Die Küste, 69 PROMORPH (2005), 379-391

Morphological Changes in a Tidal Flat Area: A Comparison of Radar, Optical and In-Situ Data

By KLAUS RICKLEFS, SUSANNE LEHNER and JAN RAUSCH

Summary

For assessing the suitability of in-situ bathymetric measurements and remote sensing satellite data (ERS-1 and 2, Landsat-TM and MSS, IRS-1C PAN and LISS-III) to detect morphological changes in tidal flats and the information content obtained by both methods, two highly morphodynamic test areas have been chosen within the Dithmarschen Wadden Sea (German Bight): the shoals Tertius Sand and D-Steert. Both sand banks show a distinct shoreward drift, which is due to sediment motion driven by general sea level rise and hydrodynamic forces such as waves and currents. Morphological changes related to sedimentation, erosion and redeposition can be shown by analysing in-situ data. Moreover, the shift of water level contours due to topographical changes can be quite efficiently demonstrated by comparing the contours extracted from satellite images of different years.

Zusammenfassung

Um die Brauchbarkeit und den Informationsgehalt von „klassischen" Seevermessungsdaten sowie Satellitenfernerkundungsdaten (ERS-1 and 2, Landsat-TM and MSS, IRS-1C PAN and LISS-III) zur Quantifizierung morphologischer Veränderungen in Wattgebieten abschätzen zu können, wurden zwei Testgebiete ausgewählt, die eine ausgeprägte Morphodynamik zeigen. Es waren dies die im Dithmarscher Wattenmeer (Deutsche Bucht) gelegenen Sände Tertius Sand und D-Steert. Beide Sandbänke zeigen infolge intensiver Sedimentumlagerungen, die durch einen Anstieg des Meeresspiegels sowie durch Wellen und Tideströmungen bedingt sind, eine ausgeprägte landwärts gerichtete Verlagerung. Morphologische Veränderungen als Folge von Ablagerung, Abtrag und Umlagerung von Sedimenten können durch die Auswertung von Peildaten hinlänglich erfasst werden. Die sich aus den Umgestaltungsvorgängen ergebenden Verlagerungen der Wasserlinien können darüber hinaus effizient aus dem Vergleich von Konturlinien abgeleitet werden, die sich aus Satellitenbildern unterschiedlicher Jahre extrahieren lassen.

Keywords

Remote Sensing, Optical Data, Radar, German North Sea Coast, Tidal Flats, Water Level Contours.

Contents

1. Introduction

For updating information on bottom topography of tidal flat areas, ship-based bathymetric measurements but also satellite monitoring can be applied. Satellite imagery is often used as a tool for obtaining a synoptic overview of the area under investigation, whereas in-situ measurements offer higher resolution for detailed mapping. Depending on the task, data from both methods can be used for calibration and validation of numerical morphodynamic models (ROMANEESSEN, 1998; LEHNER, 1999). The suitability and limitations of each type of data for assessing the morphodynamics of a coastal area is the main objective of this paper. Study area is the Dithmarschen Wadden Sea. Three types of datasets are the basis of this investigation: bottom topography interpolated from bathymetric measurements taken between 1974 and 1997, synthetic-aperture radar (SAR, onboard of ERS-1 and 2 satellites) images from 1992 to 1999 and optical images (Landsat-TM & MSS and IRS-1C PAN & LISS-III) from 1973 to 1997.

2. Investigation Area

The Dithmarschen tidal flat area, located in the southeastern part of the German Bight is part of the Wadden Sea of the Federal State of Schleswig-Holstein. The two chosen test areas Tertius Sand and D-Steert are indicated in Figure 1. These two shoals are built up of mainly fine sand with minor medium sand components. The tidal regime in the area is semidiurnal with tidal ranges from 3 to 3.5m. Located at the seaward borderline of the Dithmarschen Wadden Sea and bordered by deeper tidal channels in the North and South both sand banks are highly exposed to the energy of the North Sea waves. In combination with tidal currents this leads to pronounced morphological changes. The strong environmental dynamics result in lateral migration in mainly easterly direction and in changes of elevation, which, especially in the case of D-Steert, lead to the temporary formation of a supratidal sand.

3. Methods

3.1 Ship-Based Bathymetric Survey Data

The topographic data are result of ship borne bathymetric measurements carried out by the Federal Maritime and Hydrographic Agency of Germany (BSH). The investigated datasets acquired in 1977, 1984, 1992 and 1997 were chosen to meet the same time frame as the satellite data. The grid interpolation was carried out within the coordinate boundaries of the test areas for each year. The datasets were interpolated on a 12.5 x 12.5 m grid (same size as the SAR pixels). Sediment budget changes were calculated by subtracting the measurements of two years for one area, such that positive values indicate sediment accumulation and negative values erosion. All depth values are referred to the German Ordnance Datum ("Normalnull" = NN).

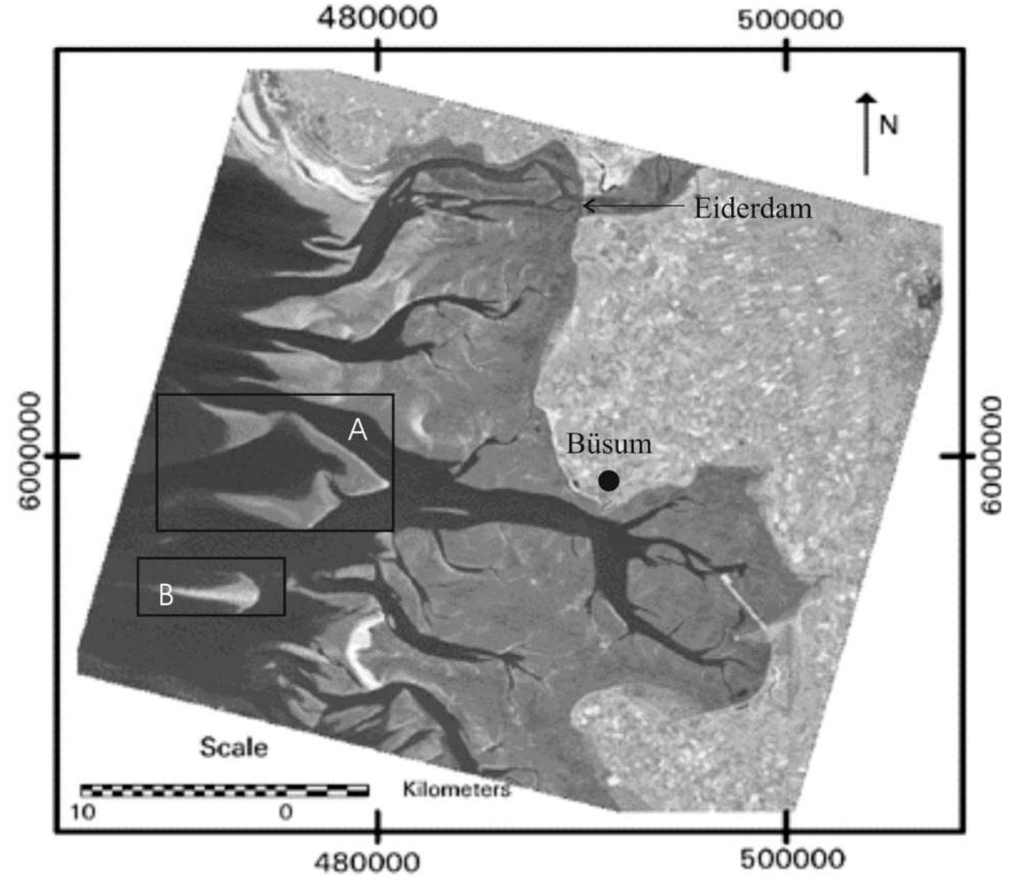

Fig. 1: The test areas within the Dithmarschen Wadden Sea. A = Tertius Sand, B = D-Steert (Image: Landsat-MSS, April 10th, 1976. Coordinates in UTM)

3.2 Remote Sensing

Data from both passive and active satellite borne sensors were used. Passive sensors are characterised by the ability to capture part of the radiation that is emitted and / or reflected from the earth's surface. The passive sensors applied in this study are mounted on Landsat and Indian Remote Sensing Satellite (IRS) satellite platforms (KRAMER, 1996). Landsat carries a multi spectral sensor (MSS) composed by four bands that simultaneously record reflected radiation in the green, red, and reflected infrared (2 bands) portions of the electromagnetic spectrum with a resolution of 70 m. Besides being able to map a larger variety of earth features due to its 7 bands, one of the advantages of Landsat Thematic Mapper (TM) sensors over MSS sensors lies within the Thematic Mapper's higher image resolution (30 m;

only band 6 has a resolution of 120 m). The second dataset used was taken from an IRS-1C platform. It carries three types of sensors on board, out of which two were used for this research: the LISS-III, with 23 m spatial resolution and a panchromatic sensor (PAN), with 5.8 m spatial resolution.

Radar is an active sensor, which emits its own source of energy and thus makes it independent from daylight and cloud cover. It directs the microwave radiation towards the targeted object in order to measure the returned energy of the backscattered signal. Launched by the European Space Agency (ESA) in 1991 and 1995, ERS-1 and ERS-2 were the first satellites collecting commercially available synthetic aperture radar (SAR) data during all weather conditions as well as during day and night (BAMLER and SCHÄTTLER, 1993). The SAR achieves its high-resolution by synthesising a long antenna, moving the antenna along the flight track and receiving the backscattered signals coherently. SAR processing transforms the received raw data to higher resolution (30 m) SAR images. Table 1 shows the investigated radar and optical images and their corresponding water levels.

Table 1: Investigated satellite datasets, with the corresponding water level at Büsum gauge (*German ordnance level Normal Null, NN)

Date	Time	Water level (m NN*)	Sensor
05.10.1973	09:57	–1.03	Landsat-MSS
10.04.1976	09:42	–2.10	Landsat-MSS
22.08.1984	09:56	–0.87	Landsat-TM
26.03.1992	10:24	–1.39	ERS-1
14.03.1996	10:25	–1.11	ERS-1
12.08.1997	10:45	–1.58	IRS-1C (Pan & LISS-III)
20.12.1997	10:22	–1.60	ERS-2
08.04.1999	10:25	–1.53	ERS-2

3.3 Water Level Contour Extraction

In this study, the main information extracted from the satellite data is the boundary between water and tidal flats or beaches (CHEN and SHYU, 1998; KOOPMANS and WANG, 1995; MASON and DAVENPORT, 1996; MASON, GURNEY and KENNETH, 2000; WANG and KOOPMANS, 1993). Tidal gauge water level recordings are correlated with shorelines extracted from the images. Main difficulties in this extraction process known as edge detection in SAR images are related to speckle noise. Due to the coherent nature of illumination, SAR images are speckled and therefore edges can only be extracted by means of a complex chain of algorithms. In a first step, a wavelet edge detection method suggested by MALLAT and HWANG (1992) is applied to detect all edges above a certain threshold. A block-tracing algorithm then determines the boundary area between land and water defining a coastal area. A refinement is achieved by local edge selection in this coastal area and propagation along the wavelet scales. In a final step, the refined edge segments are joined by an active contour algorithm. The method applied here is described in detail in NIEDERMEIER et al. (2000).

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4. Results

4.1 Topography of D-Steert based upon Bathymetric Survey Data

The 1977 topography interpolated from in-situ bathymetric measurement data (Fig. 2) displays D-Steert as an elongated high sand body, stretching in east-west direction. The highest parts are between NN –1.0 and 0 m. The sand is flanked on its northern side by the tidal inlet Süderpiep extending from east to west. In the south it is bordered by a second channel which spreads into a wide shallow water area in easterly direction. The most obvious attribute of the D-Steert bank is its migration from west to east which is clearly depicted by the sequence of bathymetric data plots given in Figure 2. In 1977 the highest parts of the sand bank form a quasi symmetrical body with its main axis in the W-E direction. Increasing sediment accumulation on the southern part leads to an apparent effect of rotation of the main axis. In the 1997 image it is orientated in the WSW-ENE direction. The digital terrain model of this year also shows some quadratic patterns as far as heights above NN are concerned. Although these black patches represent areas which have not been surveyed it is obvious that, compared to the previous years, there was a significant accumulation of sediments that forced both a change in shape and an increase in volume.

The process of eastward migration described above is also clearly visible from the sediment balance maps (Fig. 2). Sediment accumulation is slightly higher on the southern part

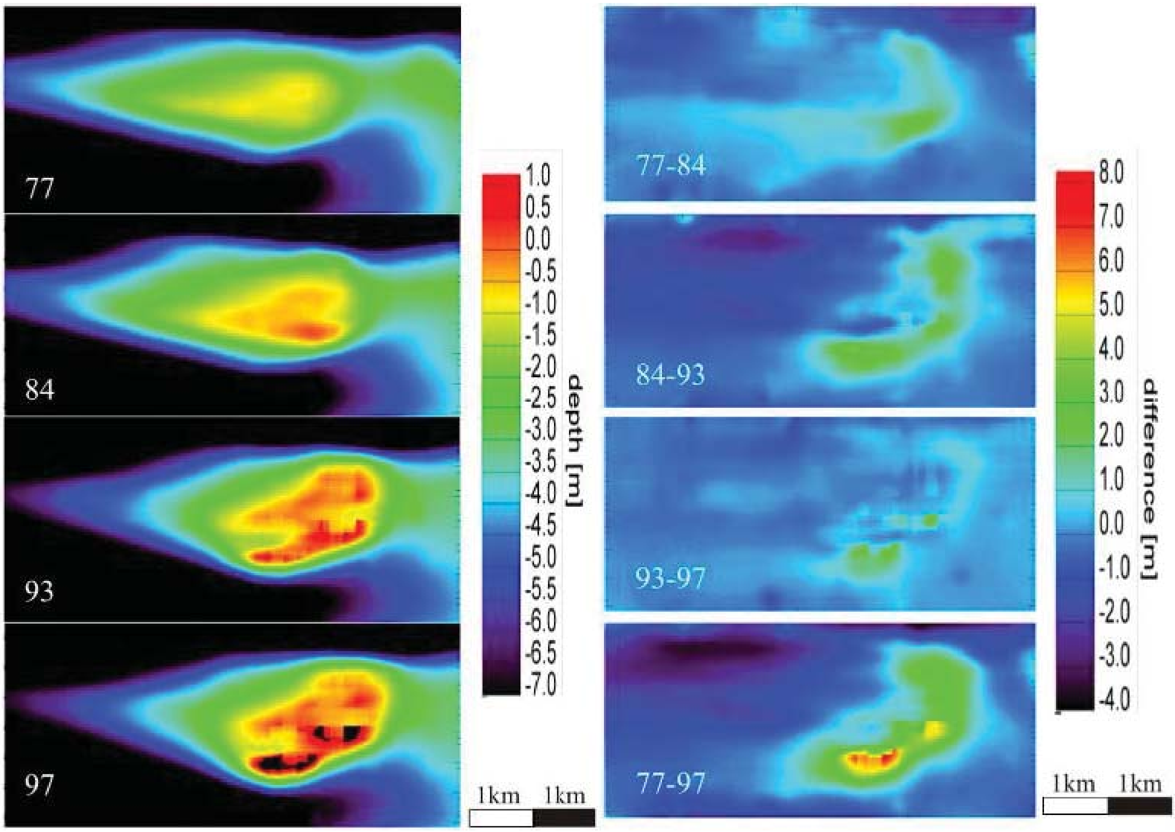

Fig. 2: Topography (left) based upon in-situ measurements of D-Steert in the years: 1977, 1984, 1993 and 1997 (top to bottom); and sediment balance (right) for sequences: 1977 to 1984, 1984 to 1993, 1993 to 1997 and 1977 to 1997 (top to bottom)

of the shoal. Erosion takes place on the western part, whereas towards east, accumulation increases. Between 1993 and 1997 erosion and accumulation are limited on D-Steert; only in the south-east 2 m of mainly sandy sediments were accumulated. During the twenty years between 1977 and 1997 the trend of erosion west of D-Steert and deposition east of it is confirmed by the volume analyses. Sediment deposition in the southern part reaches values of approximately seven metres. This redeposition results in a movement of D-Steert in a more south-easterly direction and characterises an eventual shift of the main axis from W-E to WSW-ENE.

4.2 Water Level Contours of D-Steert Extracted From Optical Data

Fig. 3 shows the evolution of D-Steert sand bank based on the extraction of water level contours from optical sensor data. These sensors permit long-term monitoring (24 years) of the evolution, an advantage over ERS-SAR data that have been available since 1992. The analysis of the images reveals that after a southward migration from 1973 to 1976 the D-Steert sand bank starts moving eastward in subsequent years. The initially elongated arrow-like shape changes rather drastically to an elliptic body oriented in the SW-NE direction in 1997. A similar shape can be also observed in the radar data.

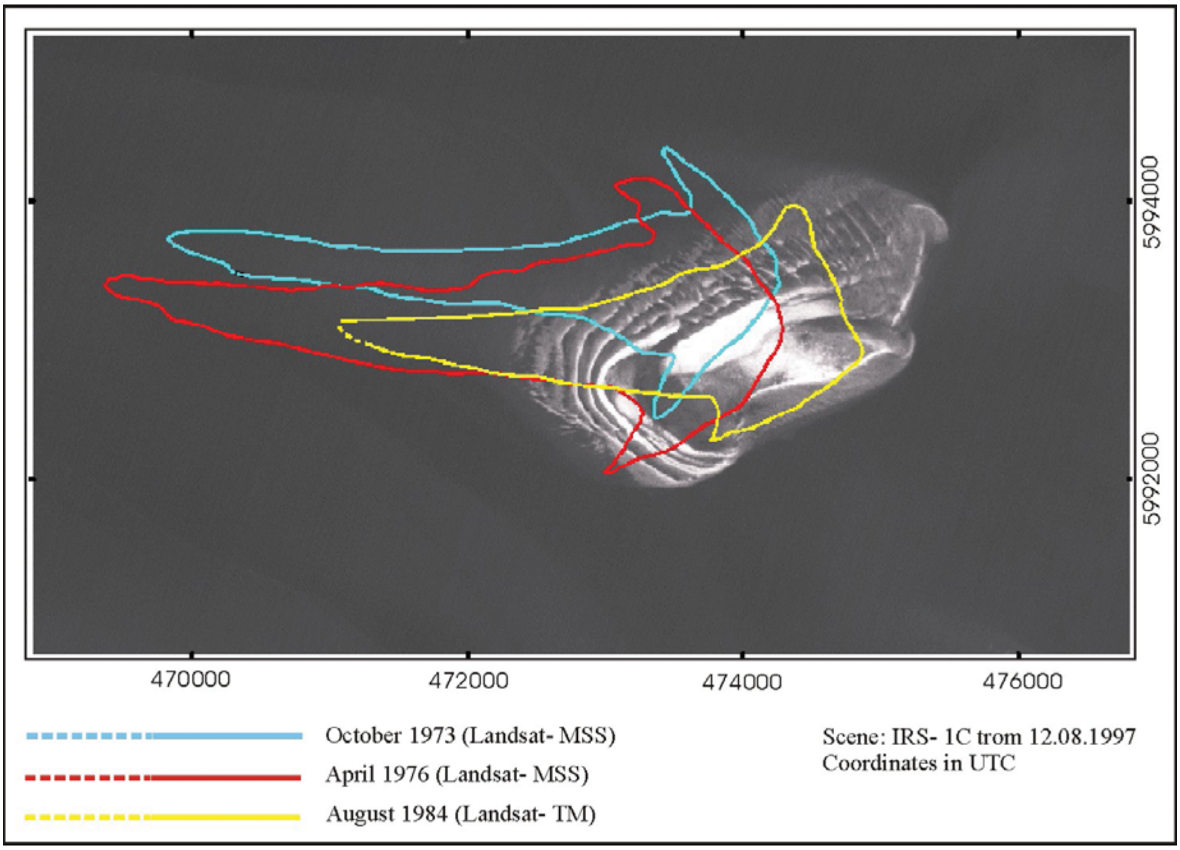

Fig. 3: Evolution of D-Steert's water level contours based upon optical data (over 1997 PAN image)

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4.3 Water Level Contours of D-Steert Derived from SAR Data

Fig. 4 shows the results of the edge detection method extracting the water line around D-Steert from ERS SAR images for the years of 1992, 1996 and 1999. The northern boundary of D-Steert's eastern part clearly migrates towards east while water level contours move southward in the nsouthern part. Even more pronounced, the low water contour on the western bank also retreats in south-easterly direction. Overall, the erosional and depositional processes lead to a tendency of rotation of the longitudinal axis in a counterclockwise direction from W-E to SW-NE.

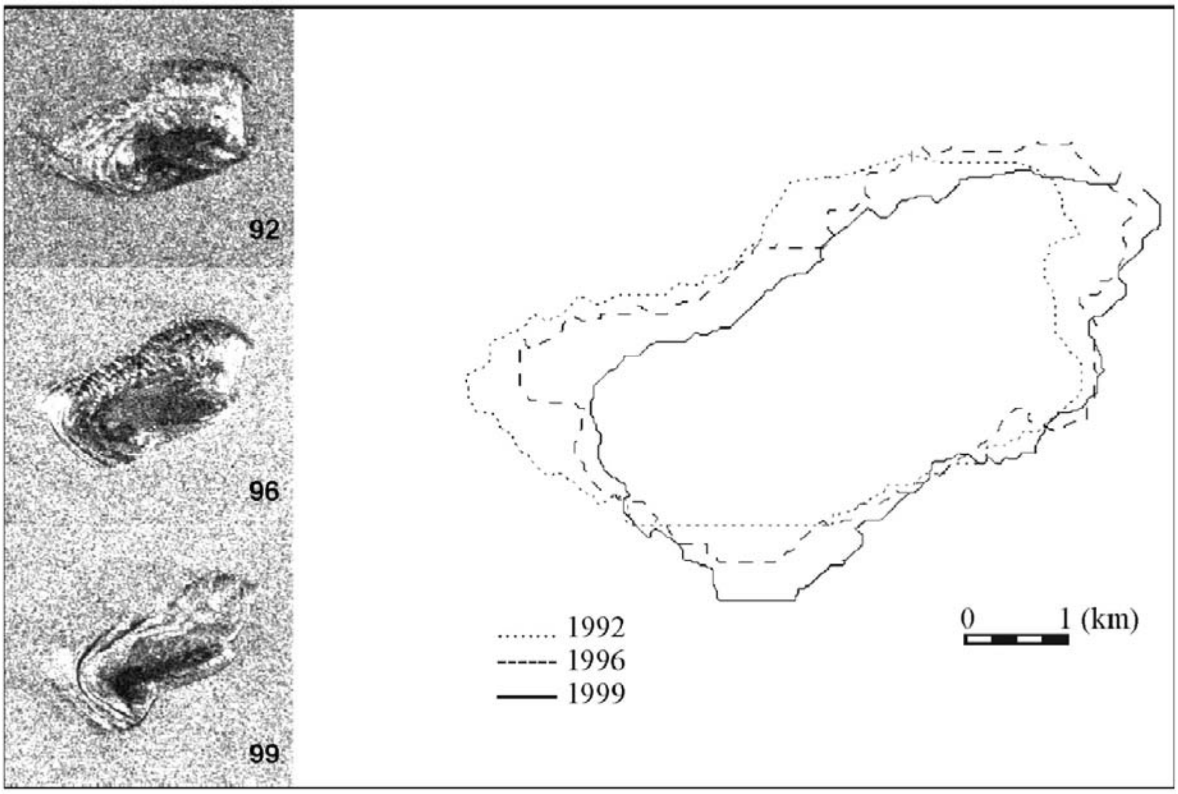

Fig. 4: Evolution of D-Steert's water level contours extracted from SAR

4.4 Summary of Topographic Changes of D-Steert

Changes of D-Steert's shape can be easily observed on satellite images. On the one hand, sediment accumulation occurs on the southern side. This is proven by sediment balance data but also clearly expressed by the advance of the water line derived from satellite images. On the other hand, a redeposition of sediments takes place from the western to the eastern side, also visible in the sediment balance data and as a migration of the remotely sensed water level contours. Besides the data from in situ measurements, the most reliable information on sand bank migration can be obtained from edge detection data extracted from the SAR. However, information derived from these data is limited to those areas which are dry during low water.

4.5 Topography of Tertius Sand based upon Bathymetric Survey Data

Tertius Sand is composed of three connected sand banks which will be named here for simplification (visible in Figs. 5, 6 and numbered in Fig. 7) as Island 1 for the northernmost one, Island 2 for the middle one and Island 3 for the southernmost one. In the north and in the south these three sands are bordered by the tidal channels of the Norderpiep and the Süderpiep, respectively.

The concave side of this group of sand banks is turned towards the open North Sea. As shown in Fig 5, the highest elevations (NN –1.0 m) are found on the southernmost part of the bank in 1977. From 1977 to 1997 its frontal crest clearly migrates landwards. Island 2 increases in height while Island 3 loses parts of its higher areas.

The most intensive accumulation takes place in the south eastern (landward) side of Island 1. Similarly, the side exposed to the open sea is subjected to erosion causing the intensive migration of this shoal. Accumulation also takes place north of Island 2 and south of Island 3. Strong sediment input can be perceived on the eastern border of Island 1 as well as in the south of Island 3. Erosion takes place mainly in the deeper parts of the Süderpiep channel and west of Island 1. The pattern of sediment changes is comparable for all four observed time windows indicating a strong movement of the northernmost Island of Tertius 1 towards the mainland as well as an accumulation that leads to a southward migration of Island 3.

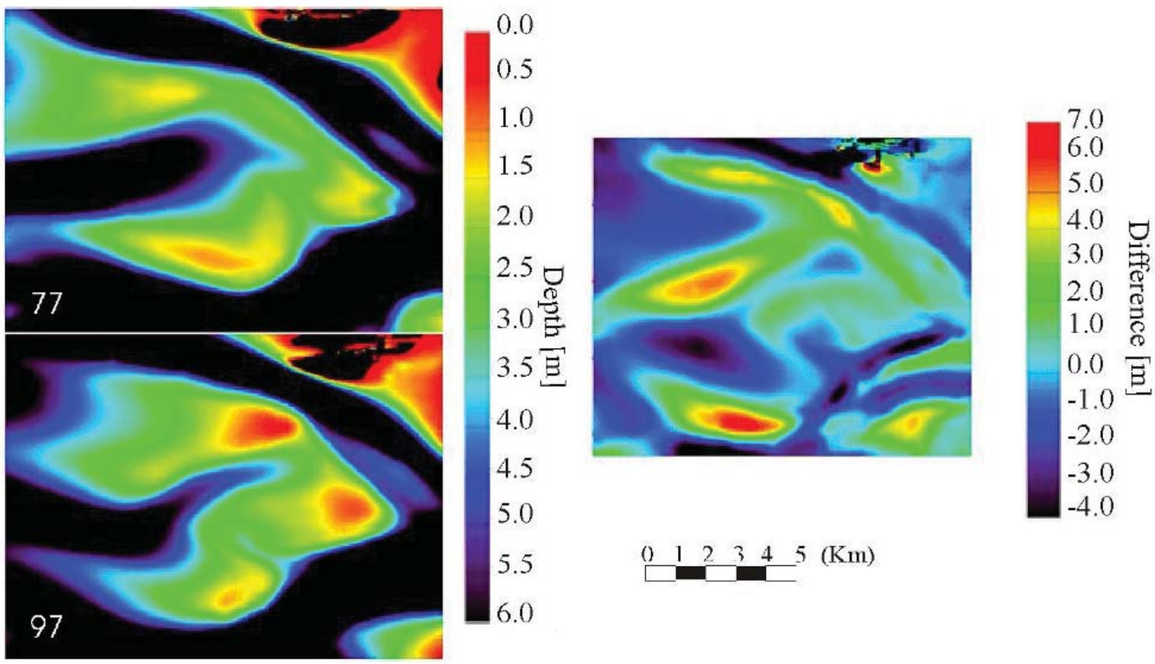

Fig. 5: Topography based upon in-situ measurements of Tertius Sand in 1977 (upper left) and 1997 (lower left) and sediment balance between 1977 and 97 (right)

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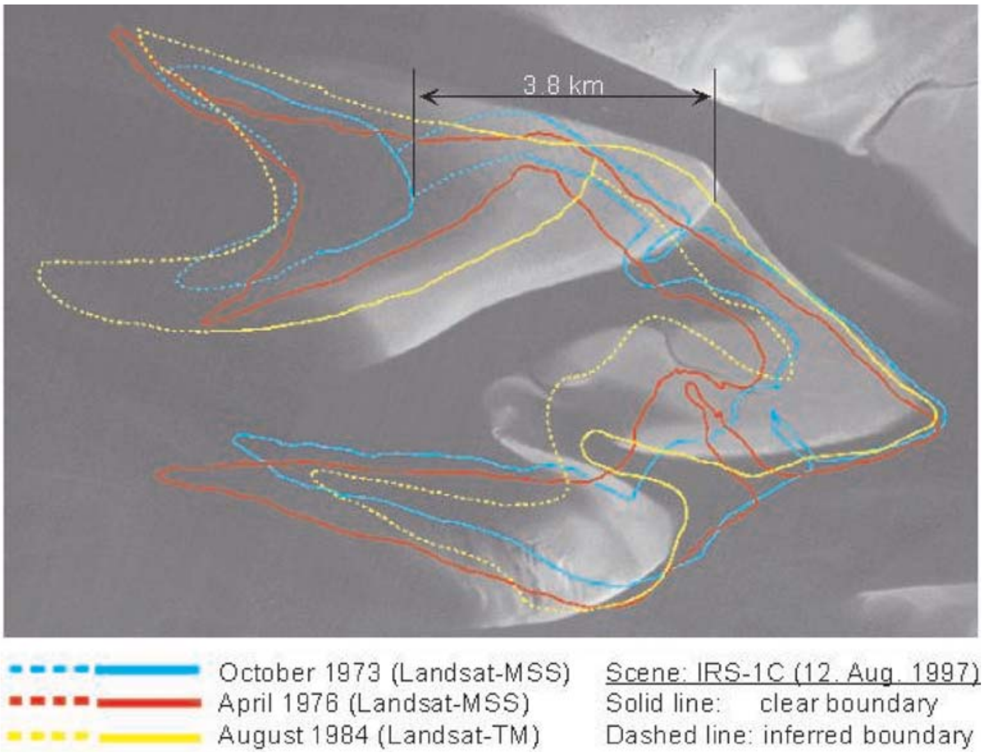

Fig. 6: Evolution of Tertius Sand's water level contours extracted from optical IRS-Pan data

4.6 Water Level Contours of Tertius Sand Extracted from Optical Data

The analysis of the waterlines derived from optical data (1973–1997) shows a reduction of the area of Island 3 combined with a tendency to migrate in a southwesterly direction (Fig. 6). The situation for Island 2 can be described by stability of the central part and a retreat of the southern boundary to the north. Contrary to Island 2, the marked water level contours of Island 1 exhibit a landward migration of the sand body of up to 3.8 km.

4.7 Water Level Contours of Tertius Sand Derived from SAR Data

In general, Tertius Sand can be identified very well on ERS-SAR images (Fig. 7, small image) and water level contours (Fig 7) can be precisely extracted from these data sets. Among other things, the morphological evolution of the area between 1992 and 1999 is characterised by strong changes of the seaside contours of the three islands, which form Tertius Sand. In contrast, those boundaries of the Island 2 and 3 that are facing towards the mainland remain stable or undergo very little changes. The same is true for the border line between Island 1 and the northern adjacent tidal channel of the Norderpiep. However, Island 1 as a whole (marked in the radar image, Fig. 7) slides along this line in the direction of the mainland. From 1992 to 1999 this migration is in the order of 700 m. That means that the entire Island 1 is in motion, unlike the other sand bodies, which are stable in their eastern and unstable in their western parts.

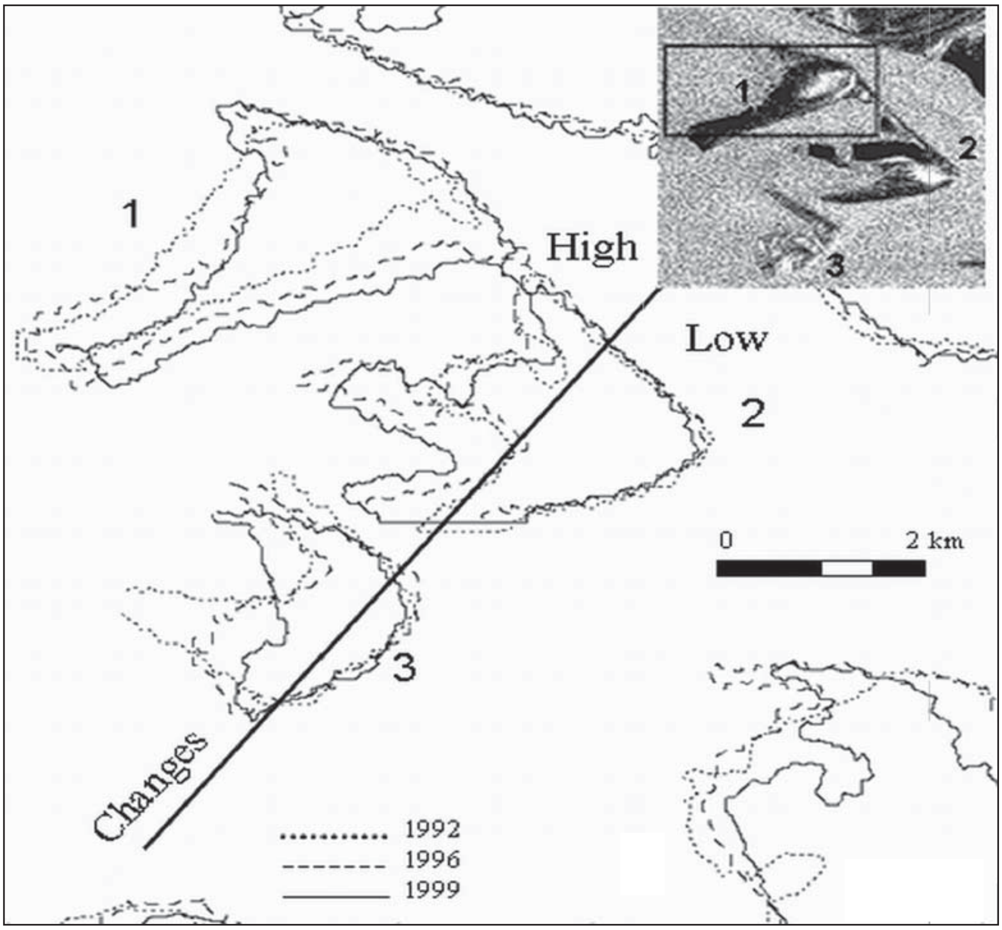

Fig. 7: Evolution of Tertius Sand's water level contours extracted from SAR

4.8 Summary of Topographic Changes of Tertius Sand

The sediment balance presented in Fig. 5 shows a tendency of accumulation in areas in the vicinity of the adjacent channels that already show a higher elevation. In contrast, there seems to be ongoing erosion in the westerly exposed lower lying areas. This evolution eventually leads to steeper seaward slopes of the shoals.

Results from bathymetric measurements (Fig. 5) and from optical remote sensing data clearly (Fig. 6) show a pronounced landward migration of the seaward parts of Tertius Sand. For the south-eastern part of Island 1 this tendency is also documented by the SAR data (Fig. 7). However, the landward migration is not very obvious for the SAR-data-derived water level contours in the north-western part of Island 1. This discrepancy displays a typical limitation of the used water level contour method in areas with relatively gentle slopes. Here small changes in the water level lead to an abrupt change in the area size and, therefore, to a pronounced advance or retreat of the water level contour.

5. Discussion

Fig. 8 shows a comparison between the water level contours resulting from bathymetric and radar data sets on an optical IRS-PAN base image of the entire Dithmarschen Wadden

Sea area of 1997. To take in to account water level slopes in the area, measured elevations were taken from two tidal gauges for the appropriate time window. For the outer parts we used data from Trischen Island gauge station (NN –1.3 m) and for the inner parts from Büsum gauge station (NN –1.6 m). In this way a better match between the topographic units visible in the base image and the water level contours can be achieved. The red lines in Figure 8 represent the NN –1.6 m (inner part) and the NN –1.3 m (outer part of the domain) isolines derived from a digital elevation model, which is based on in-situ bathymetric data. SAR data (Dec./20/1997) were acquired for a situation with the water level at NN –1.6 m at Büsum gauge station. The derived contour lines are given in yellow. In areas with distinct

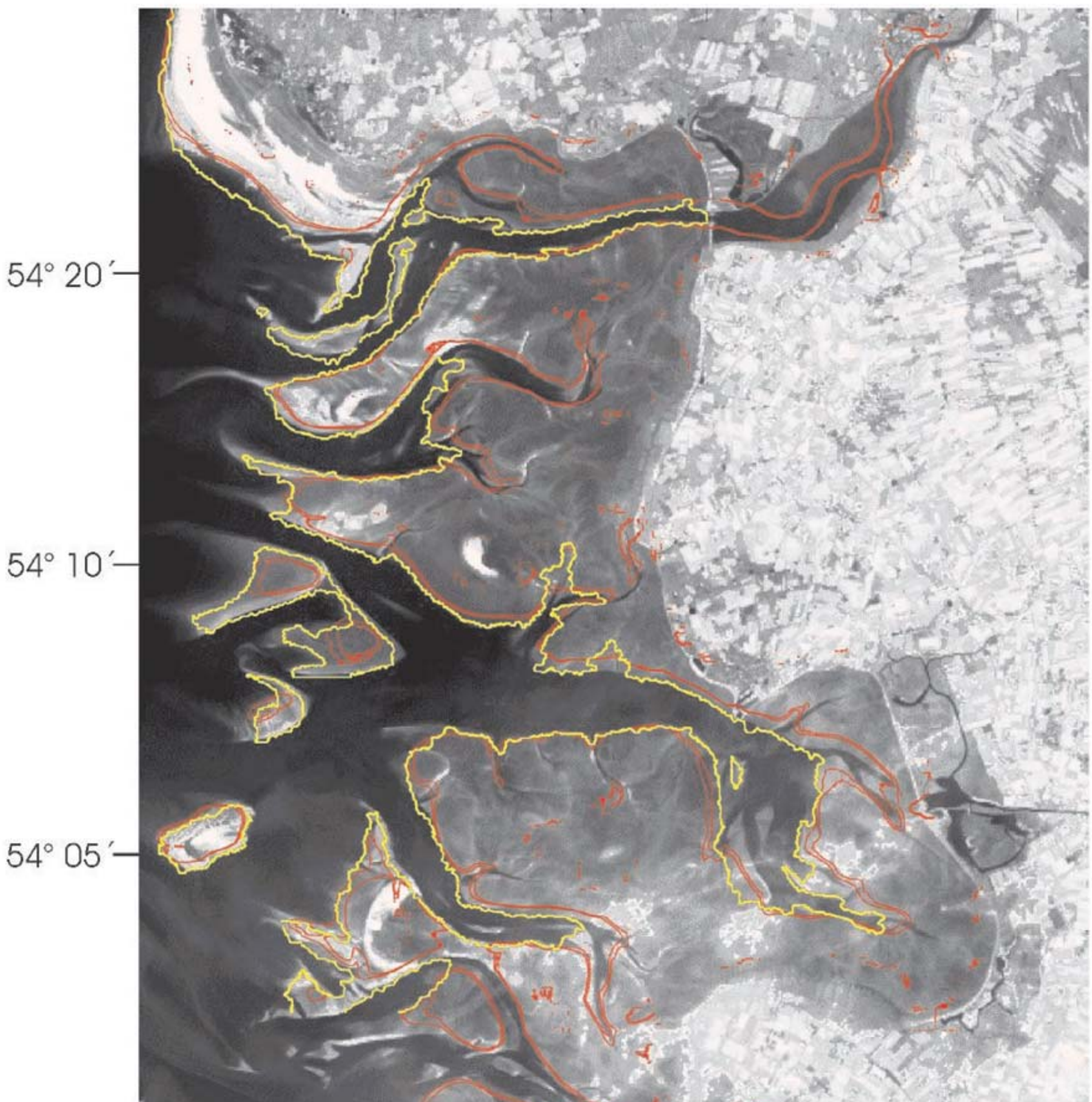

Fig 8: Water level contours for the year 1997 extracted from SAR data (yellow line) and from interpolated bathymetric data (red line)

"SAR-data-edges" tantamount to steep topographic gradients both isolines show a relatively good correlation and match well with the topographic units visible in the underlying optical image. Examples are the areas south of the Eider estuary and north of the Norderpiep. Isolines match less in areas which are characterised by gentle slopes. This applies to some parts of the Tertius Sand or the inner part of the Meldorf Bight.

The partly good correlation between the contour lines means that, although radar data are unavoidably contaminated by speckle noise, the used edge detection algorithm has proven to be efficient in tracing boundaries between intertidal areas and water. However, an important prerequisite for a good match is that both data sets are related to the same water level base. We are quite sure that this is not true for every case. Thus, unknown spatio-temporal variability of the tides or resulting water levels as well as the slope characteristics of the area account for some of the discrepancies. Due to the size of the area and the complexity of the factors, which may lead to local variability of water levels, an estimate of the error cannot be made.

6. Conclusions

The combination of data from SAR, IRS, Landsat and ship-based surveys has proven to be a useful tool for assessing topographical changes in the Wadden Sea. Remote sensing data basically yields information on the water level contours. Older, low resolution (MSS) optical sensors, can give information about the topographical evolution within a larger historic time span. High-resolution optical sensors (TM, PAN, LISS-III) are very suitable for extracting coastlines with simple algorithms at a high degree of accuracy. However, optical methods are dependent on daylight conditions and low cloud coverage.

For continuous coverage the extraction of tidal flat-water-boundaries from synthetic aperture radar data is a valuable method as it offers the advantage of data being available at all weather conditions on a weekly basis and, therefore, shows the potential of updating bottom topography between high and low tide in the Wadden Sea.

A main future challenge for further development of algorithms using radar remote sensing data is the extraction of water level contours at coastal areas with gentle slopes. In addition, interferometric methods making use of two or more images of the same area will be used to deduce topographic information in the Wadden Sea (SIEGMUND et al., 2004). With new high resolution radar satellites to be deployed in the TerraSAR-X mission which is to be launched in 2006 mapping of the Wadden Sea will be possible for a resolution higher than 5 m.

7. Acknowledgements

Part of the work was funded by the BMBF within the framework of the TIDE project. The topographic data has been kindly made available by the Federal Maritime and Hydrographic Agency (BSH).

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