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Mapping mud content and median grain-size of North Sea sediments – A geostatistical approach

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ABSTRACT

Sediment grain size is well known for its influence on biogeophysical processes and hence, grain size parameter maps, important elements in an integrated ecological modelling strategy. In this study, a large database was compiled from legacy data on grain size parameters and distributions in North Sea surface sediments. The database was analysed by means of non-linear regression to enable a consistent quantification of various grain size parameters. In a second step, multivariate geostatistics (kriging) were employed to predict the spatial distribution of percentage mud content and median grain size in the North Sea with a resolution of 1 × 1 nautical miles. The results show that incorporation of secondary information in the interpolation led to a physically more realistic representation of large-scale patterns compared to deterministic approaches. An evaluation of map confidence, however, suggests only minor differences in the quality obtained by different kriging techniques. It appears that the data density and distribution are not an issue when it comes to performance. Instead, insufficient metadata constrain the assessment and harmonisation of data sets and introduce uncertainty into the predictions.

1. Introduction

Marine sediments are mixtures of grains of varying sizes. Clearly, these mixtures cannot be fully characterised by means of a single parameter or proxy. Any such attempt is a compromise between the representation of certain properties and loss of information on the true nature of the seabed. As spatial databases with complete descriptions of grain size distributions become increasingly available to researchers in marine environmental sciences, a simplified representation of sediment texture is no longer the only possible option. Instead, the data offers opportunities to calculate and map any primary or secondary grain size parameters. These include categorical and continuous variables derived from the conversion of grain size measurements into sediment classes (Wentworth, 1922; Folk, 1954; Shepard, 1954; Flemming, 2000) or parameter inferred from statistical operations on cumulative-frequency curves, respectively (Krumbein, 1936; Folk, 1954). While categorical approaches to sediment characterisation play a role in almost every broad-scale habitat classification (Harris, 2012a), quantitative measures may be more meaningful to surrogate-based mapping of species occurrence (Coggan et al., 2012; Harris, 2012b) geomechanical properties and sediment transport (Soulsby, 1997; Goff et al., 2004; Wilson et al., 2008) and biogeochemical variables (Wiesner et al., 1990).

A well-known obstacle when assembling grain size data is the inconsistency between data sets that arise from different standards for sampling, analytical processing and interpretation (Van Heteren and Van Lancker, 2015). Such lack of harmonisation is most often observed across national borders, but usually not apparent until the data is visualised. An attempt to improve on this issue is the European Marine Observation and Data Network (EMODnet) launched by the European Commission in response to the requirements of future maritime policy. However, the aim to integrate numerous classification schemes across Europe constrains the informative value of the harmonised products, with broad classifications being the likely outcome (Long, 2006), rather than gridded representations of quantities (Stephens et al., 2011). This situation is somewhat unsatisfying, especially if one considers that compilations of full grain size distributions offer more flexibility in calculating and mapping different parameters consistently and on demand.

One of the first studies that used information on grain size parameters to produce regional seabed-sediment maps was Figge (1981) who added percentage mud to the sediment types of the Folk classification scheme, thus modifying the original sediment map of the German Bight. Later on, Tauber and Lemke (1995) further accounted for sorting as a modifier to map the sediment distribution in the western

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Baltic Sea. More recent studies on mapping sediment properties in the North Sea also employ stochastic models to predict the spatial distribution of grain size parameters at local and regional scales (Verfaillie et al., 2006; Stephens et al., 2011; Stephens and Diesing, 2015). This kind of interpolation not only estimates the target variable at unsampled locations but also quantifies the remaining uncertainty. Often it involves the use of auxiliary predictors obtained from, for example, high-resolution Digital Elevation Models (DEMs), acoustic soundings and optical remote sensing.

Among the vast array of stochastic models, kriging in its various forms (Goovaerts, 1997) has become one of the most popular methods to predict sedimentological parameters (e.g., Verfaillie et al., 2006, 2009; Goff et al., 2008; Lark et al., 2012; Jerosch, 2013). One advantage of kriging is that the underlying model considers spatial autocorrelation (i.e., the statistical relationships between neighbouring observations) when calculating prediction and variance surfaces. Moreover, noise inherent to the data can be parameterised as part of the model. This places less confidence in individual observations while emphasizing the overall spatial trend that is critical to broad-scale mapping applications.

The aim of this study was to demonstrate whether or not it is feasible to predict sediment characteristics across an area as large as the North Sea using legacy grain size data and bathymetry as an environmental predictor. To achieve this, we employed kriging with external drift (KED) to interpolate estimates on relative proportions of the grain size fraction < 63 μm (or $\text{mud}_{\%}$) and median grain size (or D_{50}) in surface sediments. Apart from presenting seamless map layers of both grain size parameters, issues with respect to collation and harmonisation are discussed.

2. Material and methods

2.1. Study area

Our study area enclosed most of the North Sea between approximately 4°W to 12°E and 51°N to 61°N (Fig. 1). For predictive mapping, we superimposed a grid with a resolution of 1 × 1 nautical miles. We excluded the Kattegat, the Orkney and Shetland archipelagos, the Wash, the back barrier tidal flats of the Wadden Sea Islands as well as to firths, fjords and estuaries. These regions were either sparsely covered by the available data or poorly resolved by the grid.

The seafloor topography divides the study area (roughly along the line from Flamborough Head to Cape Skagen) into a deeper northern part, where water depth usually exceeds 60 m, and a shallow southern part (Fig. 1). The northern part is morphologically dominated by Fladen Ground and the Norwegian Channel. Glacially sculpted features such as the Dogger Bank and Oyster Grounds, and younger, tidally generated, elongated sand banks (e.g., Norfolk Banks, Flemish Banks) are prominent features in the southern part. Present-day changes of water depths in the North Sea are mainly driven by moving sand waves (Wright, 1992). The effects are evident in nearshore zones (Heyer and Schrottke, 2013) and within the error margin of bathymetric soundings (± 20 cm) elsewhere (de Haas et al., 1996). Noticeable exceptions are confined areas where aggregate extraction, dumping and dredging can change the seafloor topography significantly (Wienberg et al., 2004).

The large-scale distribution of surface sediments in the North Sea mainly results from the glacial deposition and later abrasion of siliciclastic debris that has been redistributed by currents and waves. Today, it can be regarded as a dynamic equilibrium between external input, erosion, deposition and export (Mason, 2012). In areas where erosion dominates over deposition the seabed usually consists of coarse sediments that show a high spatial variability. Otherwise, grain size is rather uniform across areas that are covered with fine sediments or migrating bed forms. In general, higher mud contents are found in deeper parts of the northern North Sea such as Fladen Ground and the Norwegian Channel, where the bed shear stress is reduced (for a description of bed shear stress see Supplementary material Fig. S1). Exceptions are wide sandy patches whose existence indicates low suspended matter input as an additional driver of sediment composition (Pohlmann and Puls, 1994). In the southern North Sea, the mud content is usually low (< 1%) but can exceed 8% in areas where lower bed shear stress allows deposition of fine material or where clayey geological substratum prevails. Only a few spots show exceptionally high mud contents. This has been attributed to the local accumulation of suspended matter from external sources (Fettweis and Van den Eynde, 2003). According to Eisma (2009), such supply from cliff erosion, river input and adjacent seas plays a significant role in the mud budget of the North Sea. In contrast, the North Sea receives only little amounts of sand and gravel. However, gravel (grain size fraction > 2000 μm) may dominate the seabed in areas affected by cliff erosion. Highest gravel contents are found off the southeast coast of England, where currents velocities of > 1.5 m/s (at spring tide) generate the strongest bed shear stress in the entire North Sea (Fig. S1).

2.2. Data collection

Raw data on sediment grain size distributions originate from over 100 individual data sets that have been compiled from various sources (cp. Supplementary material Table S1). The resulting database holds information on grain size parameters from > 40,000 seabed samples collected between the early 1960s and 2010. Not included were measurements in close vicinity to dumped dredging spoils, sand excavation pits and oil platforms. Sample density equals about 1 observation per 17 km^2. The spatial distribution, however, is not uniform with some areas such as the German Bight being more densely covered than others (see Supplementary material Fig. S2 for an overview of the geographic sample distribution). This clustering is unproblematic for prediction but even beneficial when it comes to the modelling of patchiness at smaller spatial scales.

We used water depth as the only external predictor in this study. Data was gained from a Digital Elevation Model (DEM) that derives from a combination of the GEBCO_08 grid and > 60 high-resolution data sets of bathymetric soundings (W. Puls, unpublished data). The DEM resolution increases from 50 m in nearshore zones to 400 m in the open North Sea. We resampled the DEM on the 1 by 1 nautical mile (nm) prediction grid before water depth was queried at each sediment sample position. In some areas, this resolution was not sufficient to resolve the small scale variability of prevailing bed forms such as sand ripples and dunes. At this point, we also must not forget to state that bed shear stress (Fig. S1) showed a significantly stronger relationship with $\text{mud}_{\%}$ compared to water depth. This is not really surprising given that bed shear stress is directly responsible for sediment transport and erosion (Soulsby, 1997). Nevertheless, we decided to use water depth, let's say as a proxy variable, mainly because the quantification of bed shear stress is not independent of sediment grain size distribution but a function of D_{50}. Moreover, the modelled bed shear stress data was not available in high resolution but only on a 7 by 7 km grid, and their spatial extent was limited to the area south of 59.5°N.

2.3. Parameter estimation and data manipulation

When reported, we preferably used the $\text{mud}_{\%}$ and D_{50} values of a sample, which was the case in 79% and 17% of the data sets, respectably. If not available, the values were approximated according to the approach described in Bobertz (2000), formerly developed by Tauber (1995). Therefore, we fitted a logistic function to the cumulative grain size frequency curve: $F(\phi) = [1 + \exp(-1.7(\phi - D_{50}) / (so - sk \times \tanh(\phi - D_{50})))]^{-1}$, where ϕ is the mass percentage of a grain size fraction on the Wentworth scale, D_{50} the median grain size, so the sorting and sk the skewness parameters. The estimates are valid for $so > sk \times \tanh(\phi - D_{50})$. For $so \leq sk \times \tanh(\phi - D_{50})$, $F(\phi) = 1$ if $sk > 0$ and $F(\phi) = 0$ if $sk < 0$. The estimated parameters are largely