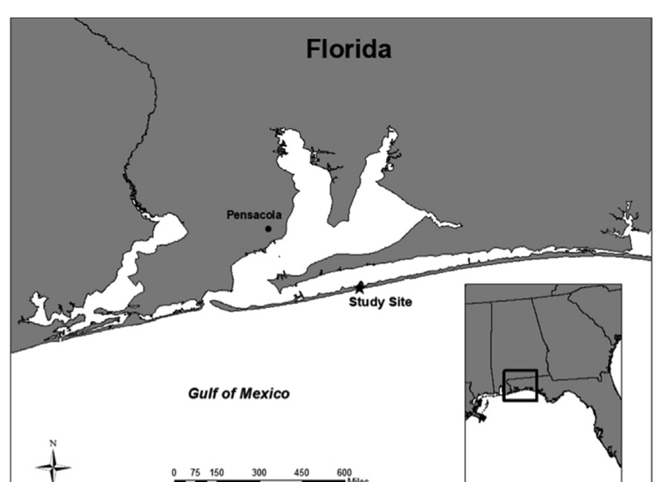

Fig. 2. Map of study site located on Santa Rosa Island in the western panhandle of Florida.

Fig. 3. Image of the RWD in the field during (left) and a couple days after installation (right). The study site was cleared of asphalt and gravel lag and raked smooth after installation. Notice the presence of the asphalt and gravel lag in the upper right and left corners near the dunes. Post installation image also depicts the additional PVC pipe utilized to elevate the sensor cable above the vane.

away and range in height between one and three meters. The data presented in this paper is associated with a larger project aimed at evaluating the impact of the asphalt and gravel lag on dune development and growth. The temporal demands of this experiment necessitated the construction of a device that would measure differences in transport between areas with and without the gravel lag over the course of a few months. This paper specifically focuses on the device utilized to collect that data and highlights its utility to monitor omni-directional aeolian transport activity across multi-scalar timeframes.

2.3. Field experiment

Data collection occurred during the months of March, April and May 2017. An analysis of wind data gathered from a National Climatic Data Center (NCDC) weather station located along the shorefront in downtown Pensacola (~18 km from the study site) found these three months to produce substantially higher concentrations of wind events greater than 6.0 ms^{-1} [estimated threshold velocity at 2 m calculated using the Bagnold (1941) model and the average grain size of 0.33 mm].

Wind speed was measured with an array of MetOne 014a-mini cup anemometers placed at heights of 0.25, 0.5, 1.0, and 2.0 m with wind direction measured with a MetOne 024a wind vane positioned at a height of ~2.5 m above the bed. A single Wenglor particle counter incorporated into the 360-degree rotating device measured aeolian sediment transport activity throughout the study period. All instruments were sampled at 1 Hz. The average wind speed and direction and total transport activity were then subsequently logged every 1 min on a Campbell Scientific CR1000 data logger.

2.4. Data analysis

Measured wind speed, direction, and transport activity by the RWD were visualized via wind roses and a sand rose, respectively, over sixteen principal wind direction azimuths. We also constructed aeolian sediment drift roses following the method proposed by Fryberger and Dean (1979) as modified by Bullard (1997), Pearce and Walker (2005), and Miot Da Silva and Hesp (2010). These roses indicate the sand drift for each of the sixteen wind directions and a vector resultant drift direction, which indicates net transport drift direction and magnitude. We applied the Fryberger method to two aspects of our data. First, in the more traditional approach by using the general wind data measured at our study site throughout the 3-month data collection period and second, using only the specific winds directly associated with transport activity measured by the Rotating Wenglor Device. We chose to construct this analysis to illustrate the advantage of our device, which monitors actual transport activity, over assessing theoretical transport from meteorological station data and drift potential models, such as the popular Fryberger method.

3. Results and discussion

Fig. 4 illustrates the temporal transport activity measured by the RWD. The majority of transport activity occurred over 22 days, throughout the 3-month data collection period, producing eight high intensity transport events and a variety of smaller, lower intensity events. Fig. 5 shows a wind rose fabricated from the wind speed measured at 2.0 m and wind direction measured throughout the study

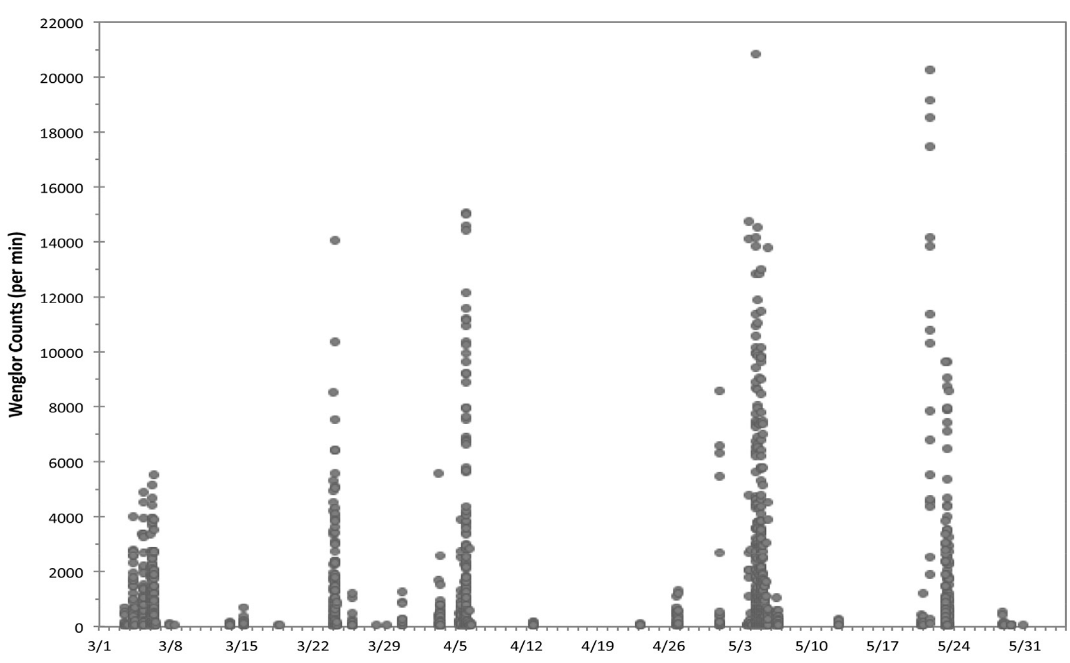

Fig. 4. Temporal record of transport activity measured by the Rotating Wenglor Device (RWD) throughout the three-month study period of March, April, and May.

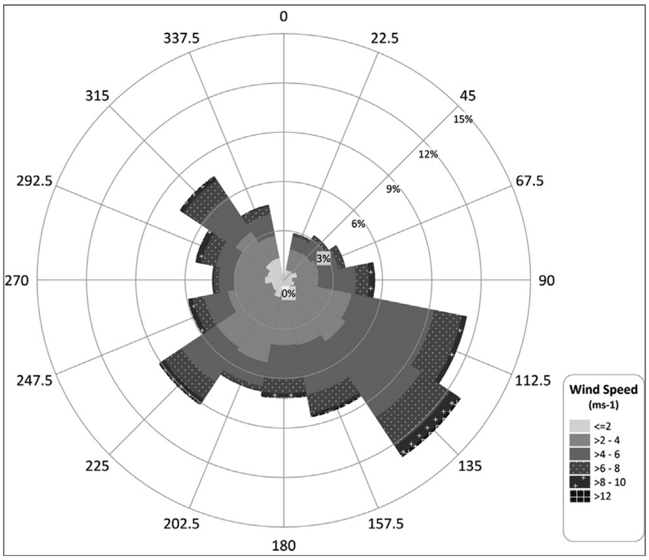

Fig. 5. Wind rose depicting the frequency of wind speed and azimuthal direction measured at an elevation of 2.0 m.

period. Wind speed fluctuated from 0 to 17.8 ms^{-1}, with an average speed of 4.2 ms^{-1}. Wind direction was dominant from the southeast in both total percentage (35% of all winds) and strength (38% of all winds greater than 6.0 ms^{-1}, estimated threshold velocity). The overall wind distribution pattern, however, was tri-modal with a large percentage of winds also occurring from the southwest and northwest. These three directional ranges account for 72% of total winds and 79% of all winds exceeding the estimated threshold velocity.

Fig. 6 illustrates a sand rose associated with transport activity measured by the RWD throughout the study period. The RWD observed transport activity over a similar tri-modal distribution pattern as indicated by our general wind data; however, measured transport occurred most frequently from the northwest to north-northwest. This finding was unexpected. Conventional wisdom would suggest that dominant transport activity would be produced from the southeast as the stronger, more prevalent winds occurred from this direction (see Fig. 5). This highlights a major benefit of the RWD. Studies associated with meso-scale dune development generally attempt to characterize transport activity using drift potential models, such as the Fryberger method (Fryberger and Dean 1979), constructed from the daily (or hourly at best) wind speed and direction data collected from a local meteorological station (sometimes kilometers away) (e.g., Bauer and Davidson-Arnott, 2003; Walker and Barrie, 2006; Miot da Silva and Hesp, 2010; Delgado-Fernandez, 2011; Delgado-Fernandez and Davidson-Arnott, 2011; Smith et al., 2017; Radera et al., 2018). Studies, however, have shown poor correlations between measured coastal dune development and transport activity derived from drift potential models (DavidsonArnott and Law, 1996; Hesp and Hyde, 1996; Baas, 2007; Delgado-Fernandez and Davidson-Arnott, 2011; Walker et al., 2017). This is in part due to the fact that not all winds are geomorphically effective. The influences of one or more supply-limiting controls (e.g., grain size, soil moisture, vegetation, surface roughness, sand supply, etc.) are critical in regulating aeolian transport activity and thereby the effectiveness of the wind field to move sediment (de Vries et al., 2014). Thus, the characterization of the amount and directional variability of transport activity based solely on available wind energy greatly reduces our ability to accurately assess dune development and evolution.

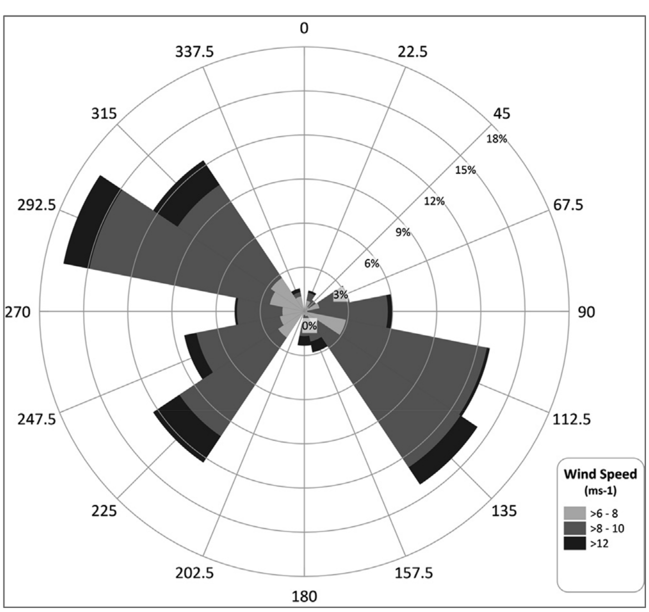

Fig. 6. Sand rose illustrating the frequency of winds (speed and azimuthal direction) which produced transport activity measured by the Rotating Wenglor Device (RWD).

The implications of the above discussion can be further clarified when analyzing our data using the Fryberger drift potential method (Fryberger and Dean, 1979) (Fig. 7). As indicated in Section 2.4, we applied the Fryberger method to two aspects of our data. First, to our general wind data measured at 2.0 m (F-Drift & F-RDD) and second, using the specific winds directly associated with transport activity measured by the Rotating Wenglor Device (RWD-Drift & RWD-RDD). First, Fig. 7 illustrates that the more traditional approach of using the Fryberger method with solely our wind data produced a drastic overestimation of transport drift (F-Drift) for all azimuthal directions and most significantly from the southeast direction, compared to the RWD derived drift values (RWD-Drift). This supports our findings described above. Second and perhaps most significant, is that this disparity in the 360-degree directional transport produces a substantial difference in the resultant drift between the two approaches, both in direction and magnitude. The RWD data produced a resultant drift direction (RWD-

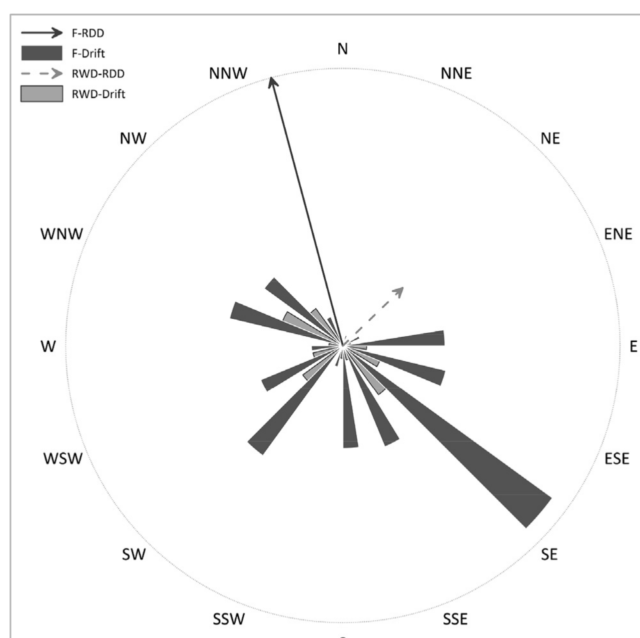

Fig. 7. Comparison of the transport drift and resultant drift direction constructed via the traditional Fryberger method from our general wind field data (F-DP & F-RRD) and the winds specifically associated with transport activity measured by the Rotating Wenglor Device (RWD-DP & RWD-RRD).

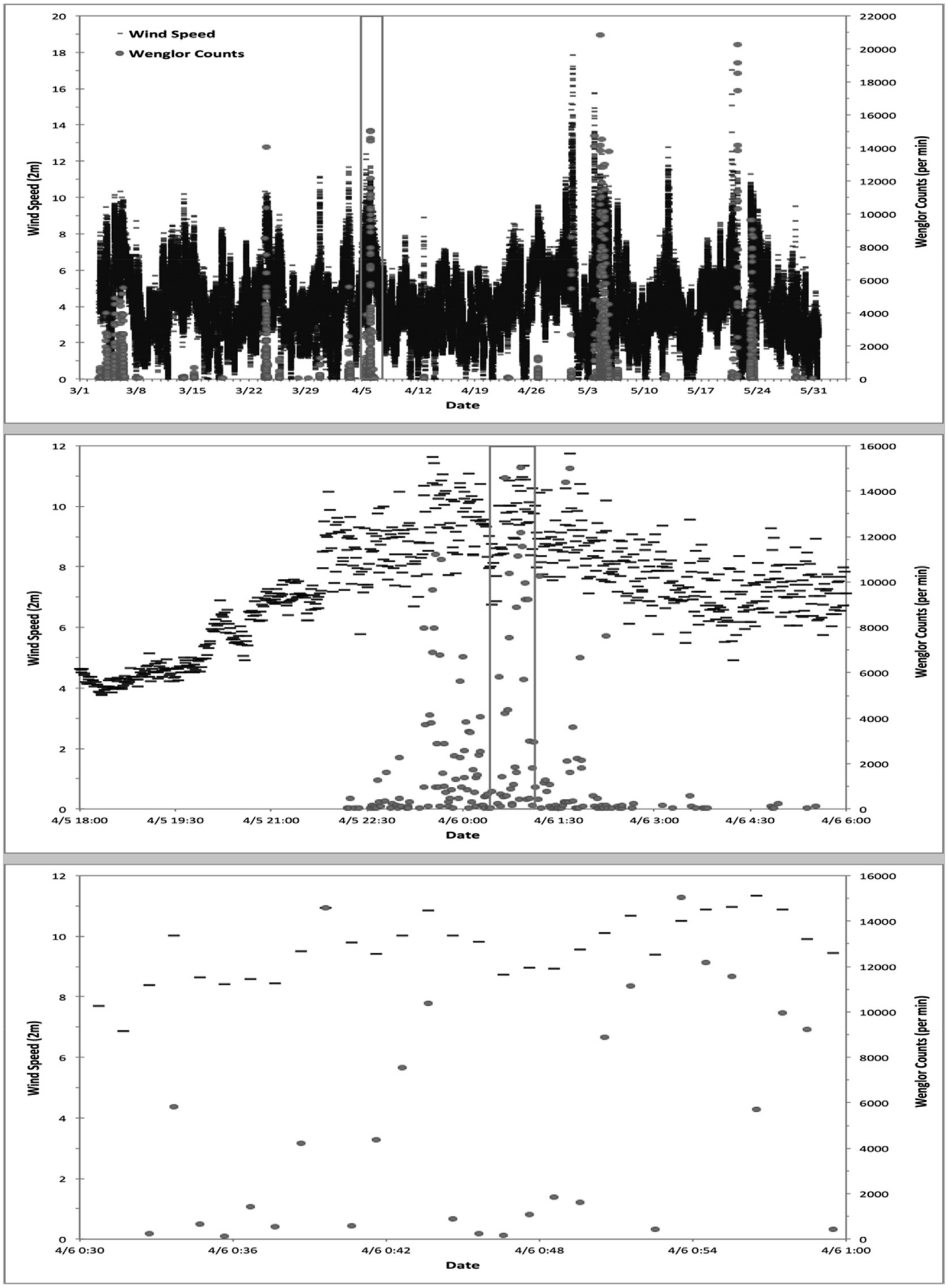

Fig. 8. Illustration showcasing the capabilities of the Rotating Wenglor Device (RWD) to record micro-scale transport activity over a meso-scale signal. Squares represent the subset of data depicted in each subsequent lower graph.

RDD) toward the northeast at a relatively low rate of drift compared to the Fryberger method, which predicted 3.3 times more transport with a resultant drift direction (F-RDD) focused a full 65-degrees westward. These findings indicate that the use of a theoretical drift model, like the Fryberger method, constructed solely from our general wind data, would forecast dune growth towards the northwest; however, actual transport data measured from the RWD illustrates that dune evolution would occur towards the northeast and at a rate three times slower. Therefore, the RWD, which measures actual transport activity, provides a more accurate correlation to dune development than models produced strictly from meteorological station data.

Another key benefit of the RWD is its ability to directly evaluate 'cross-scale' relationships in aeolian transport processes. Walker et al. (2017) assert that an understanding of the range of processes, feedbacks, and linkages at the micro-scale is required to inform and verify the assumptions that underlie the physical modeling of beach-dune interaction at the meso-scale. Traditionally, this has been accomplished by documenting 'snapshots' in time of micro- or meso-scale processes and attempting to up- or downscale the allied forces and/or parameters to correlate landform evolution (Delgado-Fernandez and Davidson-

Arnott, 2011). A number of researchers have written about the complications with modeling landform evolution by theoretically 'cross-scaling' coastal aeolian processes (e.g., Sherman, 1995; Bauer and Sherman, 1999; Bauer et al., 1999; Barchyn et al., 2014). Furthermore, Coulthard (2009) states that these 'snapshots' produce knowledge that misses the transition from one scale to another, which Sherman (1995) asserts is vital to providing scientists, managers, and planners with an appropriate set of tools for decision-making. The lack of a sediment transport time series (micro- and meso-scale) at the same temporal resolution and duration as wind data makes it difficult to assess the relative significance of wind events of different magnitude and direction. This cross-scale correlation has the potential to have a major impact on aeolian studies. The RWD, however, has the capability to overcome this multi-scalar issue as it can record omni-directional transport activity at multi-hertz intervals, via the Wenglor sensor, over a range of days to months. It allows researchers to visualize and isolate specific micro-scale transport events contained within a meso-scale transport signal (Fig. 8).

4. Conclusion

Electronic sensors have become a popular tool to measure aeolian saltation in recent years. However, the use of these devices in meso-scale research is rare. This is in part a result of considerable spatial and temporal variability in aeolian sediment transport activity occurring over the meso-scale, thus requiring that instruments not only need to be able to measure micro-scale saltation processes but also the ability to capture transport across the full azimuthal range. Unfortunately, these electronic devices struggle with the latter, which has minimized their use in meso-scale research. This study showcased two key benefits of the Rotating Wenglor Device (RWD) to quantify meso-scale omni-directional transport activity: 1) RWD produces a more accurate measure of meso-scale transport activity than data derived from meteorological stations and theoretical transport drift models. 2) The device allows transport activity to be measured over weeks to months at high-resolution micro-scales. This cross-scalar measurement can allow researchers to correlate long-term sediment activity with micro-scale processes. Both of these findings have serious ramifications on the accuracy of evolutionary beach-dune system models as well as a variety of coastal dune management scenarios.

CRediT authorship contribution statement

Phillip Schmutz: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Resources, Writing - original draft, Writing - review & editing, Visualization, Funding acquisition, Project administration. **Tynon Briggs:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Funding acquisition. **Peter Tereszkiewicz:** Conceptualization, Methodology, Writing - review & editing, Data curation.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aeolia.2018.11.003.

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