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Hulskemper, D., Anders, K., Antolínez, J. A. A., & Lindenbergh, R. (2026). Uncovering Causation of Short-Term Sandy Beach Surface Dynamics Measured by Permanent Laser Scanning. In C. Coelho, C. Hallin, F. Sancho, & P. A. Silva (Eds.), *Coastal Dynamics 2025: Volume 2* (pp. 338-344). (Coastal Research Library; Vol. 42). Springer.
https://doi.org/10.1007/978-3-032-15477-4_51

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Uncovering Causation of Short-Term Sandy Beach Surface Dynamics Measured by Permanent Laser Scanning

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Abstract. The causal drivers of short-term changes (days to months) in human-, wind-, and wave-driven sand transport on a sandy beach are not often considered in an integral and data-driven approach. However, improving current knowledge on (urban) sandy beach topographical change requires the incorporation of multi-scale, cross-sectional and human factors. In this research we process a time series of 21,194 hourly point clouds, obtained in a Permanent Terrestrial Laser Scanning setup. From this 3D time series we extract 5,102 short-term temporary surface dynamics, through a method called 4D objects-by-change (4D-OBCs). The causal drivers of two of these 4D-OBCs are investigated in detail. One is interpreted as an aeolian depositional surface dynamic (1), and one as a bulldozer deposit, that consecutively eroded under high wave energy conditions (2). The dynamics show clear correlation to a particular combination of wind direction and intensity (1), and wave height and wave period (2), indicating that point cloud time series derived 4D-OBCs are useful data to study causality of short-term surface dynamics of different origins. However, to study these surface dynamics systematically and derive statistical proof of causal relations we must consider multivariate correlations, as well as spatiotemporal dependence between sediment dynamics and larger scale morphological changes on the beach.

Keywords: Permanent Laser Scanning · Beach morphodynamics · 4D objects-by-change · LiDAR · Coastal monitoring

1 Introduction

Sandy coasts are dynamic environments, constantly shaped by natural processes and human activities. Rising sea level intensifies coastal squeeze, threatening the livelihoods of coastal communities [1]. Thorough knowledge of the complex interplay between natural forces, human actions, and sand redistribution is thus essential to ensure the effectiveness of management strategies under changing conditions.

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C. Coelho et al. (Eds.): CD 2025, COASTALRL 42, pp. 338–344, 2026.

https://doi.org/10.1007/978-3-032-15477-4_51

Traditionally, sandy beach dynamics have been studied by focusing on long-term (years – decades) natural behavior of beach-dune systems [2] or on short-term (days – months) processes, but often lacking integration [3]. The relationship between human activities, beach-dune sand redistribution, and broader coastal dynamics remains poorly understood [4].

Enhancing our understanding of the gaps in our knowledge requires a spatiotemporal holistic approach. We need to consider the impact and conditions of short-term surface dynamics – existing for only hours to months – over the full cross-section of the sandy beach and place them in the perspective of longer-term change. This requires high frequency, quality, and coverage of observations over long time scales. Only recently, Permanent Laser Scanning (PLS), acquiring hourly 3D elevation measurements at cm level accuracy over extended periods of time (months – years), offers the data to advance our understanding [5]. The challenge, however, is to automatically extract relevant surface dynamics from these millions of observations and link these to causal parameters.

This study presents a framework through which the causal parameters of short-term sandy beach surface dynamics can be studied in large point cloud time series datasets. Our goal is to answer the questions: (1) How can short-term surface dynamics be derived automatically from extensive time series of point clouds? (2) How can causation of short-term surface dynamics be uncovered? The research questions will be answered by, first, extracting short-term surface dynamics from a point cloud time series as 4D objects-by-change (4D-OBCs) [6], and second, assessing the environmental conditions in which two examples of these short-term surface dynamics existed.

2 Datasets

2.1 Permanent Laser Scanning Dataset

In a PLS setup, a terrestrial laser scanner is permanently mounted in a fixed position and acquires elevation data as point clouds over regular intervals for an extended time. For this study, an open-source dataset of 21,780 hourly point clouds (Fig. 1) is used, acquired with a Riegl VZ2000 at Noordwijk, The Netherlands (52.24°N, 4.42°E) between 2019-07-06 and 2022-07-21 [7]. Here, elevation measurements of the dune area (top), backshore (center), and part of the intertidal area (bottom) are obtained. The systematic errors between point clouds [8] are corrected using transformation matrices as provided with the dataset at 4TU.research data [7]. Point clouds containing strong noise were also removed.

2.2 Data of Candidate Causal Parameters

The candidate causal parameters considered in this study are hydrodynamical and meteorological. Hydrodynamic causation is considered through two variables: significant wave height (H_s) and period of significant waves (T_p), sourced hourly at IJmuiden by Rijkswaterstaat. Meteorological causation is considered with the hourly mean wind speed (u), and the wind direction (θ), obtained at Hoek van Holland by the KNMI.



Fig. 1. Example of a point cloud of the beach at Noordwijk colored using aerial photography of the Dutch government (pdok/beeldmateriaal.nl). The black box indicates the area of the point cloud used for the analysis.

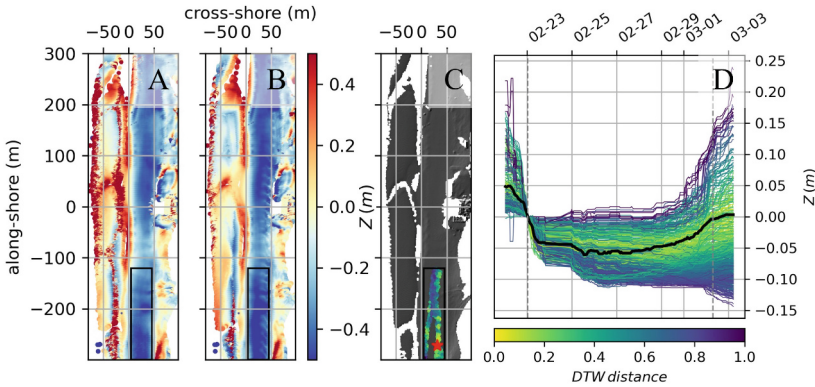


Fig. 2. Spatial (A, B, C) and temporal (D) representation of a 4D object-by-change (4D-OBC). A) elevation change with respect to first epoch of the dataset at start of the 4D-OBC. The black box indicates the bounding box of the 4D-OBC. B) elevation change at the last epoch of the 4D-OBC. C) Spatial outline of the 4D-OBC (colored area). The colors indicate the Dynamic Time Warping distance (DTW) to the seed time series (red star). D) time series of elevation change with respect to the start of the 4D-OBC, of the seed (in black), and other points incorporated in the 4D-OBC (colored by DTW distance, corresponding to C). The temporal extent of the 4D-OBC lies between the two dashed lines.

3 4D Objects-By-Change Extraction

The 4D objects-by-change method is used to extract a dataset of temporary surface dynamics (4D-OBCs) from the 21,780 point clouds, of which the causation and conditions can be studied. A 4D-OBC represents the spatial and temporal extent of a temporary deposition or erosion event within a point cloud time series (Fig. 2). They are extracted by, first, detecting breakpoints in the time series of elevation change. These breakpoints indicate a change in local elevation dynamics. From each breakpoint a temporal region is segmented, which extends in time until the elevation of the first breakpoint is reached again, thereby representing a temporary surface change (Fig. 2D). These temporal segments are used as seeds for subsequent object segmentation and are sorted based on neighborhood similarity of the time series. Starting with the first seed, a spatial region is grown based on a similarity criterion between the time series, for which the Dynamic Time Warping distance (DTW) is used (Fig. 2C). This is done successively for each seed candidate that is not yet incorporated in another 4D-OBC. For a more detailed description refer to [6].

For this study, the workflow is executed in parallel for nine temporal subsets, to allow for faster computing and reduce memory use. After extraction, if the percentage of time series in a 4D-OBC with a different sign than the seed is larger than 10 percent, the 4D-OBC is not considered. This can occur if the seed time series shows only little elevation change. Also, 4D-OBCs are filtered out with an unrealistic (> 1 m) and instant absolute change in height in the intertidal area.

4 Results

The methods result in the extraction of 5,102 4D-OBCs over the course of three years. Figure 3 shows the number of different 4D-OBCs as function of time. There are no active 4D-OBCs in between the subsets, as all are either finished at the end or not taken over to the next subset. From the set of 4D-OBCs, two are studied in detail to understand the causal conditions of their existence, namely, an erosional surface dynamic on the backshore, and an anthropogenic depositional surface dynamic on the backshore in front of a beach pavilion.

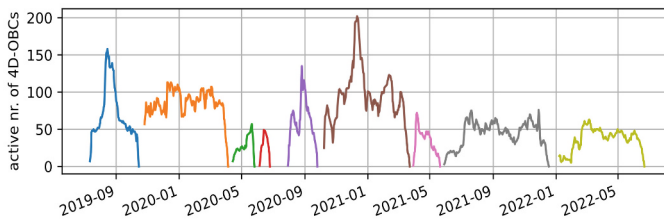


Fig. 3. Active 4D objects-by-change over the three-year dataset. Each color represents one of nine temporal subsets.

4.1 Causal Conditions for Two 4D Objects-By-Change

Figure 4B and C show the temporal volumetric change and spatial outline of the 4D-OBC, also presented in Fig. 2. The cross-shore location is centered around the high tide line. Figure 4A shows the evolution over time of two candidate causal parameters of this surface dynamic, namely the hourly mean wind speed and wind direction. The colors in A and B correspond to the slope of the volumetric change at that point in time.

We can observe that during the initial phase of the 4D-OBC, erosion occurs under a relatively high wind speed (≥ 9 m/s) with a slight landward direction. The direction approaches a right angle to the coast before the erosion halts under lower wind speeds (≤ 9 m/s). During this stabilization of deformation, the wind alternates intermittently between landward and more seaward directions. At the final depositional part of the surface dynamic the wind speed increases again, but now the direction stabilizes for a short period into a longshore direction, in contrast to previous oblique directions. In Fig. 2B, at the end of the 4D-OBC duration, spatially intermittent elevation increases

(sand waves) occur, perpendicular to the coastline, which are signs of sand transport in long shore direction.

Figure 4D, E and F show a representation of a depositional surface dynamic. This dynamic is likely initiated through bulldozer work, pushing sand from the front of the building (on the right) seaward. The initial deposition occurs under calm conditions, i.e., small wave period and wave height. The stable period (colored black) coincides with some increase in wave period. However, only when the wave height is also enhanced, does the volume of the 4D-OBC start decreasing. This decrease is slow when the wave height lies between 0.5 and 1 m; and faster when the wave period also increases.

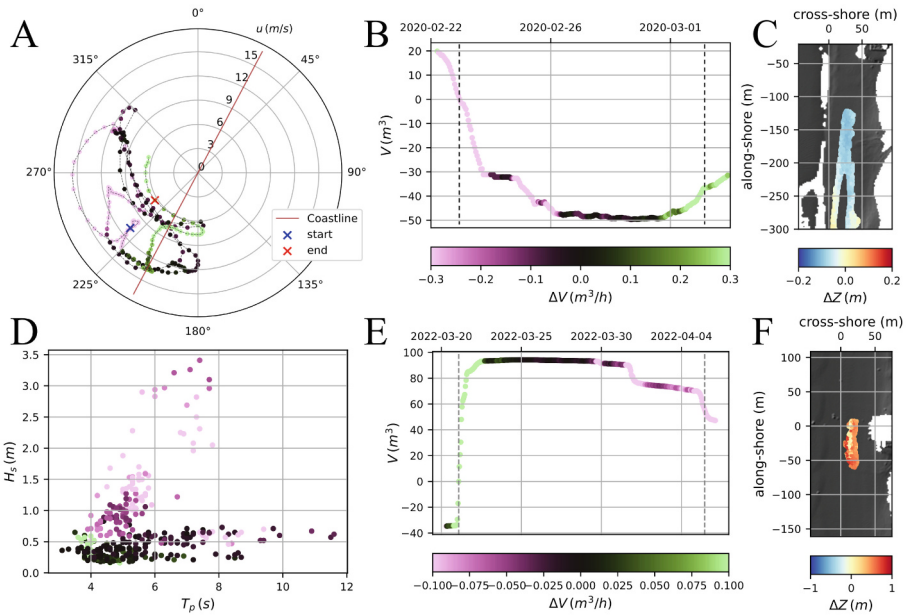


Fig. 4. A) Two causal parameters at different points in time (12h mean): wind speed (u), and wind direction, during an erosional 4D object-by-change (4D-OBC) on the beach, near the dunes. B) temporal volumetric evolution of the 4D-OBC. With the extent of the 4D-OBC between the dashed lines. The color scale in A and B represents the slope of the volumetric change w.r.t. the start of the 4D-OBC. C: spatial outline and height change at center epoch of 4D-OBC. D) T_p : wave period and H_s : significant wave height (12h mean), during a depositional 4D-OBC on the backshore, in front of a beach pavilion. E and F are alike B and C.

5 Discussion and Conclusions

The results show that 4D objects-by-change (4D-OBCs) extracted from large point cloud time series contain information on causal conditions of short-term surface dynamics. These conditions are defined by combinations of multiple variables, and only under certain combination and sequencing does the deformation rate in the surface dynamics alter. For example, the depositional recovery after wind erosion occurs only when wind direction stabilizes parallel to the coast and wind speed decreases compared to prior erosion

under a shoreward direction. This possibly relates to fetch length variations, a known driver of sand transport. The other 4D-OBC discussed here is driven by combinations of wave period and wave height, which affect total water level and wave energy, variables often used to predict wave-driven sand transport. Both analyses thus show a clear relation to known causal conditions, which implies that dense point cloud time series in combination with 4D-OBC extraction can be used to study causality of short-term beach dynamics.

To statistically prove the causal relations, uncover unknown causal relations, and scale up the causal analysis to all the 5,102 4D-OBCs, future work will consider correlation to multivariate sequences of causal parameters. Additionally, coastal system memory will be considered, encompassing spatial and temporal dependencies. Within a 4D-OBC, this memory dependency is already a conditioning factor; a local accumulation is part of a temporary disturbance or trend in a morphodynamic equilibrium, which is (partially) eroded away again as part of the morphodynamic adjustment. The conditional dependencies should, however, be considered in a multiscale approach, extending further than the short-term represented by the 4D-OBCs. For example, the seasonal presence or location of a berm will influence the potential of hydrodynamic forcing and the fetch length on the backshore. Thus, we will investigate the parameterization of the beach topography, as well as spatial interdependency between presence of 4D-OBCs.

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