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Measurement and modeling of the spatiotemporal dynamics of beach surface moisture content

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ABSTRACT

The spatiotemporal dynamics of surface moisture exert a significant influence on the operation of aeolian transport systems at many beaches. However, we currently lack the detailed understanding of variability in surface moisture required to incorporate it into aeolian models. This problem is addressed here through direct measurements and simulation modeling of beach surface moisture over a twelve-day period, and through quantification of the relative contributions of evaporation, condensation and groundwater inputs to surface moisture. It was found that the beach surface can be characterized spatially in terms of three moisture zones: a consistently dry zone (< 3%); a variable zone (3% to saturation); and a consistently wet zone (> 40%). The relative influence of groundwater inputs was found to decrease moving landward, as the depth of the water table increased and the amplitude of tidally-induced water table fluctuations decreased. The critical pressure head (groundwater depth) at which evaporation begins to impose a demonstrable influence on surface moisture variability was found to be 90–100 cm. Temporally, beach surface moisture is a function of the lunar tidal cycle at longer-term time scales (weekly), and diurnal tidal and evaporation cycles. A numerical model was used to simulate capillary transfers of moisture from the water table to the surface, and moisture losses due to evaporation. The model was found to reliably replicate the measured spatiotemporal variability in surface moisture. In the dry zone, where most aeolian transport would be expected to occur, simulated moisture contents were typically within ± 0.2% of measured volumetric contents.

1. Introduction

It is generally acknowledged that the beach hydrological system is a critical parameter influencing a broad range of environmental phenomena including earth-atmospheric energy fluxes, beach stability, nutrient cycling, water purification, coastal water resource budgets, and interstitial biological activity (e.g., Hesp, 1991; McLachlan, 1989; Famiglietti et al., 1998; Barrilleaux and Grace, 2000; Horn, 2002; Abu-Hamdeh, 2003; Chen and Hu, 2004; Legates et al., 2010; Vicinanza et al., 2010). The cohesive forces induced by the presence of moisture at the sediment surface are often cited as a factor influencing aeolian transport, one that acts to limit the frequency and magnitude of transport events (e.g., Namikas and Sherman 1995; Cornelis and Gabriels, 2003; Wiggs et al., 2004a,b; Davidson-Arnott et al., 2008; Rotnicka, 2013; de vries et al., 2014; Haehnel et al., 2014; Poortinga et al., 2014; Edwards and Namikas, 2015; Hoonhout and de Vries, 2016). Thus, beach surface moisture can exert an important control on coastal dune development. Although a number of studies have explored this influence (e.g., Bauer and Davidson-Arnott, 2002; Aagaard et al., 2004; Bauer et al., 2009; Houser, 2009; Lynch et al., 2016; Hoonhout and de Vries, 2017), the applicability of theoretical aeolian transport rate models to the real world remains substantively handicapped by our inability to accurately describe spatiotemporal beach surface moisture dynamics.

A number of studies have provided data regarding the variability in surface moisture in beach environments (e.g., Atherton et al., 2001; McKenna Neuman and Langston, 2003; Wiggs et al., 2004a; Yang and Davidson-Arnott, 2005; Davidson-Arnott et al., 2005; McKenna Neuman and Langston, 2006; Zhu, 2007; Davidson-Arnott et al., 2008; Bauer et al., 2009; Namikas et al., 2010; Brakenhoff, 2015). These data clearly indicate that surface moisture content varies considerably in both space and time, both at a given beach and from beach to beach. The available database, however, is insufficient to provide for a general characterization of beach moisture variability of sufficient detail to support realistic aeolian transport or sediment budget modeling. This is in large part due to the complex and variable nature of the suite of

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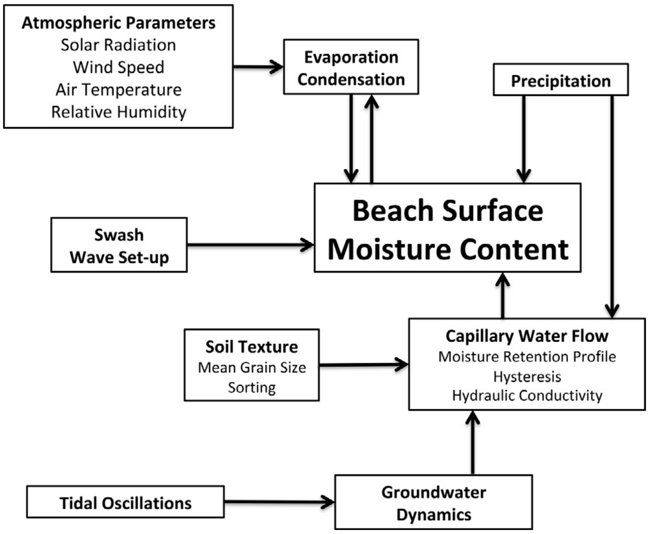

Fig. 1. Key processes and parameters that control beach surface moisture dynamics.

hydrological, meteorological and sedimentary parameters [e.g., precipitation, tidal oscillations, groundwater flow, capillary transport, evaporation, condensation, sediment size, sorting, porosity, hydraulic conductivity, etc.], which regulate beach surface moisture (Fig. 1). Although the importance of some of these parameters has been identified in previous studies (e.g., Atherton et al., 2001; Zhu, 2007; Namikas et al, 2010; Brakenhoff, 2015), our ability to model the beach hydrological system in the context of its control on surface moisture remains limited. This issue must be resolved to allow the development of realistic models of surface moisture variability, and their ultimate incorporation into aeolian transport budget and dune development models.

This study documents and models several key components of the beach hydrological system (tidal oscillations, water table fluctuations, capillary transport, evaporation, condensation), and their influence on spatiotemporal variability in surface moisture content. The specific research objectives are to: 1) measure spatiotemporal variability in surface moisture across a spring-neap tidal cycle; 2) link measured surface moisture variability to contemporaneously monitored controlling processes/parameters; and 3) construct a physically-based numerical model capable of reproducing the measured variability in beach surface moisture over both space and time.

2. Methods

2.1. Study site

The field experiment was conducted over 12 days (January 18–29), at Padre Island National Seashore on the central Texas coast (Fig. 2). The native quartz sediment is well sorted with a mean grain size of about 0.14 mm. The beach environment at the time of the study was comprised of a gently sloping berm extending about 50 m from the foredune to the berm crest. Scattered, small embryo dunes extended approximately 5–10 m onto the beach from a well-established 2–3 m high foredune. The central Texas coast experiences a micro-tidal range (typically less than one meter), with mixed but predominately diurnal tidal cycles (Weise and White, 1991).

2.2. Field methods

2.2.1. Surface moisture measurement

To map spatial and temporal surface moisture patterns, a grid of measurement points was established across the beach (Fig. 3). The

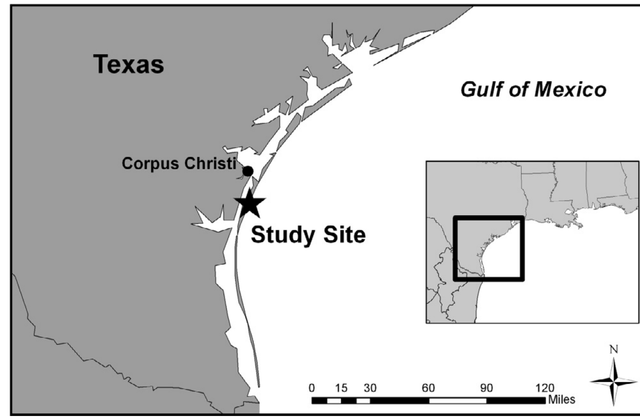

Fig. 2. Location of Padre Island National Seashore field site.

moisture grid comprised of 12 alongshore lines sequentially designated as L1 to L12. The lines were spaced at 2.5 m to 5 m intervals in the cross-shore direction, and each line consisted of five measurement points spaced 5 m in the alongshore direction. Measurement of surface moisture contents were performed using a Delta-T Theta soil moisture probe, modified to limit measurement depth to 1.0 cm (Tsegaye et al, 2004; Yang and Davidson-Arnott, 2005; Schmutz and Namikas, 2011). Grid moisture contents were measured six times per day (dawn, mid-morning, solar noon, mid-afternoon, sunset, and middle night). The sampling schedule was based on consideration of expected rates of change in surface moisture, as well as the desire to minimize the small but cumulative surface disruptions resulting from probe insertion. During high tide, swash process often submerged measurement lines L10-L12 (seaward-most lines). Therefore, measurements were not collected during these times as the beach surface sediment was presumed saturated (45% content by volume – determined through laboratory analysis from this study and past research conducted by the authors at the field site).

2.2.2. Water table depth and tidal elevation measurements

Water table depth was monitored using four groundwater wells (designated W1 to W4 on Fig. 3) that were installed on lines L1, L4, L6 and L9. A pressure transducer (PT) (Global Water WL400 or KPSI 730) was installed in each well and monitored at five minute intervals to document water table fluctuations. Tidal oscillation was initially monitored using a Global Water WL400 pressure transducer installed in the nearshore zone 50 m seaward of the berm crest. However, this instrument failed on the second day of the experiment so all tide data utilized in this study was obtained from a National Oceanic and Atmospheric Association (NOAA) tide gauge located at Bob Hall Pier, about 10 km north of the study site. Previous work by Zhu (2007) has demonstrated that data from this NOAA gauge correlate closely with pressure transducer measurements at the study site.

2.2.3. Potential evaporation and atmospheric measurements

Potential evaporation rates were measured using a standard National Weather Service Class A evaporation pan (Fig. 3) equipped with a digital depth sensor (readable to 0.01 mm) mounted within a stilling well. Measurements of the evaporation pan water elevation were recorded six times per day, concurrent with each set of moisture grid measurements.

Wind speed and direction were measured using a set of three RM Young cup anemometers at elevations of 1.0, 2.0 and 5.0 m above the beach surface, and a Qualimetrics Micro Response wind vane at the top of the weathermast (5.5 m) respectively. Air temperature and relative humidity were monitored using two Campbell Scientific HMP45C temperature/humidity transmitters installed on the mast at elevations of 1 m and 5 m. Precipitation was monitored using a Texas Electronics