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Sedimentary rhythms in coastal dunes as a record of intra-annual changes in wind climate (Łeba, Poland)

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ABSTRACT

It is shown that coastal dunes bear a so far unread archive of annual wind intensity. Active dunes at the Polish coast near Łeba consist of two genetic units: primary dunes with up to 18 m high eastward-dipping foresets, temporarily superimposed by smaller secondary dunes. Ground-penetrating radar (GPR) data reveal that the foresets of the primary dunes are bundled into alternating packages imaged as either low- or high-amplitude reflections. High-amplitude packages are composed of quartz sand with intercalated heavy-minerals layers. Low-amplitude packages lack these heavy-mineral concentrations. Dune net-progradation is towards the east, reflecting the prevalence of westerly winds. Winds blowing parallel to the dune crest winnow the lee slope, leaving layers enriched in heavy minerals. Sediment transport to the slip face of the dunes is enhanced during the winter months, whereas winnowing predominantly takes place during the spring to autumn months, when the wind field is bi-directional. As a consequence of this seasonal shift, the sedimentary record of one year comprises one low- and one high-amplitude GPR reflection interval. This sedimentary pattern is a persistent feature of the Łeba dunes and recognized to resemble a sedimentary "bar code". To overcome hiatuses in the bar code of individual dunes and dune-to-dune variations in bar-code quality, dendrochronological methods were adopted to compile a composite bar code from several dunes. The resulting data series shows annual variations in west-wind intensity at the southern Baltic coast for the time period 1987 to 2012. Proxy-based wind data are validated against instrumental based weather observations.

1. Introduction

Long-term data series on past wind-field evolution are most relevant for the calibration of climate models and for the prediction of the socio-economic consequences of climate shifts. Wind is the main driver of sedimentological processes on aeolian dunes, making them a potential archive of wind-field variations. Consequently, shape and architecture of aeolian dunes were used in numerous studies to reconstruct the long-term evolution of storminess and changes of the prevailing wind direction (Bristow et al., 2010; Clemmensen and Murray, 2006; Clemmensen et al., 2001, 2007, 2014; Costas et al., 2012b, 2013, 2016; Havholm et al., 2004; Lancaster et al., 2002a; Orford et al., 2000; Reimann et al., 2011; Wilson et al., 2001). Attempts to reconstruct past wind strength from aeolian dunes focuses on sediment grain-size or dune migration velocity (Bristow et al., 2005; Forman et al., 2008; Lancaster et al., 2002b; Lindhorst and Betzler, 2016; Tsoar et al., 2004; Yao et al., 2007).

This study proposes a new, non-invasive approach to reconstruct annual wind-intensity variations from aeolian dunes. Exemplarily applied to dunes at the southern Baltic Sea coast, a proxy-based data-series of annual wind intensity for the time period 1987 to 2012 is presented and validated against a time series of instrumental based weather observations.

2. Study site

The study area is situated at the Polish Baltic coast, 90 km northwest of Gdańsk close to the small village Łeba (Fig. 1). Mid- to Late Holocene coastal barrier sediments are covered by an active dune field consisting of eight barchanoid dunes up to 600 m long and 27 m high. Individual dunes consists of primary dunes, superimposed by secondary mesobarchans, which are up to 8 m thick and 250 m long (Borówka, 1980, 1990). The primary dunes are

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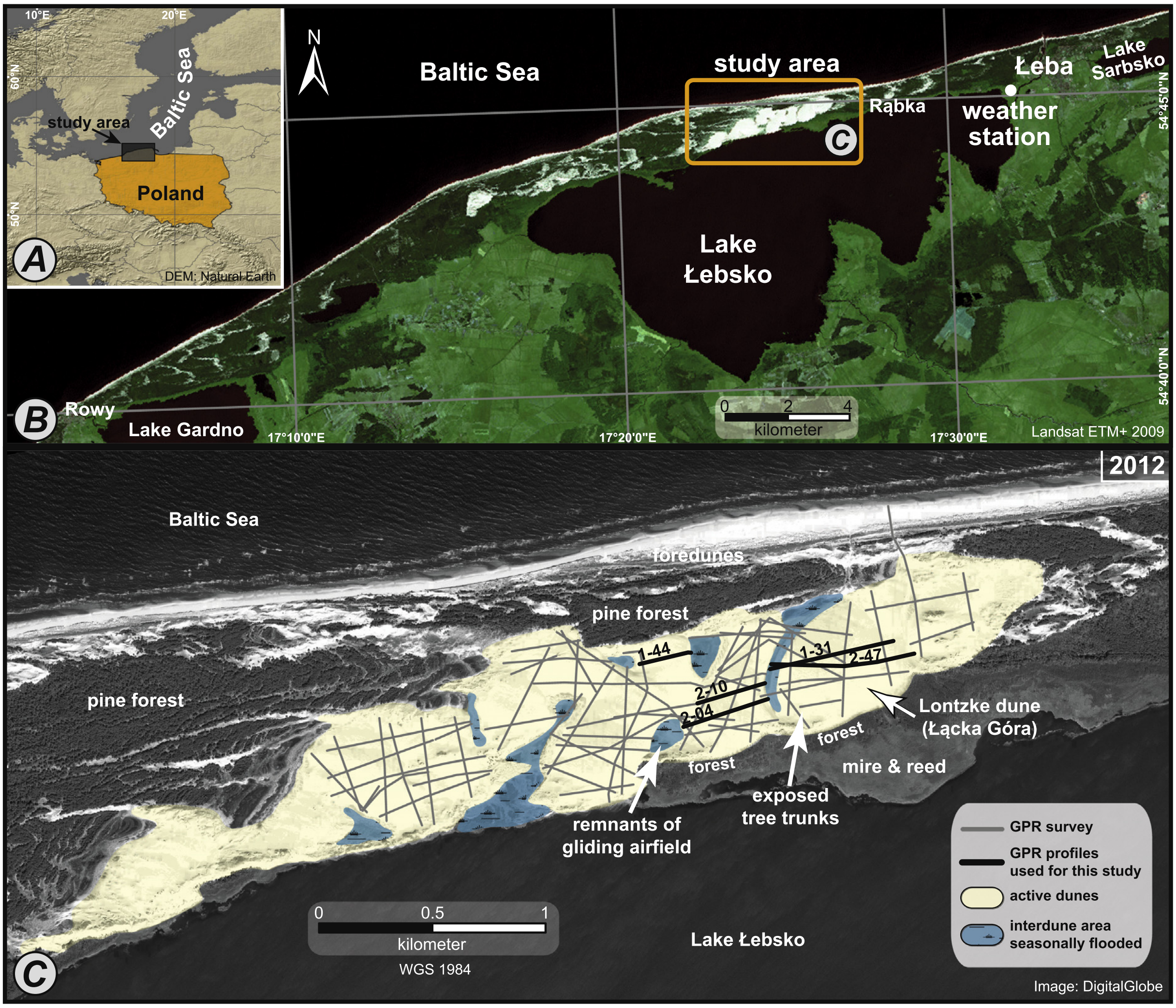

Fig. 1. A) Location of study area at the Polish Baltic Sea coast; B) Łeba barrier with active dunes and position of the weather station; C) Aerial image of the dune field obtained in the year 2012. Bold lines: GPR profiles used in this study.

regarded as persistent feature of the Łeba dune system, being present since at least 1900, whereas the secondary dunes vary in size on a sub-annual time scale (Borówka, 1990). Dune sands of Łeba are in general composed of 99.5% quartz and less than 1% heavy minerals, including amphiboles, garnets, and small amounts of zircon and ilmenite (Borówka, 1979).

The study area is part of the Słowiński National Park and public access to the dunes is prohibited since the year 1967. The dunes of the Łeba system show a continuous eastward movement parallel to the recent coastline, with an annual rate of migration in the range of 10 to 12 m (Ptak and Rudowski, 2014). Psammophytes and pine trees planted during the second half of the 19th century AD border the dune area towards the coast, whereas the southern limit of dune activity is formed by the lagoonal Lake Łebsko (Fig. 1). The dense back-beach vegetation restricts sand transport from the beach to the dunes (Borówka and Rotnicki, 1995).

Four stages of past dune development are preserved, interrupted by phases of soil development (Borówka, 1990, 1995). The first phase of aeolian activity, characterized by the formation of foredune ridges and parabolic dunes, terminated between 4 and 3.5 ka BP, according to radiocarbon dating of paleosols. The second phase of aeolian activity between 3.3 and 2.5 ka BP was characterized by the presence of barchans and parabolic dunes up to several meters high. A third phase, with up to 25 m high barchanoid and parabolic dunes terminated around 1.5 ka BP. Subsequently, there is no evidence for dune development until 0.5 ka BP, when aeolian activity resumed (Borówka, 1990).

3. Methods and data sets

3.1. Ground-penetrating radar

The internal sedimentary architecture of the dunes was imaged by means of a Geophysical Survey Systems Inc. (GSSI) SIR-3000 ground-penetrating radar (GPR) equipped with a 200 MHz antenna. The topography along the survey lines was measured parallel to GPR profiling using a Leica GS09 differential GPS (dGPS). Accuracy of this system is 2 cm for all axes (manufacturer specifications). GPR data were processed using the software package ReflexW (Sandmeier, 2013). Processing steps included: 1.) removal of the system-based time offset (static correction); 2.) elimination of the very low frequency part of the signal by subtraction of a running mean calculated for each sample (dewow); 3.) time-dependent frequency filtering (bandpass 20–380/10–300 MHz); 4.) subtraction of an average trace (background removal); 5.) topographic migration to correct for geometrical distortions caused by terrain morphology and resulting in non-vertical GPR beam