

GIS AND MAPPING OF MOVING MARINE SAND DUNES

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ABSTRACT:

The objective of works on sand dune dynamics, is to predict the evolution of the seafloor and to precisely determine the optimum recurrence for re-surveying these area because mobile dunes represent a serious threat for navigation safety. Horizontal dune displacements could be superior of 20 meters/year and vertical variations could vary by one metre in some weeks. Therefore a project on marine sand dune has been initiated. This paper present a new GIS on marine sand banks and sand dunes of the French continental shelf and a plan for new maps to show these bedforms and their historical movements.

Like in deserts and rivers, seas contain dunes. Tide, weather and climate have a decisive role on these bedforms and their movements bring about problems for hydrographic offices because they entail to resurvey sea floor to guarantee safety of navigation. The objectives of our works are to answer to some questions about the time between hydrographic survey and the representation of dunes on charts. In parallel with research on numerical modelling of dune dynamics, we develop a GIS which is the synthesis of knowledge from some decades of surveys. This system is used to compare the knowledge of bedforms with charts, to modify the surveying strategy, to look at the historical movement of the dunes and to develop new cartographical products. By their shape, dunes therefore reflect hydrodynamic conditions. Dunes are sedimentary ripples, often periodical, featuring a crest, a gentle slope and a steep slope. The orientation of their crests is generally perpendicular to the main direction of currents. Marine sand dunes with linear crests have the slowest migration velocity at the opposite, barchan dunes can reach an annual mean displacement up to 70m/y. All dunes do not exhibit a simple morphology, they could be isolated, aggregated and/or superimposed. The most important marine bedforms are sand banks which are more large and more stable, so they are potentially less dangerous, but they often present superimposed dunes. The other two cases are isolated dunes which are more rapid and field of dunes.

On charts, it is not easy to see the presence of bedforms. It could be infer by the mariner from the symbol of mobile seabed or from indentations of isobaths. In fact there is a great difference between the knowledge from surveys, and the representation on chart. We created a GIS on sand dunes and sand banks. The principal advantage of it, is to have the possibility of viewing the evolution of the dune along the time. The other progress is to know every parameter of each dune for each step of its evolution. The comparison of movements of dunes with charts is used to decide a new survey and/or a new edition of the chart. The GIS is also used to define the limits and characteristics of dune field along the time. These works concern the safety of navigation but also fishing, sand mining, mine burial, wind farm, ... Charts are not adapted to these needs. We present a master of a new map which show limits of bedforms, the position and height of crests and a vector to show the mean direction and the mean annual speed of movements.

1 INTRODUCTION

The ubiquity of dunes is established. Dunes exist in deserts and from rivers to the basis of the continental slope; similar shapes seem detectable in deep ocean environment and on Mars. Their movements bring about problems for hydrographic offices because they entail to resurvey sea floor to guarantee safety of navigation. Tide, weather and climate have a decisive role on sedimentary dynamics. Studying sand dunes should not be limited to instantaneous processes such as swell and tides but should also integrate event-related processes (storms). Thanks to the high resolution of multi-beam echo sounders (MES), it has been possible to increase the morphological accuracy. However the question is for how long (how many week, months or years) can the morphology of a dune be estimated as in conformity with the hydrographic survey? Are charts in agreement with the complex morphology of field of dunes? Can new dunes emerge between two successive hydrographic soundings? If so, for how long can we have the guarantee that no new dune will appear? To answer to these questions, studies and numerical models are done. At the same time, we develop a GIS which is the synthesis of knowledge from some decades of surveys from hydrographic office and research laboratories. This system is used to compare the knowledge of these bedforms with charts, to modify the surveying strategy, to look at the historical movement of the dunes and to develop new cartographical products.

2 AN ASSESSMENT OF THE PRESENT KNOWLEDGE

Over two hundred researchers from some thirty countries participated in the Workshops MARID, co organized by the SHOM and which took place in Lille (Trentesaux and Garlan, 2000), Twente (Hulscher, Idier and Garlan, 2004) and Leeds (Parsons, Garlan and Best, 2008). Lectures described case studies, parameterizing of structures, sea and river dune modelling using analytical, digital or physical techniques.

Issues concerning the structures and phenomena to be modelled are still at an early stage. What is the impact of grain size? of depth? How do dunes and currents interact? Without answering all these questions, the three workshops were useful to further refine the knowledge and compare problems and progress in the various fields from acquisition to modelling. Why are we only at such an elementary stage in the domain of sub-aqueous sand dune modelling? First, because the localization of sedimentary structures on the sea floor until the eighties was not precise enough to enable scientists to measure displacements of the order of some meters. A second reason is that the data and studies on dunes were, and remain, still too scarce for realistic modelling to be feasible. As Stolk (2000) said "On the migration of sandwaves only a few datasets are available". As far as observations were concerned, Le Bot and al. (2000) observe that gravel in the North Sea dunes are mobilized for several hours at each phase of tidal currents and that the currents generated by medium strength winds and storms modify the asymmetry of tidal currents to the extent they can reverse currents and the direction of dune progress. As remarked by Schüttenhelm (2000): "Sand waves in the southern North Sea are an enigmatic result of a dynamic equilibrium between sand, tidal currents and wave energy." and Mosher and al (2000) add: "The stability of the dune field remains unanswered. Repetitive multibeam bathymetric surveys and long term current flow monitoring are required to answer this

question." For many authors, the sedimentary dynamics of dunes and their modelling are complex because they are poorly defined. Powell and al (2000) consider that "the formation and disappearance of sediment bedforms, occurring under the action of waves and currents, is the result of a complex interaction between the fluid and the underlying sediment; this is poorly understood, yet extremely important, in both physical and numerical models of coastal processes. Bedforms affect bottom roughness and shear stresses, wave attenuation, and sediment transport". Many questions remain unresolved "What are the physical mechanisms causing sand waves in shallow shelf seas to migrate and at what rate?". Thus these workshops emphasize the deficit of data and the limits of studies which are too local and instantaneous.

In 2001, SHOM conducted a survey for monitoring bottom morphology and variations in near-bottom current measurements in the Straits of Dover. This survey showed that the dune short term dynamics can be directly related to the dynamics of small superimposed structures. The displacement velocities recorded, fast for superimposed structures and slow for the dune, indicate that high resolution recurrent surveys are not the best answer to improve hydrographic knowledge. In order to warn navigators against dangerous shoal waters, it would be necessary to measure the surface area occupied by a dune and its peak envelope, and above all to keep a historical record of the dune and hydrodynamic conditions it was submitted to just before the hydrographic survey so as to determine its historical high point, modelling being used to calculate its theoretical height.

3 DUNE SHAPE, NATURE AND MOVEMENTS

In order to characterize the dynamics of dunes, high-quality long-term data must be available on the velocity and direction of migration, crest shape and evolution, and grain size of the sediments. Because of the lack of data on dune formation and development, dune formation time is obtained by modelling. Such dune formation models (Blondeaux and al., 2000), still do not provide relevant results in complex sectors such as the North Sea (Idier, 2002). Dunes are sedimentary ripples, often periodical, featuring a crest, a gentle slope and a steep slope. The orientation of their crests is generally perpendicular to the main direction of currents, but angular variations reaching up to 20° are frequently observed (Le Bot, 2001). When the current cannot set in motion all sedimentary particles or when there is a sand deficit, dunes are barchanoid-shaped, whereas they have a linear shape when the current is saturated with sediments. By their shape, dunes therefore reflect hydrodynamic conditions.

According to several authors, marine sand dunes with linear crest have the slowest migration velocity (from some meters to 30m/y). On the other hand, barchan dunes are characterized by high velocities, and can reach an annual mean displacement up to 70m/y (Berné and al, 1989). Dune shape is strongly correlated to their nature. Flemming (2000) gives, for different medium grain size, the characteristic values of dune maximum height (H_{\max}) and wavelength (λ). For instance for very fine sands: $H_{\max} \approx 0.028$ m and $\lambda \approx 0.14$ m, whereas for coarse sediments $H_{\max} \approx 22.0$ m and $\lambda \approx 380$ m.

The compilation of the descriptive parameters of 1 500 dunes from various environments in every seas of the world, enabled Flemming to establish a continuous statistical model ranging from ripples to giant dunes, with the following characteristics:

- Dune height comprised between 0.001 and 22 meters,
- Wavelength ranging from 0.01 to 1000 m
- The equation of the maximum height of dunes is $H_{Max} = 0.16 \lambda^{0.84}$

The classification proposed by Ashley (1990), widely accepted today (see Table 1), concerns the sand structures generated by unidirectional currents, bidirectional currents and the combination of both. The H_{mean} of the Flemming diagram allows obtaining the height of the corresponding dunes. Such models constitute a very important basis for digital modelling. To give the good answer to the different needs, we split last class in very large dunes ($5m < H < 10m$) and giant dunes ($H > 10m$).

Classes	Wavelength (λ)	Height calculated with H_{mean}
<i>Small dunes</i>	$0.6 m < \lambda < 5 m$	$0.075 m < H < 0.4 m$
<i>Medium dunes</i>	$5 m < \lambda < 10 m$	$0.4 m < H < 0.75 m$
<i>Large dunes</i>	$10 m < \lambda < 100 m$	$0.75m < H < 5 m$
<i>Very large dunes</i>	$\lambda > 100 m$	$5 m < H < 10 m$
<i>Giant dunes</i>	$\lambda > 100 m$	$H > 10 m$

Table1. Classification of marine sand dunes

In a desert environment, barchan dunes migrate by only a few meters per year, but their shape may change within days after a storm, and ripples may appear within hours (Michaut, 2003). Similar observations are made in a maritime environment, but, because of the variability of hydrodynamic factors, there are no general data or statistical laws on the displacement velocity of sedimentary structures. Velocity integrates the depth, the slope, the nature of sediments and the hydrodynamic factors (tidal currents and waves). It appears that dune displacements vary in the course of time, thus Le Bot (2001) observes, for a series of dunes in the North Sea that the average annual displacement is 7 m, 17 m and 472 m when the time intervals between surveys is respectively 10 years, 1 year and 7 days. Therefore, the shorter the time interval between mapping surveys, the more intense the dynamics appear to be. At the present time no robust formulation of dune dynamics is available. The annual rate of displacement of a dune based on hydrographic surveys spaced out in time can then mask movements having bigger amplitude. This phenomenon is explain by an analysis of environmental variations:

- on a scale of several months to several years, migration varies as a function of storms. Both factors strengthen, slow or reverse migrations of tidal origin;
- on a decade scale, the migration is controlled by a residual tidal current. This is due to the periodicity of 8 to 11 years of the number of storms during the last two decades.

In available literature, migration rates of marine sand dunes vary from one to several tens of meters/year for very large dunes and giant dunes and rates of several tens to several hundred of meters/year for small and medium-size dunes. The actual dynamics of dunes is thus much more intense than that perceived by these comparative studies of mapping surveys over a time interval of a few years. The variability and complexity of sand dune dynamics is summarized by Kocurek (2008) “Boundary conditions makes each bedform field unique”.

4 SOME EXAMPLE OF SAND STRUCTURES

All dunes do not exhibit a simple morphology; it is true that “conventional” dunes (cf figure 1a) are the majority; but recent surveys carried out by SHOM led to the discovery of frequent exceptions (Garlan, 2007, 2008). For example, during hydrographic surveys carried out between 1998 and 2006 in the north of Brittany at depths ranging from 70 to 80 meters, SHOM evidenced meridian crested dunes having heights of 1 to 13 meters and lengths which could exceed 10 km. These hundreds of dunes are typical of an environment with a deficit in sediment (cf figure 1b). They are too deep to be shown on charts but their mapping could be important for many activities like fishing, sand mining, wind farms,... An over example is the dune alignment of north of Trégor which is a series of dunes in skein-like alignment close to northern Brittany coastline. This 5-m high structure at depths ranging from 60 to 70 meters, close to 11 kilometres in length is comparable to the "Seif dunes", described in desert environments McKee (1979) and on the planet Mars. All sand structures in deserts have much bigger dimensions (up to 10 times) than marine counterparts. This holds true for Saharan Seifs averaging heights of 100 meters and whose lengths can reach 100 kilometres. Saharan Seifs are active linear dunes formed under the action of winds of variable directions as opposed to barchans and dunes submitted to the action of winds blowing in only one direction. Seifs dunes are on the limit between transverse dunes and star-shaped dunes. Until then, Seif dunes had not been observed in the marine domain. The most important marine bedforms are sand banks, they are more large but also more stable, so they are potentially less dangerous for navigation. There is about one hundred French sand banks, the banner bank of Lézardrieux is one of them. It is a good example of the superimposed bedforms which present a series of medium, large and very large dunes which move on the bank (Figure 1d).

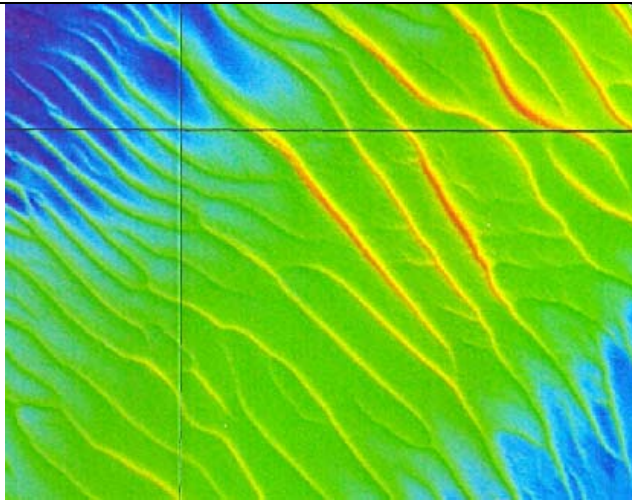


Figure 1a. Field of dunes in the north sea

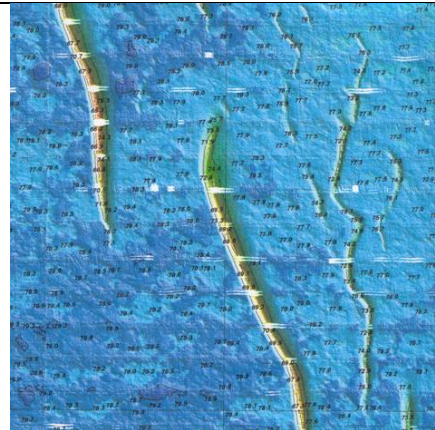
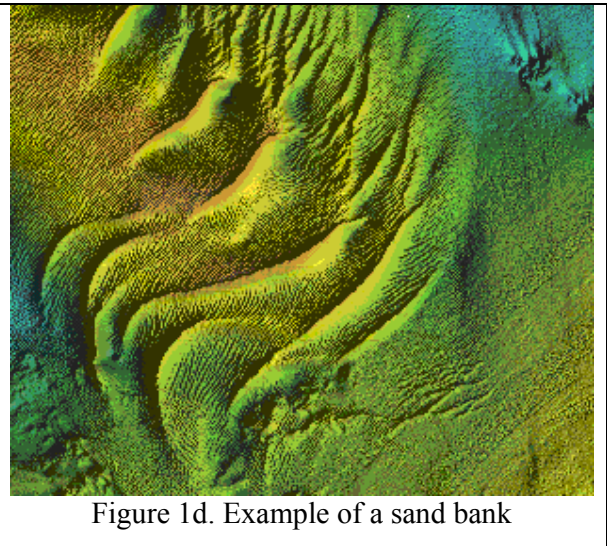
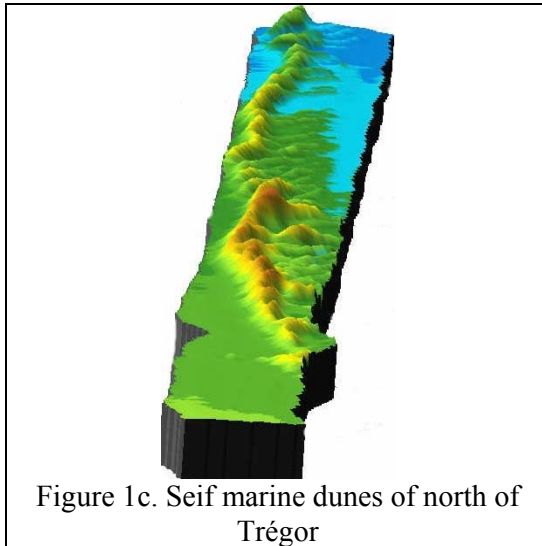
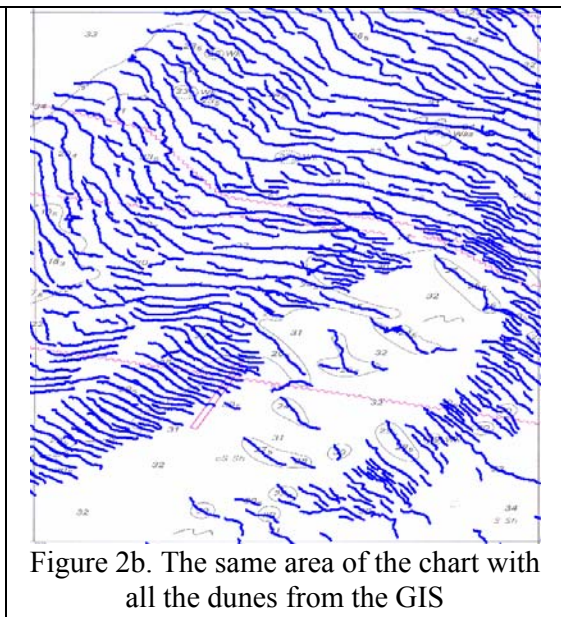
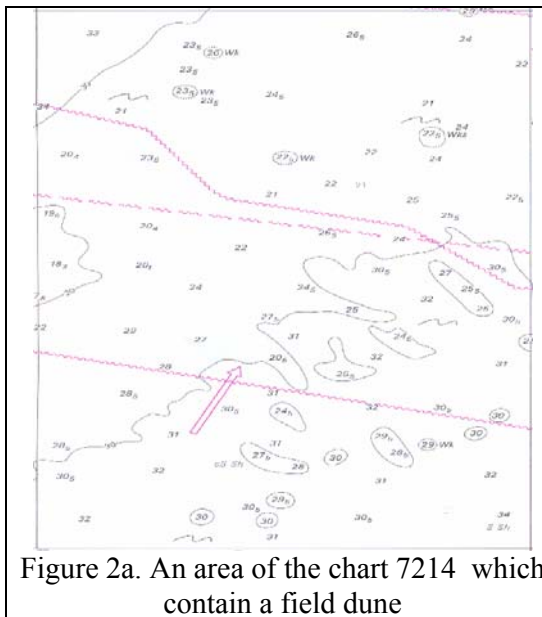


Figure 1b. Dunes in a sand deficit environment



5 GIS AND MAP

On charts, it is not easy to see the presence of bedforms. It could be infer by the mariner from the symbol of mobile seabed () or from indentations of isobaths. In fact there is a great difference between the knowledge from surveys (Figure 2b), and the representation on chart (Figure 2a).



The most important draught is about 25 metres and international rules impose to secure depth up to 26 m. So the dunes bathymetric limit for safety of navigation is 48 meters, which is the sum of the height of the highest submarine dune 22m and 26 meters. To put dunes in the GIS, we develop a software which calculate fifteen physical parameters for each dunes. These parameters (Location of top, width, length and angles of the two sides,

winding, index of symmetry, ...) are complete by the type and limit of the dune, coordinates of the crest, environment (tides, storms, ...), meteorology before the survey, depth near the dune, nature of sediments, and all the metadata about surveys, software processing and origin of data. The GIS was created in 2007, it is updating regularly when new sand dunes are discovered or when new data are acquired on a dune resurvey area. For old surveys (before 1999), only the crest of dunes are digitized from bathymetric data and/or side scan sonar mosaics. The figure 3 presents an example of one dune on the bathymetric map (figure 3a), a result from calculation (figure 3b) and the history of the dune in the GIS (figure 3c).

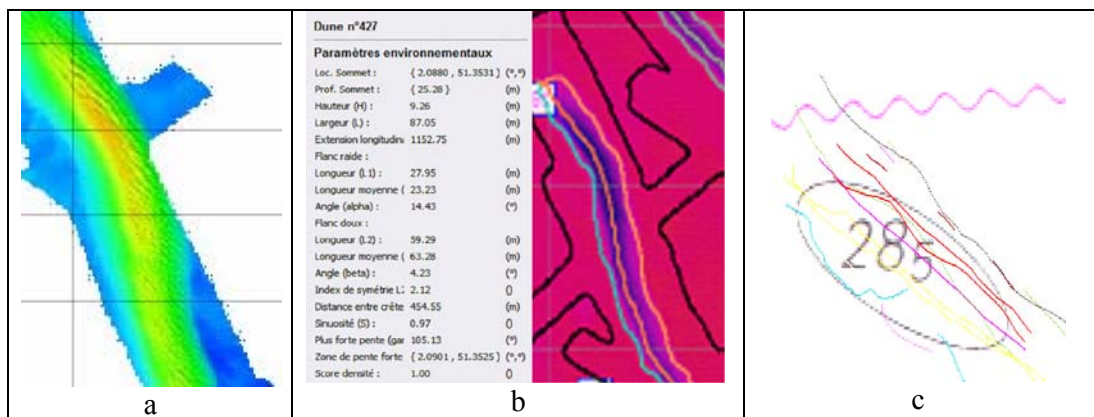


Figure 3. Dune on a MES survey (a), parameters in the GIS (b), history from different surveys (c)

In the past, comparison was done with the precedent survey and it was very difficult to see how the dunes move on a long period. The principal advantage of the GIS is to have the possibility of viewing the evolution of the dune along the time. The other progress is to know every parameter like height of each dune for each step of its evolution. One example of the navigation channel of the North Sea is shown by figure 3. The study of the movement of dunes could be calculated between each survey or between the extreme surveys and the history must be reconstructed. The comparison of movements of dunes with charts is used to decide a new survey and/or a new edition of the chart.

When the safety of navigation is not concern, for example when the crest of the dune is under 26 meter depth, there is no series of surveys and there is often only one survey to describe the dune, and it is impossible to know the speed of these bedforms. In this case the GIS is used to define the limits and characteristics of dune field and to determine profiles which must be done when ship go across the region.

Bathymetric data are not only used for the safety of navigation and sand dunes maps are a necessity for many applications like fishing, sand mining, mine burial, wind farm, ... Charts are not adapted to these needs. We realize a master of a new map which could be seen as an additional layer of charts. These maps show the limit of bedforms (sand field, isolated sand dune, sand bank) and their crests. The dunes are differentiated by different symbols in accordance to the class of dunes, and a vector to show the mean direction and the mean annual speed of movements (Figure 4).

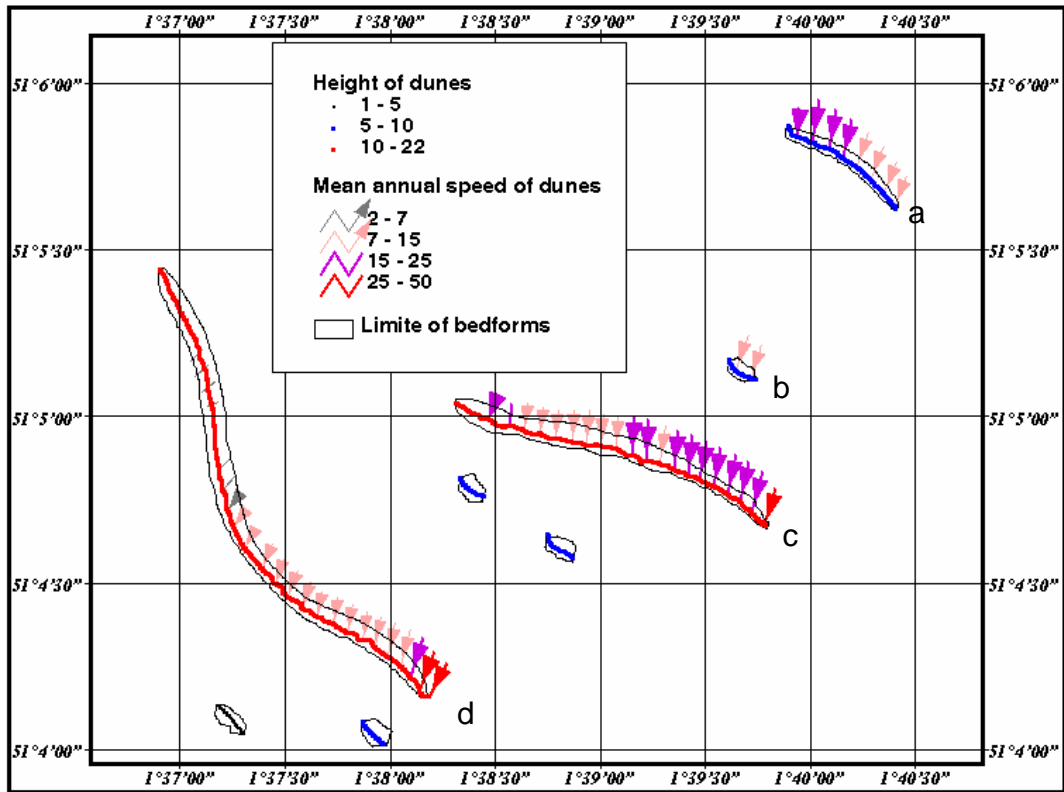


Figure 4. Project of an additional layer of charts with isolated dunes and their dynamics.

The history of the H max (in m) and of the mean annual speed (in m/y) for each isolated dune is done by an associate table (Table 2)

Hmax/Speed	2001-2002	2002-2004	2004-2007
a	9.1 m / 21 m/y	8.0 m / 25 m/y	9.0 m / 24 m/y
b	9.0 m / 25 m/y	6.3 m / 8 m/y	7.4 m / 31 m/y
c	14.0 m / 15 m/y	13.0 m / 25 m/y	13.4 m / 24 m/y
d	11.8 m / 24 m/y	11.7 m / 23 m/y	11.2 m / 24 m/y

Table 2. History of Hmax and speed of the four sand dunes shown on figure 4

For superimposed dunes on sand banks and for field of dunes, like the one shown on figure 2, some dunes from the extremities and the centre are chosen to make the associated table.

6 CONCLUSION

Dunes are controlled by the velocity and the direction of tidal currents, but are also affected by many other factors such as the availability and grain size of sediments, currents associated with swells and storms, locally raised relief both natural and anthropic as well as the slope and roughness of sediments and small morphological structures. By a retroaction phenomenon, currents are also affected by the nature of sediments and the morphology of sedimentary structures. The analysis of sand dunes movements in the

southern sector of the North Sea allowed the acquisition of a large amount of results requiring validation on other dunes and in other environments; some results are pertinent for hydrographic purposes or detection of burying objects, helping to establish a minimum recurrence for surveys:

- the saturation height of a dune is of the order of 35% of depth,
- the time for dunes to form seem to be of the order of 25 years,
- isolated dunes in the North Sea move 1.5 times faster than dunes grouped in dune fields.

To these scientific and technological aspects, should be added the impact of exceptional events (storms, hurricanes, extreme tidal conditions) which had been disregarded so far in studies and had not been taken into account in digital models. The sedimentary dynamics need to rely on long range time series integrating variable acquisition time intervals representative of the various meteorological conditions or on precise and exhaustive batches of data perfectly describing the phenomenon. This is why the French hydrographic office making up a GIS on banks and dunes of the continental shelf. The first objective is to answer to the needs for the safety of navigation. The new needs are numerous : fishing, sand mining, wind farms, mine burial, biological activity and coast protection, they all imply to develop maps like the “dune map” presented in this paper for the representation of marine sand dunes and sand banks.

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