Local Currents at a shoreface-connected Ridge in the German Bight.

Measurements during moderate and stormy winds off Norderney

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Summary

Current data at a shoreface-connected ridge in the German Bight have been sampled in January 1990 and January 1991. During the 1991 experiment a violent southwest storm hit the area so that the storm-induced currents can be compared to those under moderate periods. The storm significantly changed the tide dominated spatial and temporal current regime. Estimates suggest, that all sediment grain sizes which occur in the ridge area (0.1 to 0.5 mm) can be resuspended due to the storm-induced intensification of the bottom currents.

Lokale Strömungen an einem Zungenriff in der Deutschen Bucht (Zusammenfassung)

Im Januar 1990 und 1991 wurden Strömungsmessungen an einem Zungenriff in der Deutschen Bucht durchgeführt. Im Januar 1991 zog ein schwerer Südweststurm mit Orkanstärke durch das Untersuchungsgebiet, so daß die lokale Stömung unter extremen Windbedingungen mit der während ruhigerer Phasen verglichen werden kann. Der Sturm veränderte das vorwiegend gezeitenbeherrschte Strömungsregime grundlegend. Abschätzungen ergeben, daß die infolge des Sturms intensivierte Bodenströmung alle örtlich vorhandenen Sandfraktionen (0,1 bis 0,5 mm) resuspendieren kann.

1 Introduction

Shoreface-connected sand ridges, about 5 metres in height and some kilometres long are common features of the East Frisian coast (southern North Sea). The location of these ridges can vary from year to year while their morphological structure remains mainly conserved. Axial displacements of the order of 200 metres within 2 years have been observed, but without a preferred sea or landward direction. Although these ridges are exposed to strong tidal currents, morphological changes can only be explained by the effects of strong storms, i. e., the morphological forces can be effective for only a few days within a year (Flemming [1991]).

Two current-measurement campaigns, TOPEX-I and -II (**Top**ographical **Ex**periment) were carried out at a shoreface-connected ridge northwards off the island of Norderney in January 1990 and January 1991 (fig. 1). The ridge is about 5 m high, 15 km long and 1 to 2 km wide. Its axis runs nearly straight-lined from 295° to 115°. The water depths above the ridge amounts to 20 m and about 25 m in the troughs. According to (Swift et al. [1977]) the landward flank of the ridge near the junction to the shoreface is steeper than the seaward flank while further seawards the ridge is nearly symmetrical or steeper at the seaward flank. The mean bottom slope amounts to about 1 : 300.

During both experiments we deployed U-type moorings with Aanderaa current meters with a sampling rate of 2 minutes. A bottom-mounted 300 kHz RDI acoustic doppler current profiler (ADCP) was deployed for periods up to 36 hours at different positions. Near-bottom currents (30 cm above the bottom) were measured with an acoustic Neil Brown current meter with 1 minute sampling rate, mounted to a bottom-frame called "Rhönrad". All deployment positions are shown in fig. 1.

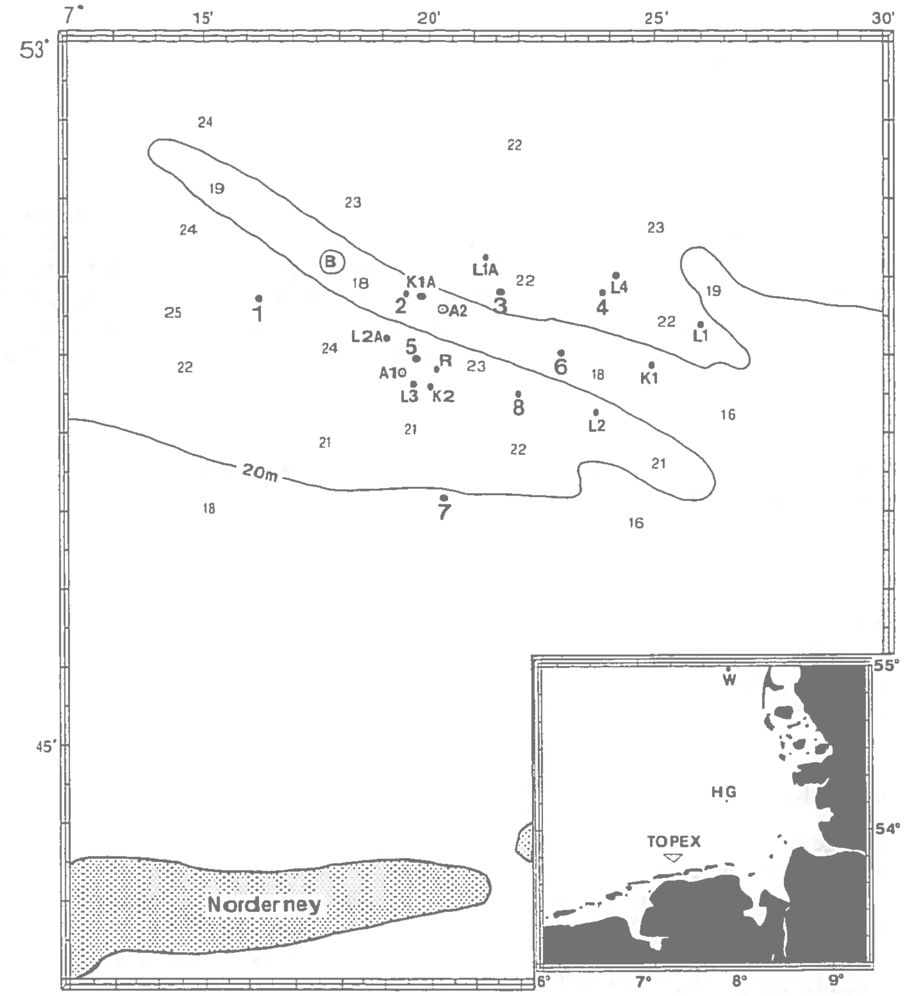

Fig. 1 TOPEX area and deployment positions. Thin numbers are depth in metres, the ridge is schematically outlined by the 20 m-isobath. K's and L's mark TOPEX-I moorings, R is the position of the „Röhnrad". 1 to 8 (bold numbers) are TOPEX-II moorings, A1 and A2 are the positions of the TOPEX-II ADCP-measurements. Tidal curents have been calculated for position B. General map: HG: Helgoland, W: Wave rider buoy.

The TOPEX-I moorings were deployed on January 19, 1990. On January 25 we changed the positions of the moorings K1, L1, and L2 to the positions K1A, L1A, and L2A. During this second deployment period two violent storms passed the investigation area. Short ("K-") moorings had instruments at 1 and 12 metres above bottom (hereafter mab), long ("L-") moorings reached up to 18 mab. Recovery of the moorings was on January 29 and 30, 1990.

The TOPEX-II moorings (1 to 8 in fig. 1), equipped with 2 or 3 Aanderaa current meters, were deployed from January 25 until 31, 1991. The sampling depths ranged between 2 and 17 mab.

2 Meteorological observations

Onboard RV "Gauss" meteorological observations were recorded every two hours so that the local weather conditions are sufficiently documented during both experiments. During TOPEX-1 strong southwesterly winds between 5 and 12 bft (16 to 80 kn) were dominating. One day before the deployment of the moorings a strong storm had passed the area. The major event, however, was the violent storm from January 25/26 with wind speed up to 80 knots. It was caused by a 970 hPa trough westwards off Ireland on January 25. On January 26 its core had deepened to 950 hPa, now lying in the northern North Sea. The storm caused storm surges of 3.5 metres at the North Frisian coast, 2.3 metres in the Elbe estuary and 1.5 metres at the island of Helgoland (Neemann [1990]). A second storm, caused by a 975 hPa trough over the British Isles hit the area on January 28 a few hours.

One year later, during TOPEX-II, most of the time the wind came from the northwest with a maximum wind force of 6 bft (27 kn). Stickplots of the local wind vectors according to 2-hourly observations taken on RV "Gauss" are shown in fig. 2.

3 Local currents under moderate winds

The flow pattern of the TOPEX area is dominated by the semi-diurnal tides. They are locally characterized by strong flood currents which exceed the ebb currents by about 20%. The maximum flood and ebb currents are about 77 and 62 cm/s for spring tides and 62 and 51 cm/s for neap tides (DHI [1988]). The sticks in fig. 3 represent the hourly total mean flow at 2 mab during TOPEX-II, related to high water at Norderney and averaged over 8 tidal periods. The currents around the ridge are nearly homogeneous, there are no significant differences between positions over the ridge and positions in the troughs. Only the southernmost mooring (7) shows a different direction.

Fig. 4 shows the vertical structure of the flow by means of ADCP-measurements at the ridge-crest and in the landward trough (A2 and A1 in fig. 1). The vertical resolution is 1 m, the measurements cover the range between 3 mab and 3 m below the surface. The scalar hourly mean currents have been related to high water at Norderney. At both positions the strongest currents occur 3.5 to 1 hours before and 3.5 to 6 hours after high water. At trough position A1 the flood current exceeds the ebb current by about 30 cm/s (>30%). The local wind blew from 310° to 320° (3 to 4 bft), i.e., it had the tendency to enhance the eastward flood current but to weaken the ebb current. During the ADCP-measurements at the crest (A2) the wind came with 2 to 4 bft from 45° to 130°. Therefore the flood current – being normally stronger than the ebb current – was weakened and both currents had nearly the same strength. Generally, the near-bottom maximum currents at the crest are up to 20 cm/s stronger than in the troughs.

A tidal current analysis of historical time series over the ridge at position "B" in fig. 1 (DHI [1988]) suggests that the maximum ebb and flood currents are focussed in a direction which cuts the ridge axis under an angle of about 20 to 30° (Fig. 5). This agrees with observations at shoreface-connected ridges about 10 miles eastwards of this area (Flemming, [1991]). Hourly averaged ADCP-data from the crest position (A2), recorded at winds less than 20 kn, suggest basically the same directions relative to the ridge at levels deeper than 5 to 6 m below the sea surface.

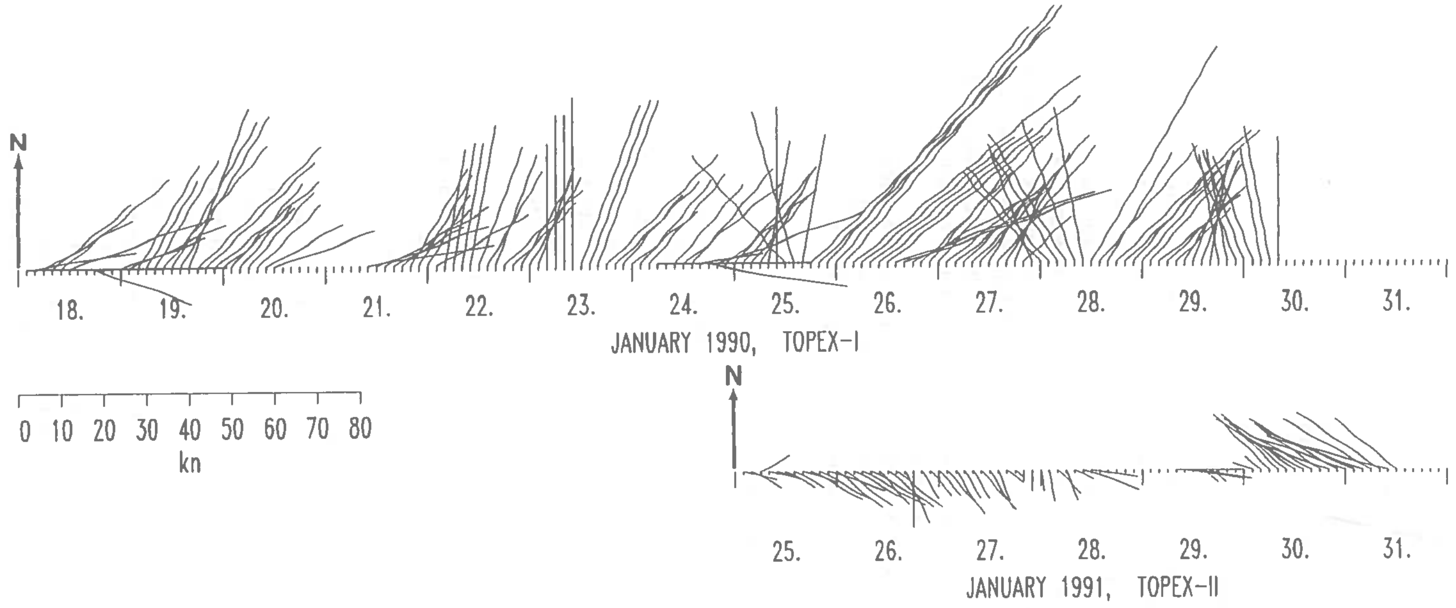

Fig. 2 Stickplots of the local wind vectors according to two-hourly observations taken on RV „GAUSS“. During the gaps in the time series the ship operated outside the investigation area.

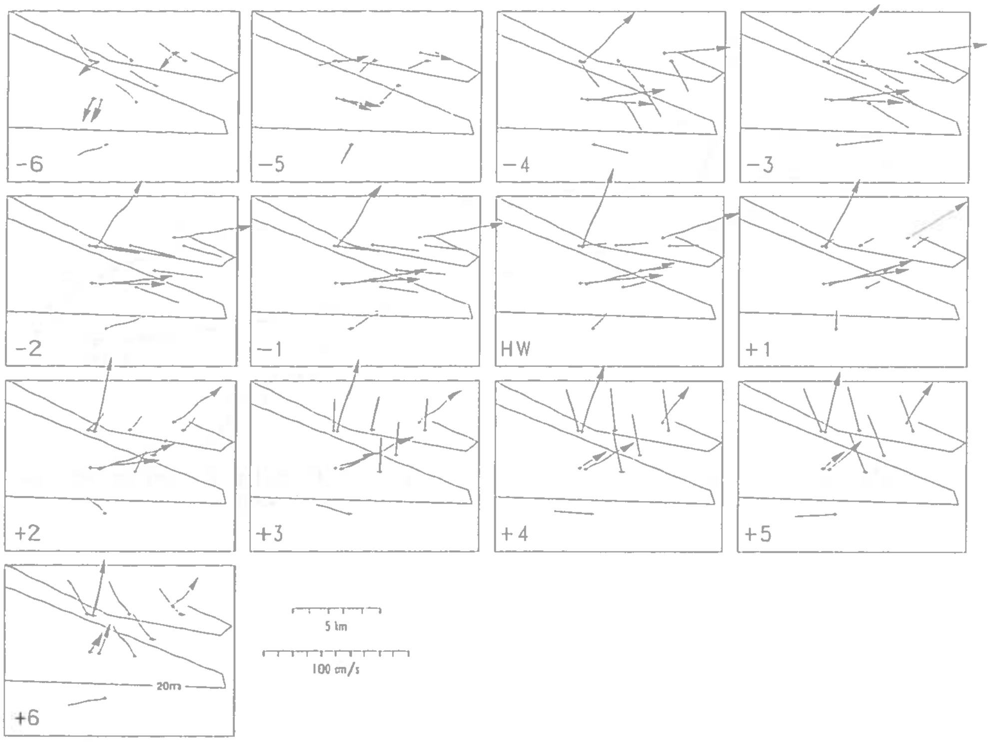

Fig. 3 **Hourly** averaged mean flow. The numbers give the hours related to high water at Norderney. **Sticks:** Mean of 8 tidal cycles (Jan. 25 to 29, 1991) at 2 mab. **Vectors:** Flow at 1 mab during the violent storm related to high water Jan. 25, 1990, 21:44 UTC. The position of the ridge is schematically outlined by the 20 m-isobath.

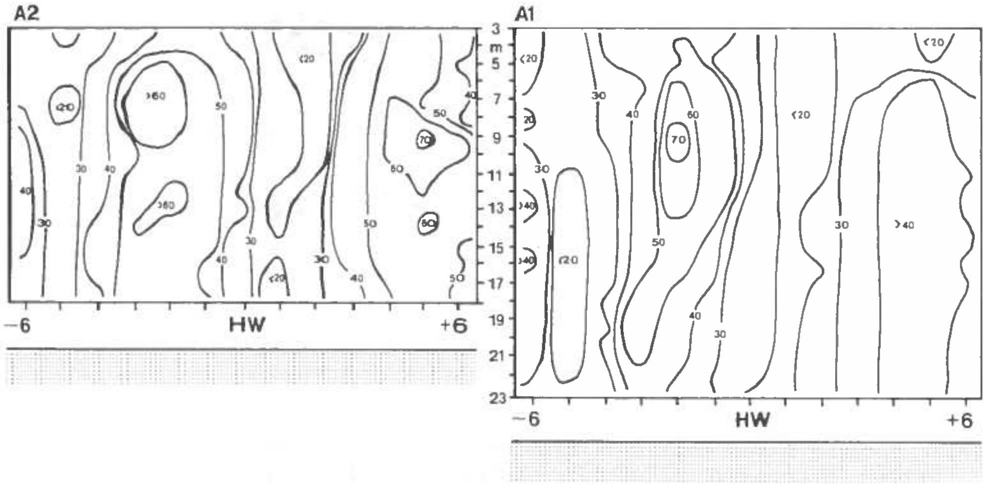

Fig. 4 Vertical total flow pattern (hourly scalar mean values) basing upon ADCP-measurements at position A2 (crest) and A1 (trough), related to high water at Norderney (TOPEX II).

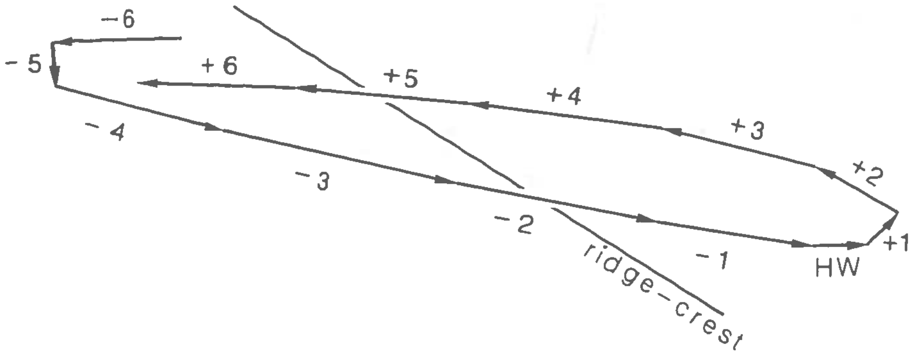

Fig. 5 Tidal current over the ridge-crest, calculated for position „B" in Fig. 1. Numbers are hours relative to high water at Helgoland (from DHI [1988]).

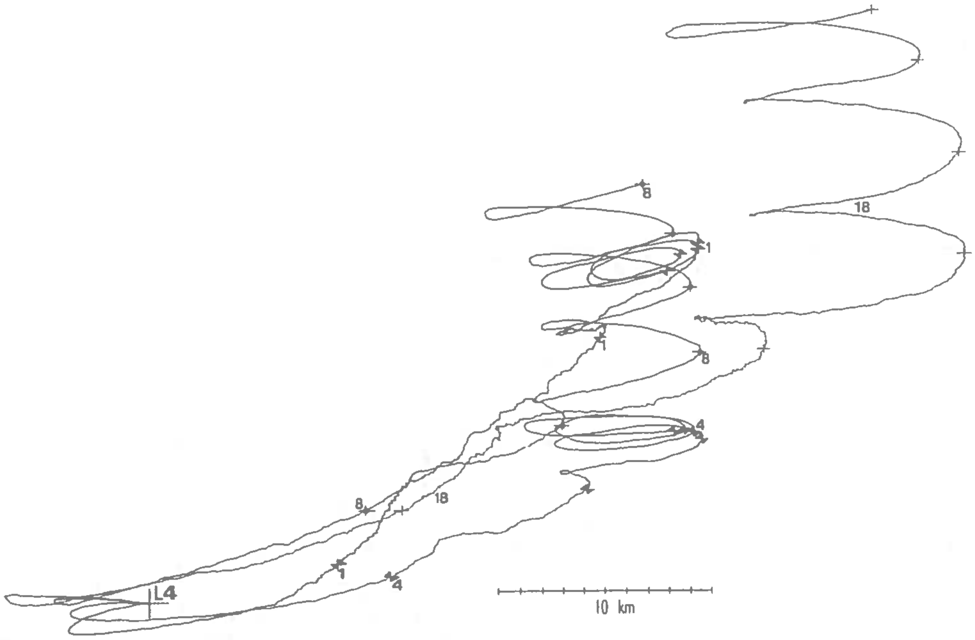

Fig. 6 Progressive vector diagrams at mooring L4 from Jan. 25 (12:00) to Jan. 28, 1990 (12:00). Symbols are given every 12 hours. The numbers give the distance from bottom in metres (24 m water depth).

4 Local currents under a violent storm

The violent storm from January 25/26, 1990, markedly influenced the flow from the surface down to the bottom. The wind speed exceeded 60 kn (12 bft) for nearly 12 hours, the prevailing wind direction was 220° to 230° (see Fig. 2). The bold vectors in fig. 3 represent the hourly averaged current at 1 mab, related to high water at Norderney on January 25 at 21 : 41 UTC. Within a few hours after the onset of the storm the near-bottom currents in the troughs approximately followed the local wind direction. At the ridge crest the current at 1 mab crossed the ridge nearly perpendicular. Progressive vector diagrams indicate, that the strong storm-induced eastward currents suppressed the directional alternation of the tidal currents for more than 20 hours (Fig. 6).

Table 1 compares the vertical energy distribution of the currents during the storm-period and during a calmer period. Shown are data from mooring K2, L3, and from the "Rhönrad" R, averaged over 24.5 hours. The first averaging period runs from January 21 to 22 with wind speeds between 20 and 30 kn (5 to 7 bft). The second period includes the violent storm. The positions of the three moorings are not more than 400 m apart.

Table 1

Vertical distribution of current speeds and energies

mab	v_{max}	v	$\boldsymbol{v}$	SF	k_E	k_M	k_E/k_M	SI	
m	cm/s	cm/s	cm/s	%	cm^2/s^2	cm^2/s^2	–	min	–
January 21 00 : 00 – January 22 00 : 30, 1990, wind: 5 to 7 bft									
18.0	196	107	39	37	5885	774	7.6	2	L3
12.0	56	38	4	10	738	7	105.4	2	K2
1.0	28	18	< 1	1	165	< 1	1646.0	2	K2
0.3	28	13	3	21	104	4	26.0	1	R
January 25 18 : 00 – January 26 18 : 30, 1990, wind: 10 to 12 bft									
18.0	247	115	100	87	2823	5039	0.6	2	L3
12.0	102	73	45	61	1716	1022	1.7	2	K2
1.0	78	43	29	67	588	425	1.4	2	K2
0.3	56	16	2	13	216	216	1.0	1	R

mab = metres above bottom, v = scalar mean speed, $\boldsymbol{v}$ = mean vector speed, SF = $(\boldsymbol{v}/v) * 100$, k_M = mean kinetic energy, k_E = eddy kinetic energy, SI = sampling interval

During the first period the scalar speed v decreased strongly between 18 mab and bottom. At 12 mab v amounts to 35 %, at 1 mab 16 %, and at 0.3 mab 12 % of the speed at 18 mab. Due to the tides the stability of the current, indicated by the stability factor $SF = (v/v) * 100$, is generally weak, only at 18 mab a slight stabilisation due to the winddrift is noticeable. At all four levels the eddy kinetic energy k_E exceeds the mean kinetic energy k_M 1).

The storm significantly enhanced the downward energy transfer. At 12 mab the mean scalar speed still amounts to 64% of its value at 18 mab. at 1 mab 38 % and at 0.3 mab 14 %. Compared to the first period, at 18 mab we observe an amplification of the mean scalar speed of only 8 %. At 12 mab this increase amounts to 93 % and at 1 mab even 145 %. Below 1 mab bottom friction reduced the increase of the mean speed to 22 % (0.3 mab). but its relative amplification is stronger than at 18 mab. This downward transfer of kinetic energy causes roughly a halving of the vertical shear between 18 and 12 mab, but a fivefold amplification of the near-bottom shear between 1 and 0.3 mab. Furthermore, the strong winddrift within the whole water column amplified the stabilty factor and considerably reduced the k_E/k_M-ratio. At 0.3 mab the storm enhanced k_M and k_E by a factor of 57 and 2, respectively. This energy surplus – together with an intensified energy input from surface waves – is available for resuspension processes.

5 Resuspension of sediments

The erosion and transport of sediment is influenced by unidirectional and oscillatory flows. Compared to the period of oscillatory wave motions, tidal currents can be considered as quasi-unidirectional. In the TOPEX area the sediment grain size D ranges between 0.125 and 0.500 mm (3 to 1 Φ, fine to medium sands) with finer sediments on the ridge and the coarsest sediments in the troughs (Swift et al. [1918]). Grain sizes greater 0.5 mm can be found at a few randomly distributed spots. The unidirectional near-bottom flow exerts a stress τ on the sediment particles which depends upon current speed and sediment grain size D. At a critical stage the particles are removed from the bottom and can be transported by the local currents. The stress can be related to the flow at 1 mab, u_{100}:

$$\tau = C_{100}\, \rho\, (u_{100})^2$$

The frictional drag coefficient C_{100} amounts to about 3×10^{-3} (2×10^{-3} to 4×10^{-3}) for hydrodynamical rough flows, i.e., for $u_{100} > 15$ cm/s (Komar [1976]), ρ is the density of sea water. Table 2 summarizes u_{100} values for different weather conditions and different locations during TOPEX-1.

The threshold stress for initial sediment movement τ_t can be evaluated from the relative stress θ_t:

$$\theta_t = \frac{\tau_t}{(\rho_s - \rho)\, gD}$$

The density of the quartz grains ρ_s amounts to 2.65 g/cm^3, g is the acceleration of gravity. The θ_t-values for the different grain sizes were taken from Komar [1976, page 109]). The bold curve in fig. 7 represents τ_t as function of D, the second curve τ (u_{100}). To mobilize sediments with a diameter of 0.125 mm, for example, the stress must exceed about 13 g/cms^2, i. e., u_{100} must be greater than 62 cm/s (broken line). During the storm u_{100} reached values up to 100 cm/s over the ridge and about 80 cm/s in the trough. Maximum grain sizes which can be resuspended are 0.48 and 0.33 mm, respectively. According to this model, nearly all locally occuring grain sizes can be resuspended over the ridge.

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1) $K_M = 0.5\, (\overline{u}^2 + \overline{v}^2)$, $K_E = 0.5\, (\overline{u'u'} + \overline{v'v'})$. u and v are the east-west and north-south components of the velocity vector.

Table 2

Mean and maximum current speeds at 1 mab (u_{100}) during TOPEX-1

Time:			
from:	21. 1. 90 18 : 00	25. 1. 90 20 : 00	27. 1. 90 18 : 00
to:	22. 1. 90 6 : 14	26. 1. 90 8 : 14	28. 1. 90 6 : 14
Wind:			
speed:	5 to 7 bft. 20 to 30 kn	10 to 12 bft. 47 to 80 kn	5 to 8 bft. 16 to 36 kn
direction:	190 to 230°	220 to 230°	140 to 160°
	cm/s	cm/s	cm/s
Ridge:			
K1 u	18.9	–	–
u_{max}	31.8	–	–
K1A u	–	57.2	24.8
u_{max}	–	100.4	43.0
Trough:			
K2 u	15.2	47.7	19.4
u_{max}	23.4	78.0	37.4
L3 u	15.9	37.7	21.4
u_{max}	24.8	78.0	38.8

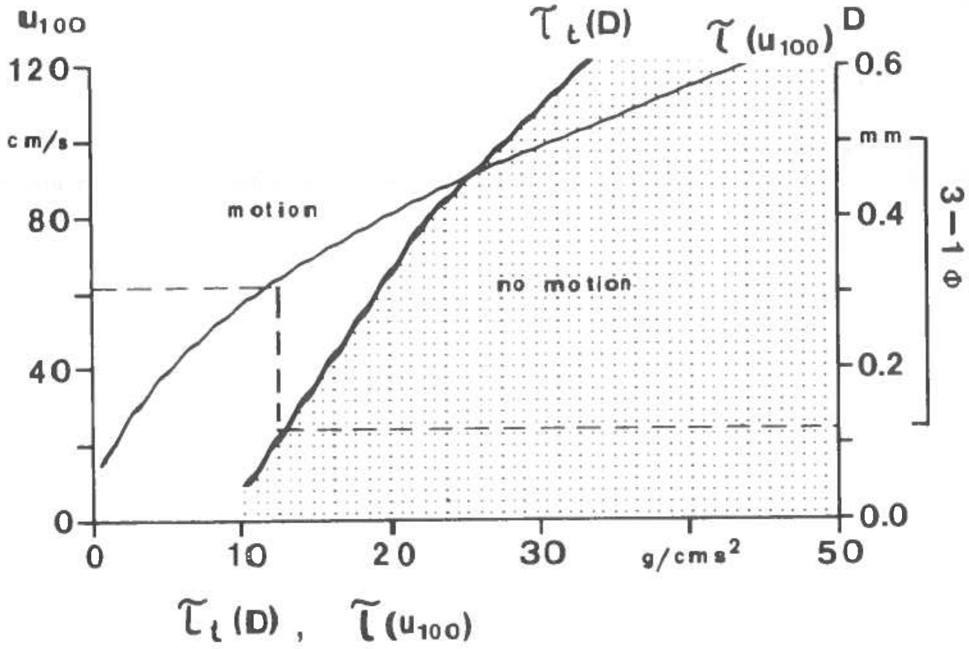

Fig. 7 a) Stress $\tau(u_{100})$ exerted by the flow upon the sediment particles as a function of the current speed measured at 100 cm above the bottom (u_{100}). b) Threshold stress $\tau_t(D)$ as a function of grain size D. The diagram holds for unidirectional flow with $u_{100} > 15$ cm/s and $D < 0.5$ mm.

Additionally, the sediments are exposed to the to-and-fro motion induced by surface waves. The maximum velocity of these oscillatory currents reach 57 cm/s at 20 m depth for a 6-second wave with a significant wave height of 2.3 m – typical for this area. On January 25/26, 1990, a wave rider buoy westwards off Sylt (see Fig. 1) recorded a significant wave height of 5 m and a period of about 9 s at a total depth of 19 m (Berger [1991]). The corresponding maximum orbital velocities at the bottom are about 150 cm/s. Regarding the offshore wind direction of the storm in the TOPEX area, the increase of sea state is probably smaller, but wave-induced near-bottom orbital currents up to about 100 cm/s can be assumed.

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