# MONITORING OF BEACH SURFACE PROPERTIES WITH REMOTE SENSING

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## Abstract

Existing aeolian transport formulae tend to overestimate the sediment transport volumes in coastal environments. Supply limiting factors like moisture content, shell patches, sediment sorting, vegetation and morphological features are believed to explain these overestimations. These supply limitations act on a variety of spatio-temporal scales that hinder relating supply and transport. Probabilistic graphical models (PGM) can be used to cope with the variety and complexity of these relations. A long term measurement campaign is started to feed such probabilistic models with data on the complex interaction between supply limitations and their influence on coastal aeolian transport and subsequently dune growth. The variety of spatio-temporal scales involved in supply limited coastal aeolian transport generally is not fully captured by traditional measurement techniques. This campaign uses, apart from traditional in-situ techniques, remote sensing and image analysis techniques to cover a variety of spatio-temporal scales that are related to coastal aeolian transport and supply limitations in particular. We aim to construct a dataset that contains long term and high resolution grid data as well as binary time series and a variety of in-situ measurements on (local) wind forcing, beach surface properties and aeolian transport. The probabilistic graphical models will be used to consolidate the dataset towards practical instruments to model the large scale and long term (LSLT) behavior we are finally interested in.

**Keywords:** aeolian transport, supply limitations, remote sensing, moisture, sediment sorting

## 1. Introduction

Large scale and long term (LSLT) behavior of sandy coasts becomes increasingly important to safeguard the world’s low-lying areas where a large part of the world’s population is living. Especially important to LSLT behavior of beaches and dunes is the net effect of successive erosional hydraulic processes during storms and accretive aeolian processes during daily conditions. About the long term net effect of the aeolian transport processes little is known.

Aeolian transport is an important factor to coastal behavior, because it counteracts the storm surge erosion of the upper beach and dunes. Wind is a first and primary prerequisite for aeolian transport to occur. However, the properties of the beach surface are at least as important since they may act as a supply limiting factor in the aeolian transport process. Due to both hydrodynamic and aeolian processes that act on different spatio-temporal scales, the beach properties change continuously in time and space.

This paper discusses an approach to investigate the process of supply limited coastal aeolian transport using probabilistic graphical models (PGM). In contrast to a deterministic approach, these models can cope with the variety of relevant spatio-temporal scales involved in coastal aeolian transport and possibly complex relations between relevant parameters. A long term measurement campaign is introduced that provides the long term, high resolution data necessary to feed these inter-scale probabilistic models. We use remote sensing techniques to extend the coverage of the spatio-temporal scales from hours or days to multiple years and from meters to kilometers with a minimum loss of resolution. The probabilistic model approach enables us to combine modeled and observed coastal aeolian behavior, focus further research and help us extrapolate our findings towards the LSLT behavior we are finally interested in.

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## 2. Spatio-temporal scales

Research to aeolian transport started with the pioneering work of Bagnold (1954) who proposed a relation between transport rate and wind speed according to Eq. (1). The relation is only slightly adapted by other authors (e.g. Kawamura, 1951) and the third power of the wind speed remained throughout the years.

$$q \propto u_w^3 \qquad \text{Eq. (1)}$$

Studies using a Bagnold-type relation often assume wind speed to be the only time-varying parameter. Other (empirical) parameters like drag and grain size are assumed to be constant in time and space. Spatio-temporal variations due to aspects like effective beach width and tidal phase are then conceptualized by a (constant critical) fetch length (e.g. Bauer *et al.*, 2002). Based on these assumptions the only relevant spatio-temporal scales in coastal aeolian research are thus related to variations in wind speed, fetch length and transport rates.

Values for critical fetch length vary from no critical fetch at all to hundreds of meters (Davidson-Arnott *et al.*, 1990, 2005, 2008; Jackson and Cooper, 1999; Lynch *et al.* 2008). Saltation measurements often show too much scatter to obtain statistical significant correlations with instantaneous wind speed (e.g. Davidson-Arnott *et al.*, 2008, 2009). A possible explanation for this scatter, suggested already by many authors, are supply limitations. Taking supply limitations into account is likely to reduce the large uncertainties in coastal aeolian research and to improve predictive capabilities of aeolian transport models for coastal environments (e.g. Wiggs *et al.*, 2004; Bauer *et al.*, 2009; De Vries *et al.*, 2012, submitted).

In literature, moisture is the most discussed supply limiter. The variability in reported fetch lengths and the lack of statistical significance in relations between wind speed and transport rates may partly be explained by surface moisture due to its time-dependency in the order of seconds, similar to wind speed (e.g. Davidson-Arnott *et al.*, 2009). In context of large scale and long term (LSLT) coastal behavior, surface moisture also involves many larger temporal scales: on the scale of a tidal cycle it influences the inter-tidal area, most likely an important sediment source, and on the scale of days it acts through rain showers (Jackson and Nordstrom, 1998) and storm surges (Vellinga, 1986), that in turn may have a seasonal modulation as well. Van Straaten (1961) also reports a climatological modulation of surface moisture depending on precipitation and evaporation rates.

Including supply limitations in general, and surface moisture in particular, in LSLT coastal aeolian research involves a large range of (temporal) scales. And surface moisture is only one example. Other beach surface properties that act as supply limiter involve again other temporal scales, like shells (storm surges, nourishments), sediment sorting (inter-storm period), vegetation (seasons) or morphology (storm events). Similarly, a new range of spatial scales is introduced by supply limitations (Figure 1).

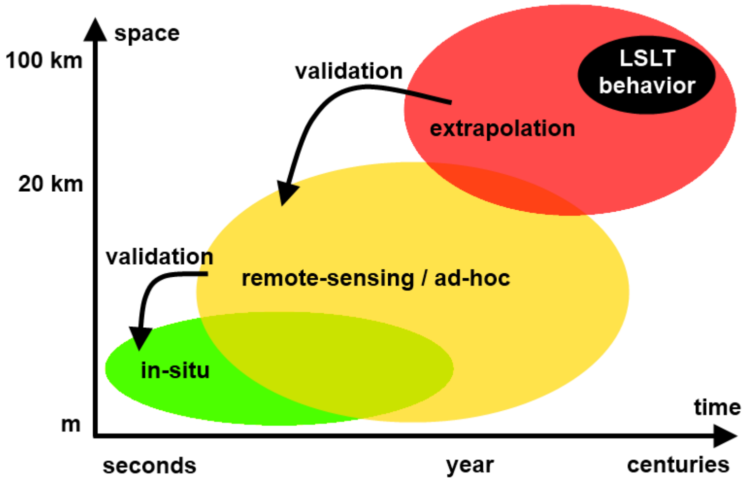


Figure 1 Relevant scales for monitoring LSLT behavior of coastal aeolian processes

Incorporating supply limitations in aeolian transport formulae is believed to be a critical step in improving the LSLT predictive capabilities of these formulae for coastal environments (De Vries *et al.*, submitted). As suggested by various authors, a deterministic approach will not be feasible with this kind of complexity across scales (e.g. Davidson-Arnott *et al.*, 2009). We propose the use of probabilistic graphical models to capture the inter-scale complexity of beach surface properties and corresponding supply limitations.

## 3. Statistical inference

Analysis of supply limited coastal aeolian transport is challenged by the variety in relevant scales and parameters and the possible complexity in relations between these scales and parameters. Probabilistic graphical models can capture this complexity. Probabilistic graphical models are data-driven models that, with a minimum of guidance, obtain statistical properties from data and provide tools to infer on these properties. The guidance only involves the specification of (assumed) dependencies. An example of such model is a Bayesian network. In a Bayesian network different nodes (properties) are connected by arrows, specifying relations between properties (Figure 2). The relations, however, are not quantified by input, but are inferred from (training) data. Bayesian networks are therefore an intuitive tool to cope with complex related data.

A trained Bayesian network provides a priori probabilities on, for example, the occurrence of aeolian transport. Predictions made by Bayesian networks naturally adapt to an increase of evidence on the situation being modeled, resulting in a posteriori probabilities. This property of such networks lines up with the increase of detail with decreasing scales. Through these networks we may obtain large scale behavior given small scale evidence, which makes it a suitable tool for modeling inter-scale behavior.

Adding evidence to Bayesian networks alters the probability density functions of the nodes. For example, without evidence the (a priori) probability that aeolian transport occurs at a given location and on a given day is 70%. When we provide the network with the evidence that it is raining, the a posteriori probability will most likely decrease. Another generic possibility with Bayesian networks is to infer on the importance of parameters with respect to each other. This means that we can ask a Bayesian network what parameters are most important to the drying of the beach, for example.

A specific type of Bayesian network is a dynamic Bayesian network where sequences are used as data. These models have the possibility to include time-dependencies and make, for example, predictions based on the weather forecast. Bayesian networks are only one example of a probabilistic graphical model. Other types of (time-dependent) models exist that can also be of use.

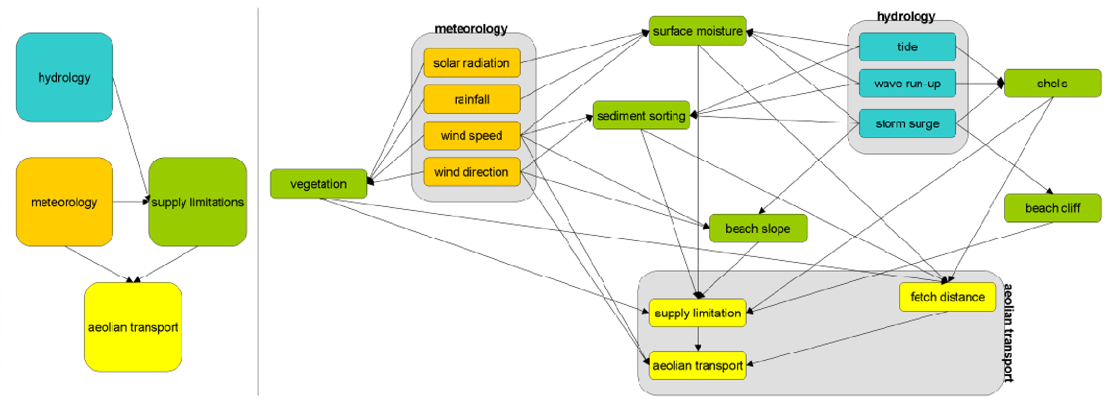


Figure 2 The global network structure for a Bayesian network on supply limited coastal aeolian transport as discussed in this paper is shown on the left. On the right, an example of an elaborated configuration is shown which may result from this research.

Ultimately, a probabilistic graphical model can be used to help us choose the supply limiting factors that we want to implement in (deterministic) coastal aeolian transport models and quantify them. The models can be easily extended with more data, more parameters, even from different disciplines. Finally, these models will be able to provide quantifications of supply limitations given data on governing parameters like meteorology, hydrology and morphology.

The extent of a probabilistic graphical model depends on the data fed to the model. The selection of appropriate parameters is an iterative process where the number of parameters (nodes) should keep pace with respect to the amount of data available to prevent under- or overfitting. In order to model inter-scale behavior we need a long term and high resolution (simultaneous) dataset that covers all relevant spatio-temporal scales (Figure 1). These data are needed for all of the nodes within the network (e.g. Figure 2). The left panel of Figure 2 shows a global network structure. This structure can be used as blueprint for the configuration of probabilistic graphical model in stages for each supply limiter. The right panel in Figure 2 shows an example of how the full network may look like after combining different supply limiters in a single network.

Recently we started an intensive monitoring campaign that is intended to cover a large part of the relevant spatio-temporal scales of the nodes depicted in Figure 2. Apart from traditional in-situ measurements, remote sensing techniques together with efficient, quickly deployable in-situ techniques will extend the reach and resolution of measurement data. In the remainder of this paper we will introduce the measurement campaign with a focus on the supply limiting beach surface properties.

## 4. Supply limitations

Coastal aeolian transport is believed often to be limited by supply of sediment. These supply limitations are related to beach surface properties. Several properties of the beach surface may hamper the ability of sediment to be transported by wind. In this paper, we refer to this phenomenon as armoring. The number of beach surface properties that armor the beach can be, depending on the definition, large, but fall apart in three main categories (Table 1).

Table 1 Three categories of supply limiting beach surface properties with examples and corresponding spatio-temporal scales. Examples marked with an asterix (*) are not taken into account in this research.

| **Category** | **Supply limiter** | **Temporal scale** | **Spatial scale / Area of influence** |
|---|---|---|---|
| Cohesives | Moisture | tide, rain shower or storm surge | inter-tidal area, beach and dunes |
| | Vegetation | seasons | dunes |
| | Organic material (e.g. benthos)* | - | - |
| Covers | Sediment sorting | inter-storm period | dry beach |
| | Shells | storm event or nourishments | high-waterline, entire beach in nourished areas |
| | Waste* | - | - |
| Morphological features | Beach slope | storm event, nourishments | beach |
| | Beach cliffs | storm event | beach |
| | Ripples | inter-storm period | inter-tidal area, beach |
| | Tire tracks | inter-storm period | beach |

Some of the beach surface properties that are taken into account in this research are briefly discussed in the following subsections with a focus on the spatio-temporal scales related to these properties. In the next section, the monitoring of these beach surface properties across scales is discussed together with the study area and the monitoring of (net) sediment transport rates.

### *4.1. Moisture content*

The threshold for motion for moist sediments is generally larger than for dry sediments due to cohesive and capillary effects. Also the saltation cascade may be influenced by moist when the (already limited number of) particles that are entrained become less effective in ejecting other particles from the bed. Many reports are available that emphasize the importance of moist in aeolian transport quantification (Davidson-Arnott *et al.*, 2009; Bauer *et al.*, 2009; De Vries *et al.*, 2012, submitted). Moisture content is a highly volatile supply limiter to aeolian transport due to complex relations between wind speed and direction, solar radiation, tide, rainfall and morphology (Figure 3; Davidson-Arnott *et al.*, 2009).

Figure 3 Patchy moist beach surface near *Vluchtenburg* uncovered due to aeolian transport processes

The main processes that increase the moist content in coastal environments are the tide and wave run-up, rain showers and ground water. Only incidentally, storm surges increase the moist content at beaches. The most important processes that decrease the moist content in these environments are solar radiation and wind, that both reduce the moist content through evaporation.

The spatio-temporal scales of the moist increasing processes are fairly large and reasonably predictable. Regarding the tide and wave run-up the governing temporal scale is a tidal cycle and the spatial scale is limited to the inter-tidal area in daily conditions. The rain showers act on a temporal scale of hours to days, but may have a seasonal scale depending on the location, and influence the entire beach and dune area quite uniformly. Storm surges act on a similar spatial scale, but have typical temporal scales of days and may modulate over seasons and even decades (Van Straaten, 1961). The scales related to the phenomena that decrease moist content are less predictable and act on a variety of spatio-temporal scales. Highly variable (local) wind conditions, also related to local differences in morphology, make the drying of the beach a short term process. On the contrary, solar radiation may add another low frequency and alternating mode to the very same process. Another complexity is that processes that increase and decrease moist content are likely to be related: solar radiation is generally limited during rain fall, while wind speeds are generally higher during storm conditions.

### *4.2. Shells*

Shells or shell fragments provide a shelter to sediments that are otherwise susceptible for aeolian transport. Like moisture, also shells hamper the saltation cascade due to this shelter. Patches of shells are often found around the high-water line (Van der Wal, 2000), which might be a crucial location in the aeolian sediment process since it separates the inter-tidal area from the beach. It is likely that the inter-tidal area is a main source of sediment for dune growth (De Vries, submitted). It is unknown what the influence of a shell patch is near the high-water line.

Shells are also often abundant in nourished areas (Van der Wal, 2000). In these cases it is expected that shells hamper the morphological behavior of the nourished area in general by reducing the erosion rate with increasing erosion. In either case shell patches are relatively stagnant and may act on large spatio-temporal scales. Storm events are likely to play an important role in the dynamics of shell patches.

### *4.3. Sediment sorting*

The grain size distribution in the top layer of a beach exposed to wind will change in time. Small grains will typically be transported first, leaving the large grains behind: the lag deposits (Van der Wal, 2000). Therefore the beach surface becomes coarser and the threshold for motion increases. The relatively coarse top layer of the beach provides a shelter to other grains similar to shells, although the supply limiting behavior will be less stringent.

Storm surges act as a reset mechanism for the sorting of beach sediments (Van der Wal, 2000; De Vries, submitted), explaining the increase of aeolian transport after a storm surge as reported in literature (e.g. Pye *et al.*, 2008). Little is known on the temporal scales in which sediment sorting settles toward a situation of maximum transport limitation in the field and what parameters are most important (e.g. grading, $D_{50}$). It is likely that local differences, possibly induced by morphological features, provide a spatial dependency as well. In calm periods, sediment sorting may lead to an almost static beach that is mobilized only after a significant storm surge (De Vries, submitted).

### *4.4. Morphological features*

Also morphological features play a role in limiting sediment transport by wind. Beach slope is a relatively known beach property that largely influences the sediment transport (De Vries, 2012), but also the existence of beach cliffs might be important. Beach cliffs are related to erosion of the beach and act as a physical boundary between the beach part remobilized due to a sediment reset on the seaward side and the still (relatively) static part on the landward side (Figure 4). The result is likely to be a considerable smaller sediment transport towards the dune compared to a situation where the cliff is absent.

Figure 4 Quadbike near beach cliff at *SandMotor*

### *4.5. Other types of armoring*

The above mentioned types of armoring are only a selection of the beach surface properties that influence the coastal aeolian sediment transport. Beach characteristics related to beach use, like the construction of terraces, tire tracks, waste are likely to hamper sediment transport. In the dune area dense vegetation acts as supply limiter and catchment for saltating sediments. It is expected that the four types of armoring mentioned above provide a good representation of the three main categories of armoring in Table 1 and that other types of armoring fit in these main categories as well.

## 5. Monitoring

An intensive and long term monitoring campaign is started to provide insight in the complex relations between wind, aeolian transport and a variety of supply limiting factors as mentioned in the previous section. In order to capture all relevant spatio-temporal scales, remote sensing techniques in combination with in-situ measurements are used to obtain the necessary long term and high resolution data. In the following, the monitoring of traditional parameters in aeolian research like wind speed and direction and transport rates are treated separately from the monitoring of beach surface properties. The main reason is that for the latter state-of-the-art remote sensing techniques are available and discussed, while for the former traditional in-situ measurements are used.

### *5.1. Study area*

The study area for the long term monitoring campaign covers almost 20km of the Holland coast in The Netherlands (Figure 5). It runs from the southern location *Hoek van Holland* to the northern location *Scheveningen*. The beach stretch is at both sides closed by large jetties and two harbor entrances. It has a dune system over the entire length. Several special coastal features are present along this stretch:

**Vluchtenburg** As compensation for the loss of natural environment after building the latest extension of the Rotterdam harbor (*Maasvlakte 2*) an artificial new dune ridge seaward of the old dune ridge has been constructed near *Vluchtenburg*. The dune ridges are separated by a dune valley. The entire area is supposed to naturally evolve towards a dynamic equilibrium. The dune valley is expected to lower, while new dunes are expected to grow due to aeolian processes.

**SandMotor** A few kilometers south of *Kijkduin*, a mega-nourishment of over 20Mm$^3$ called the *SandMotor* is constructed in 2011 (Figure 6). The nourishment replaces many regular nourishments along the Holland coast and is supposed to feed the Holland coast with sediments in a more natural and environmentally friendly way. The construction of the *SandMotor* is accompanied by an intensive and long term measurement campaign that monitors the bathymetric and topological evolution of the nourished area.


Figure 5 Overview of study area with most important locations (source: Google Maps)


Figure 6 *SandMotor* seen from *Kijkduin* with a detailed view on the Argus station (source: Rijkswaterstaat)

The study area is currently equipped with 3 Argus camera stations at *Vluchtenburg*, *SandMotor* (Figure 6) and *Kijkduin* and more are planned. The *Kijkduin* station also has a thermal infra-red camera pointed to the beach and inter-tidal area. The *SandMotor* station has two pan-tilt cameras that can be used to monitor the dry area of the mega-nourishment. X-band radar is available near the *Kijkduin* Argus startion.

The area around the *SandMotor* until *Kijkduin* is being monitored extensively in the last few years (monthly) and is continued to be monitored for the coming years (2 monthly). The monitoring includes bathymetric and topographic surveys in a dense grid resolution of about 20m. 6 months LiDAR flights cover the dune and beach area of the entire beach stretch. Many more monitoring campaigns on, for example, ecology, water management and swimmer safety are currently running as well.

### *5.2. Sediment transport rates and wind speed*

Sediment transport rates and (local) wind speed are primary parameters of interest for an aeolian monitoring campaign. Both parameters fluctuate on very small spatio-temporal scales and are only weakly correlated in coastal environments (Davidson-Arnott *et al.*, 2009). No feasible remote sensing techniques are nowadays available to monitor these parameters. Frequent in-situ measurements will therefore remain a necessity also for the remote sensing campaign discussed. It is intended to run a (semi-)continuous measurement campaign of beach surface properties and frequently complement these measurements with short term in-situ measurements on sediment transport rates using saltiphones and local wind speed and direction using local anemometers. In-situ measurements can be planned more efficiently when knowledge on the relations between beach surface properties, meteorology and aeolian transport rates increases.

An alternative approach, that will be used as well, is not to monitor instantaneous sediment transport rates, but monitor net sediment transport rates through sediment volume measurements. A possible drawback of this approach is that the frequency of the volume measurements provides a lower bound of the temporal scale that is covered by the measurements. The 6 months LiDAR flights are likely not to provide the necessary temporal resolution to be useful with the high resolution beach surface property measurements. The monthly or 2 monthly topographic measurements do not cover the dune area and therefore are most likely to miss an important sediment sink. For now, it is intended to expand these monthly measurements using traditional GPS systems that can be deployed event based in the dunes. Other measurement techniques are still under consideration, for example terrestrial laser scanning measurements.

### *5.3. Beach surface properties*

Beach surface properties are monitored using remote sensing techniques that fulfill the need for long term and high resolution measurements. All remote sensing techniques used in this study are based on analysis of coastal images obtained from Argus stations (Holman and Stanley, 2007). Besides, in-situ imaging techniques and corresponding analysis are used to efficiently and ad-hoc monitor the small scale phenomena important to coastal aeolian transport. Traditional in-situ techniques are also used to validate data obtained from the variety of coastal images.

#### *5.3.1. Coastal imaging techniques*

Remote sensing techniques enable us to monitor continuously and across different spatio-temporal scales. In this study, we focus on the use of Argus images and analysis techniques obtained from the discipline of *computer vision*.

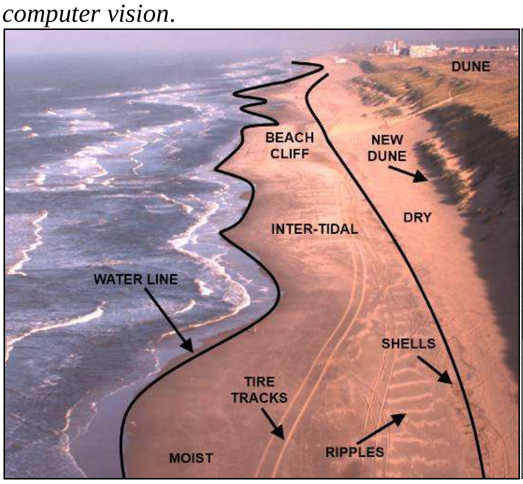


Figure 7 Argus image from *Egmond* (outside study area) with a variety of visible features

Figure 8 Example of a coastal infra-red view of *Kijkduin*

The Argus stations that are currently operational in the study area have 6 to 8 cameras each. Argus stations are traditionally used to monitor nearshore bathymetries and alongshore currents, either in the surfzone or the inter-tidal area. Recently, applications like for vegetation growth and rip-current detection are developed and new applications for aeolian research are being explored (Schretlen and Wijnberg, 2012).

Images obtained from Argus stations also cover almost the entire beach and large parts of the dune. Scrolling through the huge image collection already available many interesting features to aeolian research are visible on these images (Figure 7). Many are related to supply limitations, for example:

- Moist
- Dry beach
- Shell patches
- Vegetation
- Aeolian ripples
- Sand streamers
- Beach cliffs
- Tire tracks

These features are being recorded by Argus systems for over 10 years now (at some locations) and with an interval of a maximum of 30 minutes. Together with spatial scales of meters to kilometers it makes the coverage of scales of the Argus dataset unprecedented. Image analysis techniques provide ways to extract these features and the scales they involve.

The current Argus station at Kijkduin is recently extended with a thermal infra-red camera (Figure 8) for remote monitoring of beach surface moisture. First results show a signal in the inter-tidal area related to moisture and subsequently to tide, periods of rain, periods of drying and storm surges. Other features like a very distinct water line, tire tracks, reworked beach surfaces, vegetation and people are also clearly visible on these images. The signal is available day and night.

Soil moisture and temperature probes are placed in field of view of the infra-red camera in order to calibrate and validate the remote sensing measurements on surface moisture content by temperature from these cameras.

Macro photography is an in-situ photography technique that uses macro lenses to obtain detailed images of, for example, the beach surface. Macro photography is used to expand the dataset on beach surface properties towards smaller spatial scales. Using macro photographs of the beach surface and image analysis techniques, estimates can be made of the grain size distribution (Buscombe *et al.*, 2010, submitted; Rubin *et al.*, 2004). Macro photography has two major advantages over traditional grain size measuring techniques: only the top layer of the beach is monitored, which is most interesting for aeolian research, and the method is more efficient, which makes it possible to obtain high resolution datasets in both time and space.

Next to grain size estimates, estimates of the shell density can be made based on photographs. Where remote sensing techniques will mostly be used to locate shell patches, in-situ techniques are necessary to get a grip on the density of these patches.

Figure 9 Example of an image segmentation result: original image (left), division into 200 superpixels with colors averaged based on original image (right)

### 5.3.2. *Image analysis techniques*

Collected coastal images by itself do not provide the necessary quantification of coastal aeolian processes. Image analysis techniques are used to extract useful characteristics from the collected (unrectified) image sequences. In case of the Argus and infra-red images discussed, images are analyzed using classification algorithms. Two types of classification are mainly of interest:

- Segmentation
- Pattern recognition

Segmentation is the classification of individual pixels within an image or a sequence of images. Segmentation generally results in continuous time series of properties like the instantaneous water line, dune foot, wet surface and vegetated surface. Besides, segmentation simplifies image analysis from the analysis of millions of pixels to hundreds of so-called *superpixels*.

Pattern recognition classifies images as a whole. Pattern recognition generally results in binary time series of events like storm surges, the existence of aeolian ripples and beach use.

The Argus and infra-red images provide a static view on the area of interest. These views are generally fairly constant in terms of visible subjects, coloring and composition. Also, the features that we are interested in are generally distinct (Figure 7). These properties make these images particularly suitable for these types of automated classification algorithms. Both types of classification are explained in the following.

Segmentation

We can divide Argus images in a sky, sea, beach and dune part. Also, within the sea we can separate the surfzone from deeper water. Similarly, within the beach we can separate the inter-tidal zone from shells and dry beaches. Dividing an image in such segments is called segmentation. Basic segmentation algorithms are based on classification algorithms (e.g. K-means, Achanta *et al.*, 2010) that classify pixels according to location in the image (u and v coordinates) and pixel intensities. Classification of pixels results in clusters of pixels called *superpixels* (Figure 9**Erreur ! Source du renvoi introuvable.**, Achanta *et al.*, 2010). Pixel characteristics, like location and intensity, within a superpixel can be used to classify the pixel to be sky, sea, beach or dune (see also Aarninkhof, 2003).

The performance of segmentation algorithms can be improved by adding more information. When dealing with a sequence of images, like with the Argus dataset, pixel intensities can be tracked in time. The temporal information can also be used to cluster the pixels. In this case we obtain *supervoxels* rather than superpixels. The categories of neighboring superpixels or –voxels can also be used to improve the performance of segmentation algorithms since in many cases the probability of a superpixel or –voxel to be in a given category depends on the category of its neighbors.

Having rectified the Argus images, segmentation gives us several continuous time series, like the instantaneous water line, run-up level, fetch lengths and the location of shell patches. Moreover, it simplifies the challenge of image analysis from analyzing millions pixels to tens to hundreds of pixels and gives us the ability to focus subsequent algorithms on specific parts of an image only.

Pattern recognition

Apart from classification of pixels within an image or a sequence of images, images can also be classified as a whole, based on pattern recognition. Images can be categorized depending on whether certain patterns are present or not, for example the existence of aeolian ripples, sand streamers, beach cliffs, tire tracks or high water (Figure 7). Segmentation of images can be of use to focus pattern recognition to certain areas of the image. After all, aeolian ripples will not be found in the sky or in sea.

The pattern recognition algorithm is fed with a certain amount of images where the pattern of interest is visible and a similar amount of images where it is not. This collection of images is called the training dataset. A generic method is then to use *cascade classification* to make a generic fingerprint of the pattern (Viola and Jones, 2001). A second dataset is then used to see whether the images with the patterns present are recognized. This is the validation or test dataset. If the classification of the validation dataset is successful, the algorithm can be applied to the entire Argus dataset; otherwise the training dataset needs to be extended.

Categorizing images based on visible patterns result in a variety of binary time series, for example: a time series where the water reached the dune foot, a time series where the entire beach was moist or a time series where aeolian transport is visible.

### *5.3.3. In-situ calibration and validation*

Although remote sensing techniques potentially have many advantages over in-situ techniques, there will always be a need for in-situ techniques to calibrate and validate the remote sensing results. Traditional sieving of physical sediment samples will be used to validate the grain size estimates obtained from macro photography, for example. Similarly, in-situ soil moisture and temperature probes will be used to validate and calibrate the infra-red images.

Simple GPS measurements may validate Argus image analysis results by simply measuring instantaneous locations of water line, inter-tidal area, shell patches, beach cliffs and vegetation. In-situ investigation of the composition of beach ripples may tell us more about the source and driving forces.

### *5.4. Meteorology and hydrology*

Meteorology and hydrology provide the boundary conditions for coastal aeolian transport. These conditions will be monitored continuously through a meteorological station at the *SandMotor*. The station will perform solar radiation and rainfall measurements to determine evaporation rates. It will also measure wind profiles and directions. Water levels and wave heights are measured near *Hoek van Holland* and *Scheveningen*.

## 6. Concluding remarks

Probabilistic graphical models can be used to cope with the variety and complexity of the inter-scale relations between supply limitations and coastal aeolian transport. A long term measurement campaign is started to feed such model. This campaign uses, apart from traditional in-situ techniques, state-of-the-art remote sensing and image analysis techniques to cover a variety of spatio-temporal scales that are related to coastal aeolian transport and supply limitations in particular. We aim to construct a dataset that contains long term and high resolution on (local) wind forcing, beach surface properties and aeolian transport. Ultimately, the probabilistic graphical models will be used to consolidate the dataset towards practical instruments to model the large scale and long term (LSLT) behavior we are finally interested in.

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## References

Aarninkhof, S. G. J., Turner, I. L., T, D. T. D., Caljouw, M., and Nipius, L. (2003). A video-based technique for mapping intertidal beach bathymetry. *Coastal Engineering*, 49(4):275–289.

Achanta, R., Shaji, A., Smith, K., Lucchi, A., Fua, P., and Süsstrunk, S. (2010). Slic superpixels. Technical Report 149300, EPFL.

Bagnold, R. A. (1954). Experiments on a Gravity-Free Dispersion of Large Solid Spheres in a Newtonian Fluid under Shear. In *Proceedings of the Royal Society of London. Series A: Mathematical and Physical Sciences*, volume 225, pages 49–63. The Royal Society.

Bauer, B. O., Davidson-Arnott, R. G. D. (2002). A general framework for modeling sediment supply to coastal dunes including wind angle, beach geometry, and fetch effects. *Geomorphology*, 49:89–108.

Bauer, B. O., Davidson-Arnott, R. G. D., Hesp, P. A., Namikas, S. L., Ollerhead, J., and Walker, I. J. (2009). Aeolian sediment transport on a beach: Surface moisture, wind fetch, and mean transport. *Geomorphology*, 105(1–2):106–116.

Buscombe, D., Rubin, D. M., and Warrick, J. A. (2010). A universal approximation of grain size from images of noncohesive sediment. *Journal of Geophyiscal Research*, 115.

Buscombe, D. (2013). Transferable wavelet method for grain size-distribution from images of sediment surfaces and thin sections, and other natural granular patterns. *Sedimentology*. In press.

Davidson-Arnott, R. G. D., MacQuarrie, K., and Aagaard, T. (2005). The effect of wind gusts, moisture content and fetch length on sand transport on a beach. *Geomorphology*, 68(1-2):115–129.

Davidson-Arnott, R. G. D., Yang, Y., Ollerhead, J., Hesp, P. A., and Walker, I. J. (2008). The effects of surface moisture on aeolian sediment transport threshold and mass flux on a beach. *Earth Surface Processes and Landforms*, 33(1):55–74.

Davidson-Arnott, R. G. D. and Bauer, B. O. (2009). Aeolian sediment transport on a beach: Thresholds, intermittency, and high frequency variability. *Geomorphology*, 105:117–126.

Holman, R. A. and Stanley, J. (2007). The history and technical capabilities of Argus. *Coastal Engineering*, 54(6-7):477–491. The CoastView Project: Developing coastal video monitoring systems in support of coastal zone management.

Jackson, N. L. and Nordstrom, K. F. (1998). Aeolian transport of sediment on a beach during and after rainfall, Wildwood, NJ, USA. *Geomorphology*, 22(2):151–157.

Jackson, D. W. T. and Cooper, J. A. G. (1999). Beach fetch distance and aeolian sediment transport. *Sedimentology*, 46(3):517–522.

Kawamura (1951). Study on sand movement by wind. In *Reports of Physical Sciences Research Institute of Tokyo University*, volume 5, pages 95–112.

Lynch, K., Jackson, D. W. T., and Cooper, J. A. G. (2008). Aeolian fetch distance and secondary airflow effects: the influence of micro-scale variables on meso-scale foredune development. *Earth Surface Processes and Landforms*, 33(7):991–1005.

Pye, K. and Blott, S.J. (2008). Decadal-scale variation in dune erosion and accretion rates: An investigation of the significance of changing storm tide frequency and magnitude on the Sefton coast, UK. *Geomorphology*, 102:652-666.

Rubin, D. M. (2004). A simple autocorrelation algorithm for determining grain size from digital images of sediment. *Journal of Sedimentary Research*, 74(1):160–165.

Schretlen, J. L. M., Wijnberg, K. M. (2012), Argus video imagery in support of aeolian transport studies: an exploratory study at Vlugtenburg beach. Report Ecoshape/Building with Nature, workpackage HK 3.2, 61 pp.

van Straaten, L. M. J. U. (1961). Directional effects of winds, waves and currents along the Dutch North Sea coast. *Geologie en Mijnbouw*, 40(2):363-391.

Vellinga, P. (1986). *Beach and Dune Erosion during Storm Surges*. PhD thesis, Delft University of Technology, Delft, The Netherlands. Also published as: Delft Hydraulics communications, no. 372, 1986.

Viola, P. and Jones, M. (2001). Rapid object detection using a boosted cascade of simple features. In *Conference on Computer Vision and Pattern Recognition*.

de Vries, S., Southgate, H. N., Kanning, W., and Ranasinghe, R. (2012). Dune behavior and aeolian transport on decadal timescales. *Coastal Engineering*, 67:41–53.

de Vries, S., Arens, S. M., de Schipper, M. A., and Ranasinghe, R. (2013a). Aeolian sediment transport in supply limited situations Part II; An analysis on field data. *Aeolian Research*. In preparation.

de Vries, S., van Thiel de Vries, J. S. M., Van Rijn, L. C., Arens, S.M., and Ranasinghe, R.. A numerical implementation of aeolian sediment transport in supply limited situations. Submitted to *Aeolian Research*.

van der Wal, D. (2000). Grain-size-selective aeolian sand transport on a nourished beach. *Journal of Coastal Research*, 16(3):896–908.

Wiggs, G. F. S., Baird, A. J., and Atherton, R. J. (2004). The dynamic effects of moisture on the entrainment and transport of sand by wind. *Geomorphology*, 59(1-4):13–30.