On currents in the coastal zone of African shelf off Saint Louis*

OCEANOLOGIA, 21, 1985
PL ISSN 0078–3234

Currents
Tidal currents
Trade-winds
Canary Current
Saint Louis

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Manuscript received 2 April 1984, in final form 25 September 1984.

Abstract

Current measurements were made in the shallow zone of African shelf off Saint Louis (Senegal) between May 1980 and end of January 1981. Three characteristic periods with a different current structure were distinguished:
(i) the first period (V, XII, I and probably II, III, IV) is characterized by velocities in the interval of 15 to 33 cm/s and a pronounced southern direction of current,
(ii) the second period (VI, VII, VIII) is characterized by small velocities and the absence of a predominating current direction, with the exception of June, when the northern direction predominates,
(iii) the third period (IX, X, XI) is characterized by large velocities of currents in both directions, northern and southern.
All these situations are connected with the influence of trade-winds and their spatial-temporal changes.
In the current spectra, the predominance of semi-diurnal components (M2–12.42 hours and S2–12.0 hours) may be observed. Mean values of the semi-diurnal tidal current, calculated from dependence 2 (M2+S2), equal from 5.4 to 2.1 cm/s. The predominant type of current in the investigation area is the semi-diurnal irregular tidal current. Tidal characteristics (amplitude and phase shift) undergo deformations under the influence of changing depths (among other factors).

1. Introduction

The dynamics of the surface Atlantic water in the tropical zone is mainly determined by trade-winds and their spatial-temporal changes. Most intensive processes of enormous amounts of water masses transport under the trade-winds influence take place in the belt contained between the Equator and the 20th parallel N and S [3].

The structure of currents in the coastal zone of Senegalese waters at 16°N latitude was investigated from May 1980 to January 1981 inclusive. The area at this

* The investigations were carried out under the research programme MR.I.15, coordinated by the Institute of Oceanology of the Polish Academy of Sciences.

latitude is under the influence of cold waters of the Canary Current, flowing from the north along the West African coast. Mean velocity of this current does not usually exceed 40–50 cm/s, reaching occasionally 60 cm/s [3, 6]. Steady north-easterly trade-winds increase the intensity of the Canary Current; their weakening results in lower intensity of this current.

The intensity of the north-easterly trade-wind is of great importance not only for the horizontal drift circulation but also for the geostrophic circulation [10]. In the surface layer the drift component predominates, but when the trade-wind is weakened the occurrence of the geostrophic circulation is observed even at the surface. At this point, it is impossible to neglect the Equatorial Countercurrent opearating from the south and south-west. This current is present up to 16°N in the 100 m surface layer [3, 6]. Farther north, it flows below the waters of the Canary Current. Such configuration of currents is observed in November and December [10]. At the boundary between the two currents, there are permanent cyclonic eddies, causing–among others–the rise of abyssal waters and the so-called 'upwelling' [5, 6]. The intensity of 'upwelling' decreases from north to south. Between Cap Blanc and Cap Vert it lasts for about 6 months [6].

In the summer period, westerly and south-westerly winds prevail. In the surface layer a gradient current, directed northward from the shore, is formed. The coastal, eastern leg of the Canary Current forms an area of convergence, unobserved in winter, at the place of contact with the gradient current.

The investigated area, although close to the shore, was subject to general processes taking place within the whole continental shelf. These processes are disturbed in the coastal zone as a result of the influence of factors characteristic for this zone, such as sea-way and its transformation in the zone of decreasing depths.

2. Material

Three separate current-measuring stations were installed in the investigated area (Fig. 1). Recording current meters were suspended on metal stands placed on the bottom while their spinning elements were about half meter above the bottom. The distances between the stations were about 1 km (looking from the coast); their depths were the following: station 1–12 m, station 2–13 m, station 3–19 m. Echo-sounder measurements revealed that station 2 was located at a rocky-sandy elevation, which was of considerable importance for the interpretation of measurement results from this station.

Two stations which recorded fluctuations in the water level were also organized in the investigated area. Station G was located in the estuary of the river Senegal, near Gandiole, and station P–near the new fishing pier in Saint Louis, on the river Senegal. Their location is presented in Figure 1.

Currents were recorded by means of BPW-2 current meters with time interval $Dt=0.5$ hours and Inter-Ocean current meters with time interval $Dt=1$ hour. The analog recording of sea level changes was performed with limnigraphs with a weakly

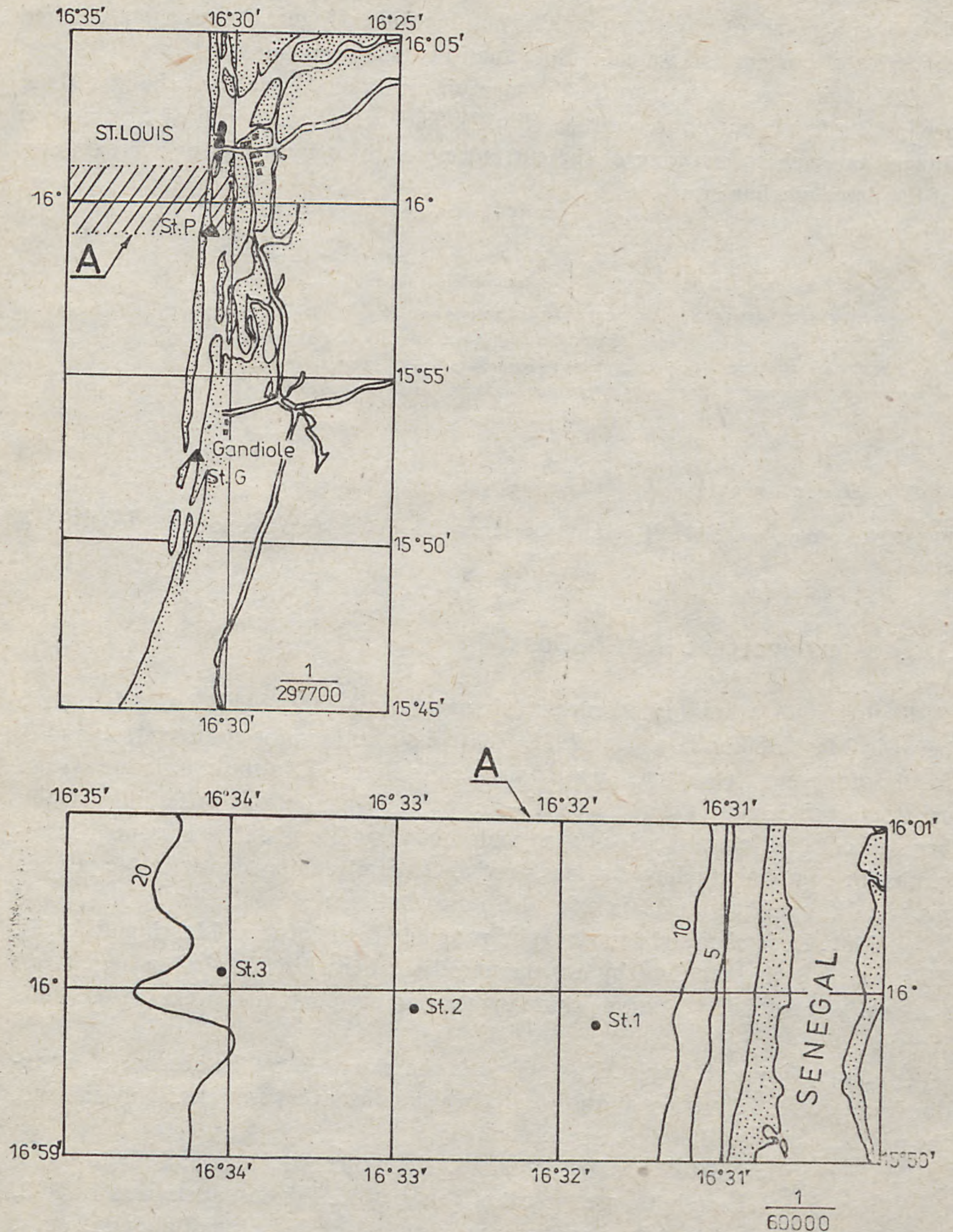

Fig. 1. Area of investigations off Saint Louis (Senegal) and location of current-measuring stations

recording paper strip. Besides, one of the Inter-Ocean current meters was equipped with a pressure sensor operating down to a depth of 15 m, which made it possible to record changes in the sea level and determine tidal constants for the coastal area. Tidal constants determined on the basis of measurements in the river estuary are flawed as a result of river 'dumping'. The diagram in Figure 2 presents a detailed timetable of current and water level fluctuations measurements.

Although there are no gaps in the measurements of the sea level changes, there are quite a few in current recordings (Fig. 2). They were usually caused by objective difficulties, such as jamming of the current meter rotor by plants or a breakdown of the drive mechanism.

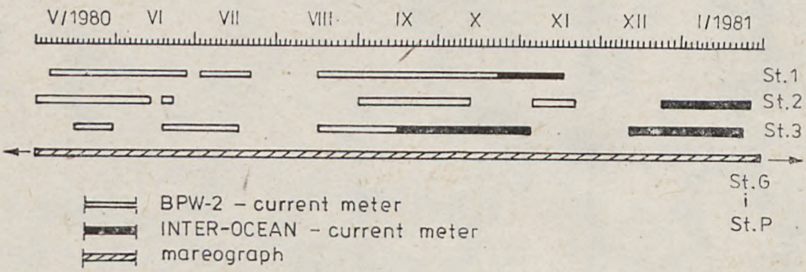

Fig. 2. Recording timetable of current measurements and measurements of sea level fluctu ations

3. Seasonal current distributions

Statistical distributions of current changes were determined for each month between May 1980 and January 1981. These distributions for stations 1, 2, and 3 for the along-shore component v are presented in Figure 3. In the coordinate system assumed, axis X ran east and axis Y – north. The distributions were built on the basis of constant current velocity intervals equalling 3 cm/s. The presented histograms for component v have various shapes. Generally, three characteristic periods may be distinguished on the basis of these distributions:

(i) May, December and January (and probably for February, March and April). This period is characterized by a pronounced southern direction of current at all stations. Velocities for the along-shore component are contained in the 15 – 33 cm/s interval;

(ii) June, July and August. The period is characterized by the absence of a predominant current direction and low current velocities at all stations. Only in June, the northern current direction predominated;

(iii) September, October, and November. High current velocities in both directions, northern and southern, are typical of this period. Besides, at stations 1 and 2, frequency maxima of velocity occurrence were noted for the value of about 15 cm/s, for both directions. At station 3, the distributions have one maximum in the velocity range of ± 3 cm/s for September and ± 6 cm/s for October.

The phenomena mentioned above depend on trade-winds and their intensity. This relationship is confirmed by the diagrams of seasonal current changes and trade-winds (Fig. 4). Diagram A shows the percentage share of current direction in the southern sector in all observed directions while diagram B presents the stability of

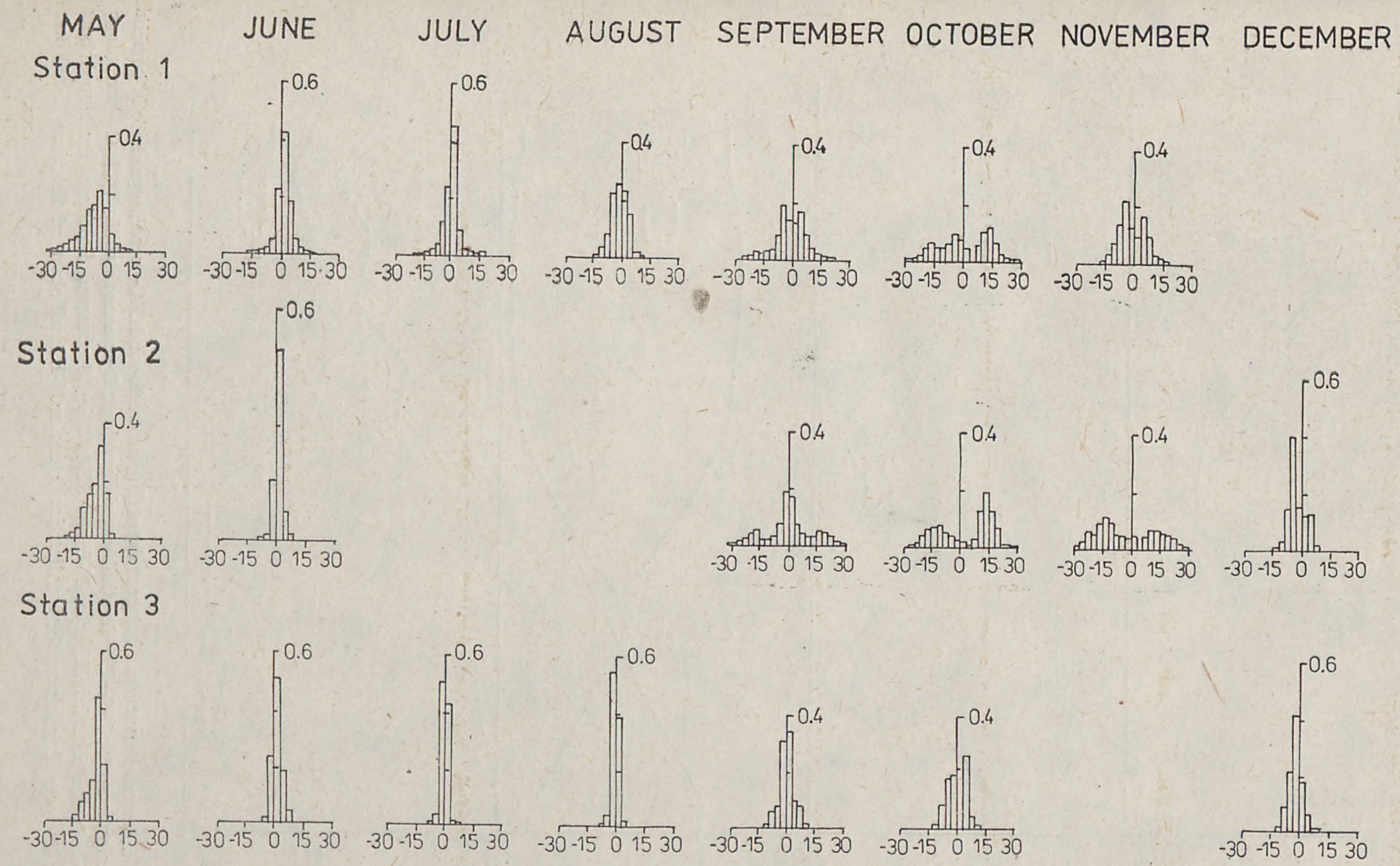

Fig. 3. Histograms of changeability of monthly along-shore current component v

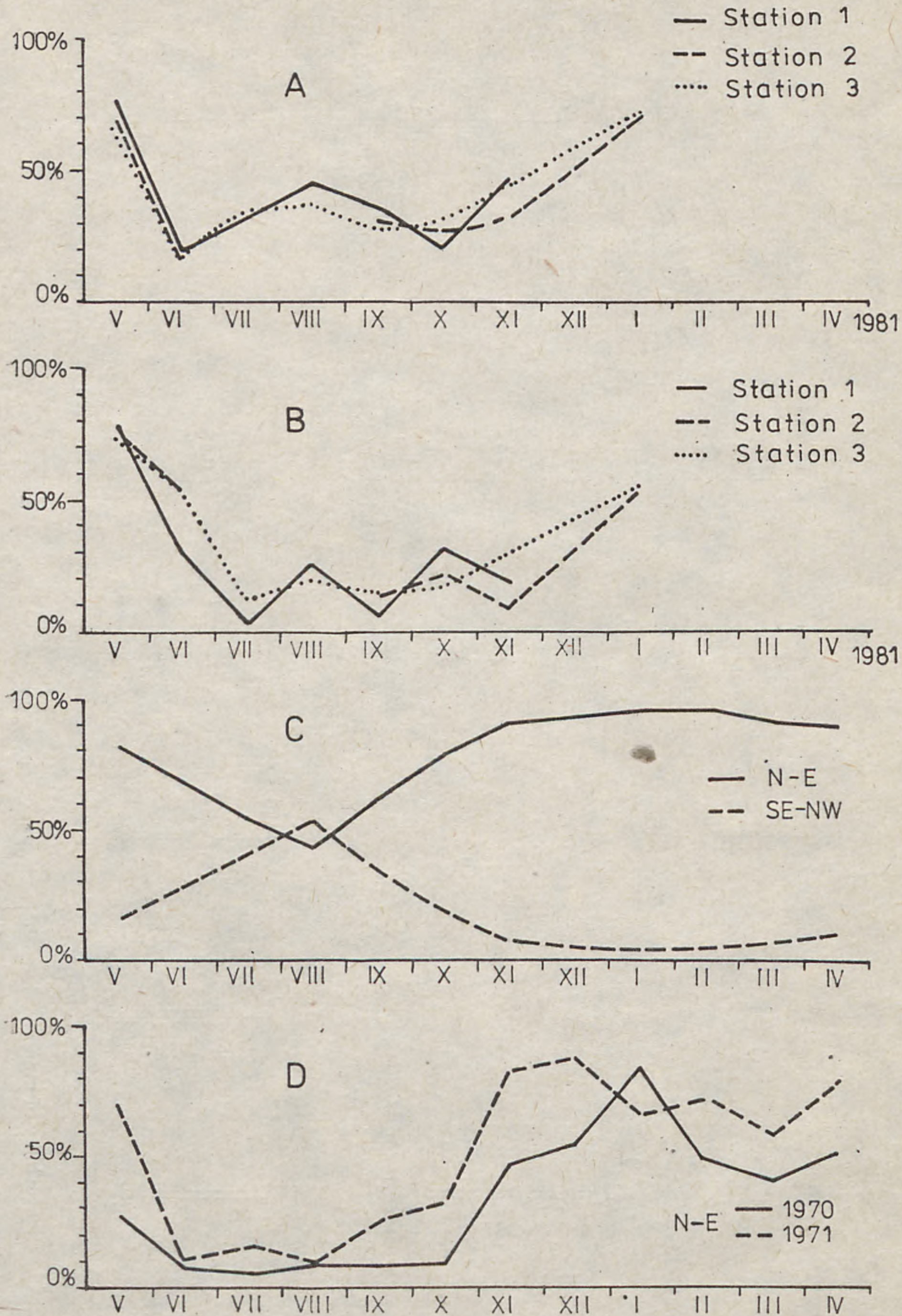

Fig. 4. Seasonal structure of current depending on trade-winds. A – percentage share of current direction in sector 165–195° in all observed directions; B – current stability [%]; C – percentage share of wind direction in sector N-E and SE-NW in all observed directions (for Nouakchott [9]); D – percentage share of wind direction in sector N-E in all observed directions (for Dakar [9])

currents (in %), defined as the relation of the vector mean to the arithmetic mean of current velocity. Diagrams C and D in Figure 4 show the frequency of wind occurrence from sectors N-E and SE-NW for Nouakchott and from sector N-E for Dakar [9]. The diagrams presented confirm clearly the influence of trade-winds on current structure and changeability in time. In the summer months, when the intensity of the north-easterly trade-winds decreases, the direction and stability of currents are similar in character. Between November and May, the north-easterly trade-wind increases in intensity acting along the coast from the north to the south. Such configuration of winds generates the most visible and stable water circulation in the whole year.

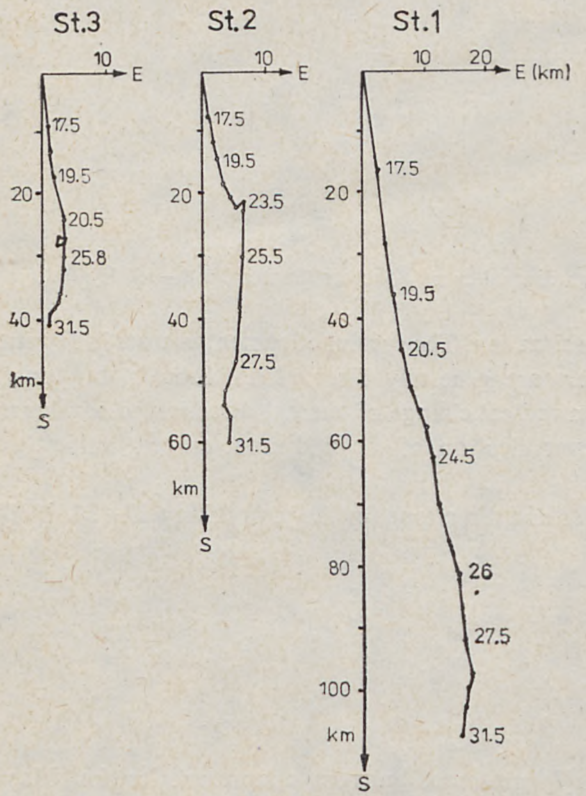

Fig. 5. Progressive development of mean diurnal current vectors (May 17–31, 1980)

Diagrams in Figures 5 and 6 present the evidence for the observed diversified systems of currents in the period of investigations. These figures present the progressive development of mean diurnal current vectors for two periods: May—a typical month for the intensive activity of the north-easterly trade-wind (Fig. 5), and the first half of September—when the trade-wind intensity decreases and the activity of the Equatorial Countercurrent becomes visible (Fig. 6). In Figure 5 current vectors are generally directed southwards and mean diurnal velocities assume almost

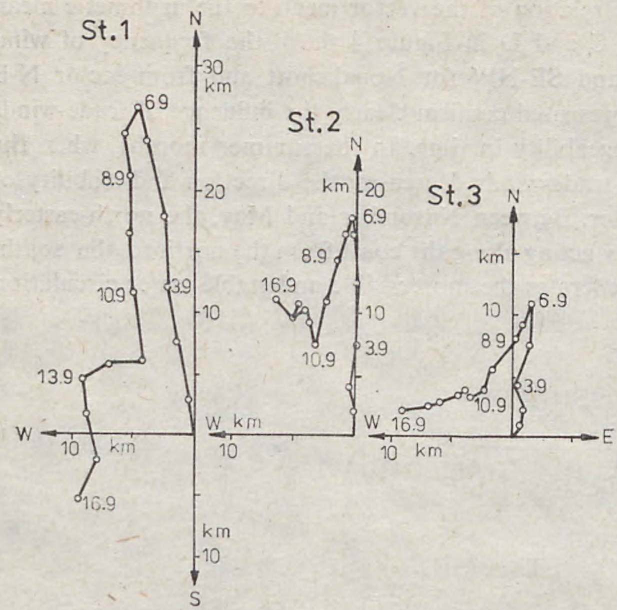

Fig. 6. Progressive development of mean diurnal current vectors (September 1–16, 1980)

equal values, which signifies a stable situation. The system of current vectors in Figure 6 is generally different. The vectors are generally directed northwards, but only until September 6. After that data a radical change of current direction to southern and western occurs. Besides, a diversification of mean diurnal current velocities may be observed.

Mean values of current velocities and directions for the period May 17–31, 1980 are the following:

Station	Velocity [cm/s]	Direction [°]
1	8.7	174
2	5.2	177
3	3.8	182

Mittelstaedt and Koltermann [7] presented current characteristics for May (May 3–18, 1968) in the shallow part of the shelf ($z=45$ m) at the latitude of Cap Blanc. Mean values of velocities and directions were the following:

Depth [m]	Velocity [cm/s]	Direction [°]
18	22	202
38	13	183

These authors determined the duration of the stable direction of mean velocity by means of a linear regression. For the period under consideration it lasted 2–3 days.

Finally, mean values on the shelf ($z=103$ m) north-west of the river Senegal estuary in the period between March 6 and 9, 1937 should be mentioned [11]. At that time, a weak current at the surface (0–20 m) was directed southwards and south-estwards. Below a depth of 30 m, the current was generally directed northwards.

4. Periodic structure of currents with special stress on tidal currents

Selected time series of current measurements were subjected to spectral analysis. The well-known Fourier fast transformation (FFT) algorithm was used for calculations. The calculated amplitude distributions of current velocities are presented in Figures 7 and 8. They are the so-called 'raw' distributions, determined without the use of smoothing and estimators. The figures present amplitude characteristics of the current velocity modulus $w=\sqrt{u^2+v^2}$ for stations 1 and 2 in May and June, 1980 (Fig. 7), and for stations 2 and 3 in December 1980 and January 1981 (Fig. 8).

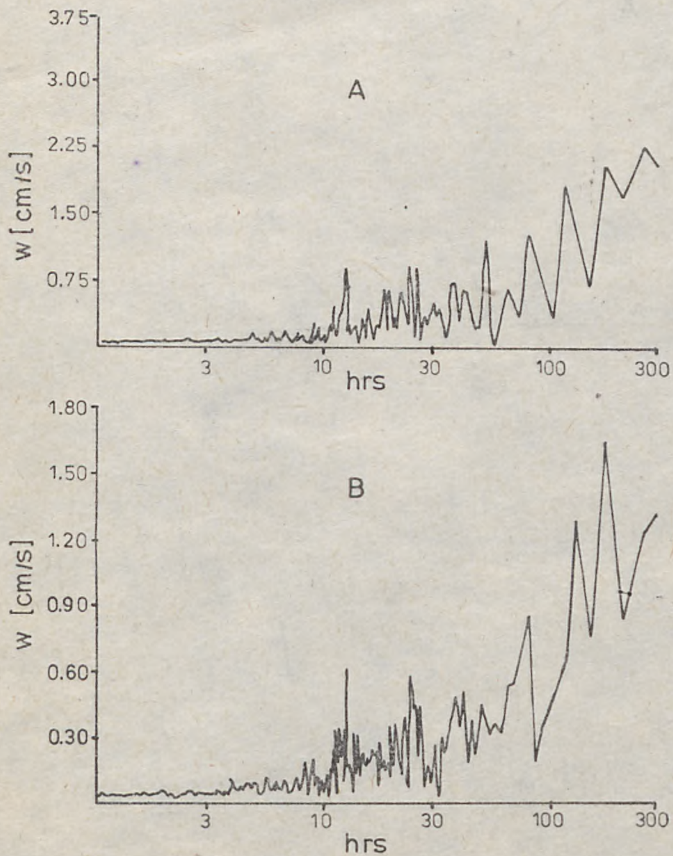

Fig. 7. Raw amplitude spectra of current velocity modulus in May and June 1980.
A–station 1: $N=2048$;, $Dt=05$ hr; B–station 2: $N=2048$, $Dt=05$ hr

The above distributions show distinct maxima corresponding to periods of tides mostly semi-diurnal (components M2 and S2) although their corresponding amplitudes are small and do not exceed 2 cm/s.

The material collected was subjected to a thorough analysis in order to separate significant energy maxima found in the investigated period interval. This was the basis for drawing (in a monthly set) of the distributions of maximum amplitudes for six selected periods (Fig. 9). These maxima were drawn for the along-shore current component. The distributions presented show the predominance of the semi-diurnal tidal component (M2 and S2). The maxima for periods of about 21.1 and 10.6–10.4 hours are also quite pronounced. These periods probably correspond to the energy maxima related to the changeability of local periodic winds. The value of current maxima amplitudes are influenced to a great extent by winds with a semi-diurnal period, connected with atmospheric pressure fluctuations at these

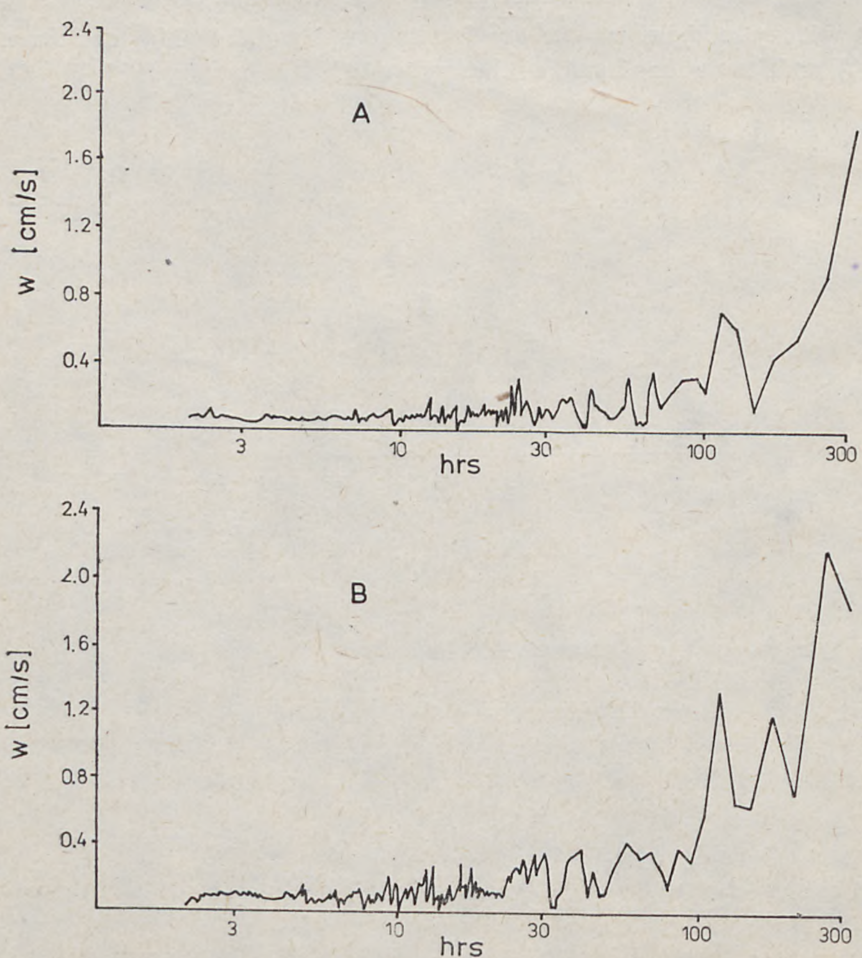

Fig. 8. Raw amplitude spectra of current velocity modulus in December 1980 and January 1981. A – station 2: $N=1024$, $Dt=1$ hr; B – station 3: $N=1024$, $Dt=1$ hr

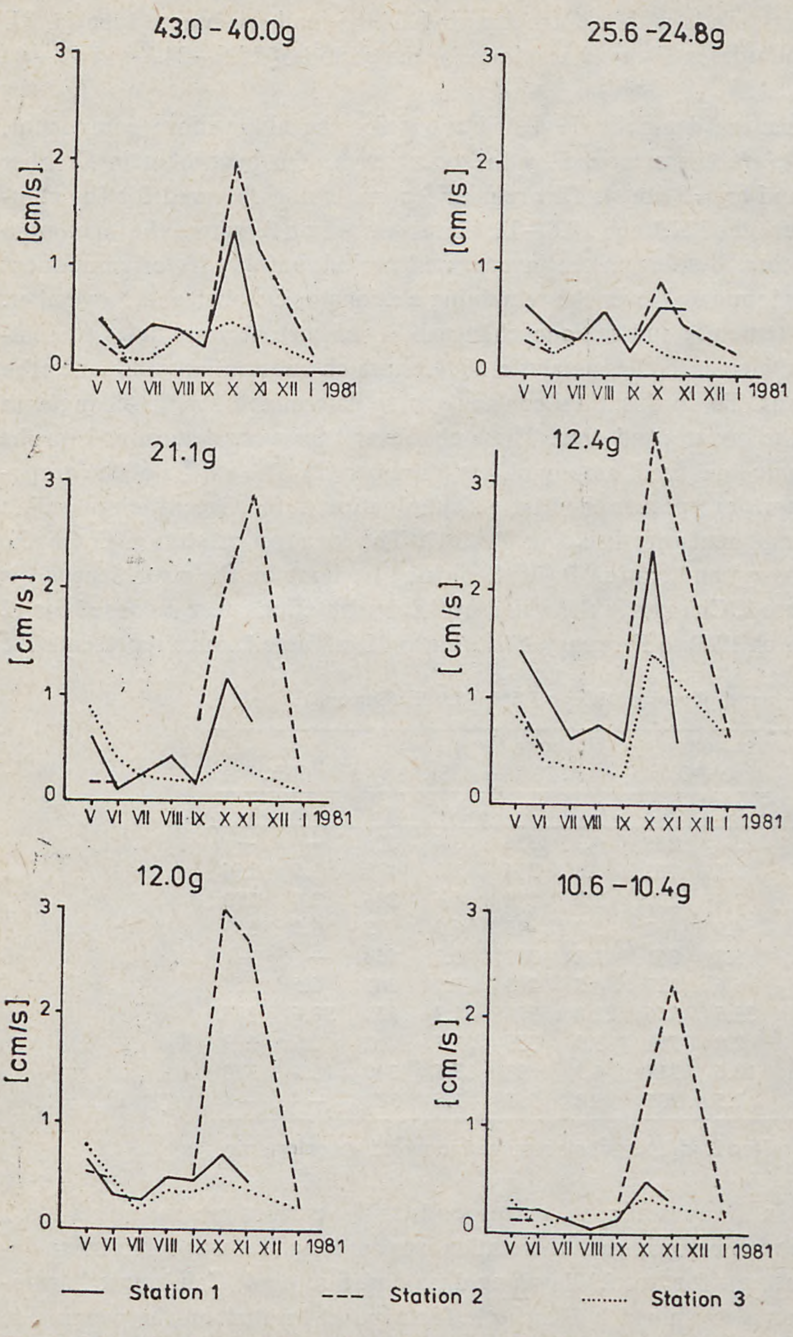

Fig. 9. Monthly changeability of maximum amplitudes of current along-shore component v for main oscillations in the investigated period interval

latitudes as well as winds with a diurnal period of the land-sea breeze type [5, 8]. The weakest amplitudes in Figure 9 are those for the period of 25.6 – 24.3 and 43 – 40 hours.

The above-mentioned amplitude distributions for the along-shore component, in a monthly set, are characterized by the occurrence of a maximum in October (v_{M2} = 3.5 cm/s and v_{S_2} = 3 cm/s). This regular feature is not observed for the components with a period of 21.1 and 10.6 – 10.4 hours at station 2, where the maximum occurs in November. Besides, in the investigated period, amplitudes of component v at station 2 predominated over the remaining stations in October and November.

The periodic structure and seasonal changeability of current amplitudes presented above necessitates a detailed analysis of tides which substantially influence the current phenomena. To do this, tidal constants were determined for the changes in the sea level in the investigated area. These characteristics were determined on the basis of a harmonic line, used, among others, in paper [2]. The values of the amplitudes and phases with respect to the Moon's culmination at the Greenwich meridian for the main components are listed in Table 1. The location of station G (in the river Senegal estuary) and station P (in the fishing harbour on the river Senegal) is presented in Figure 1. Changes in the water level at both stations were recorded for 12 months from March 1980 to February 1981. Station 1 in Table 1, most representative

Table 1. Amplitudes and phases of tides off Saint Louis (Senegal)

	Estuary (st. G)		Harbour (st. P)		St. 1		Cah.	
Component*	A	g	A	g	A	g	A	g
MSF	3.4	283	4.3	356	3.4	303	–	–
Q1	1.1	163	.8	216	2.0	181	1.6	256
O1	3.4	239	2.7	274	4.6	246	3.6	270
K1	4.9	2	3.7	41	6.3	3	6.5	353
MU2	1.8	261	1.2	301	2.7	254	–	–
N2	6.6	221	4.5	283	8.7	247	6.5	265
M2	32.5	256	22.8	324	41.9	289	38.6	283
L2	2.8	291	1.9	355	1.7	12	2.6	289
S2	12.6	317	6.9	23	17.5	340	16.4	320
M4	1.5	235	.8	267	1.5	322	–	–

* Components described by symbols assumed in world oceanography

for oceanic tides in the coastal zone, corresponds to the current-measuring station 1 (Fig. 1). The period of recordings at this station was not long, but was sufficient to determine tidal constants for two 29 day long divisions. Station 4 (Cah.) gives harmonic tidal constants, determined by Rochette for a point located on the ocean side off Saint Louis [1].

The predominance of semi-diurnal components M2 (12.42 hours) and S2 (12.0 hours) may be visible in the Table. Component N2 with a period of 12.66 hours is also significant for semi-diurnal tides. Among diurnal tides, components K1 (23.93 hours) and O1 (25.82 hours) are strongest. The results obtained at station 1 seem the

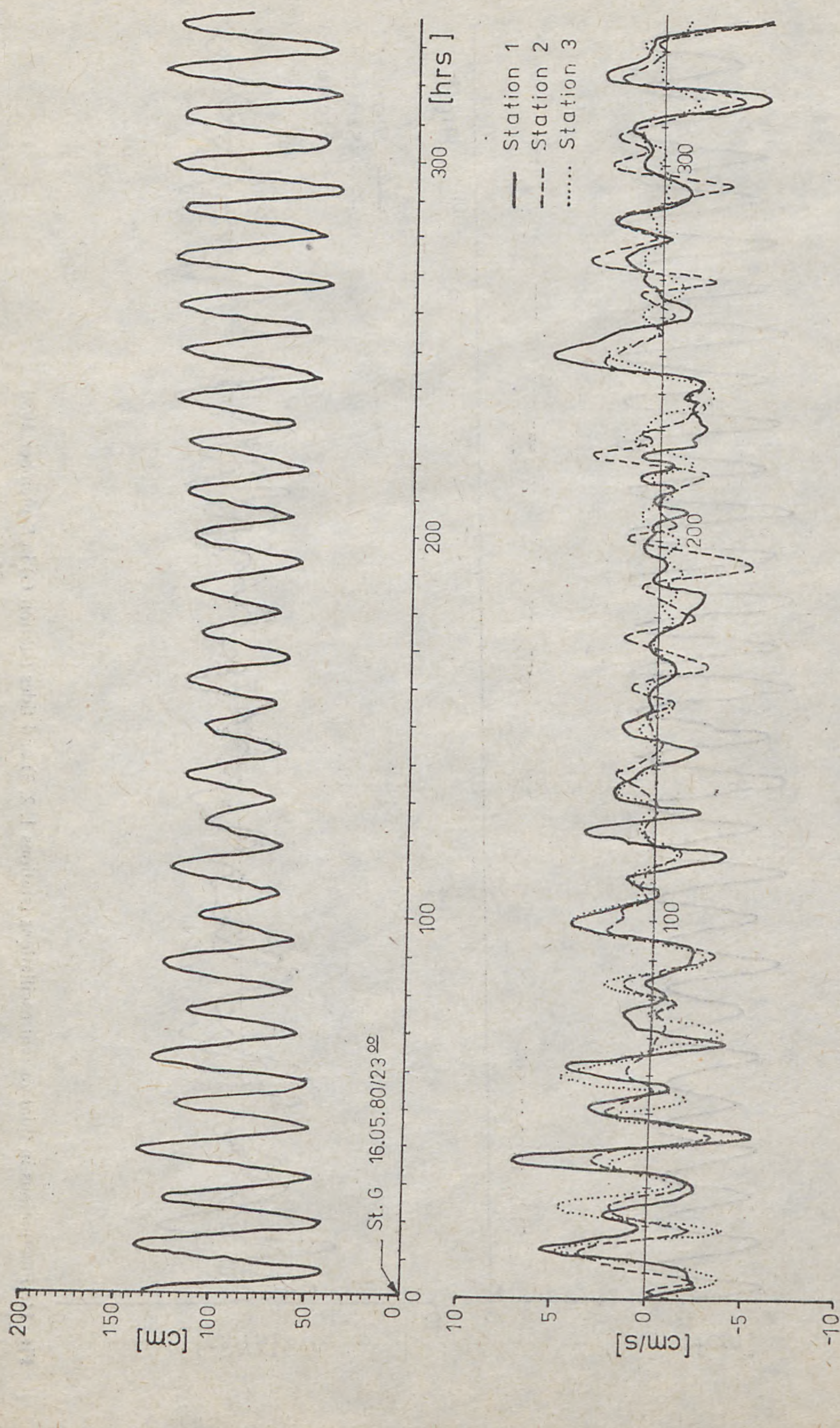

Fig. 10. Fluctuations in tidal current oscillations (stations 1, 2, 3) and tides (Station G) in May 1980

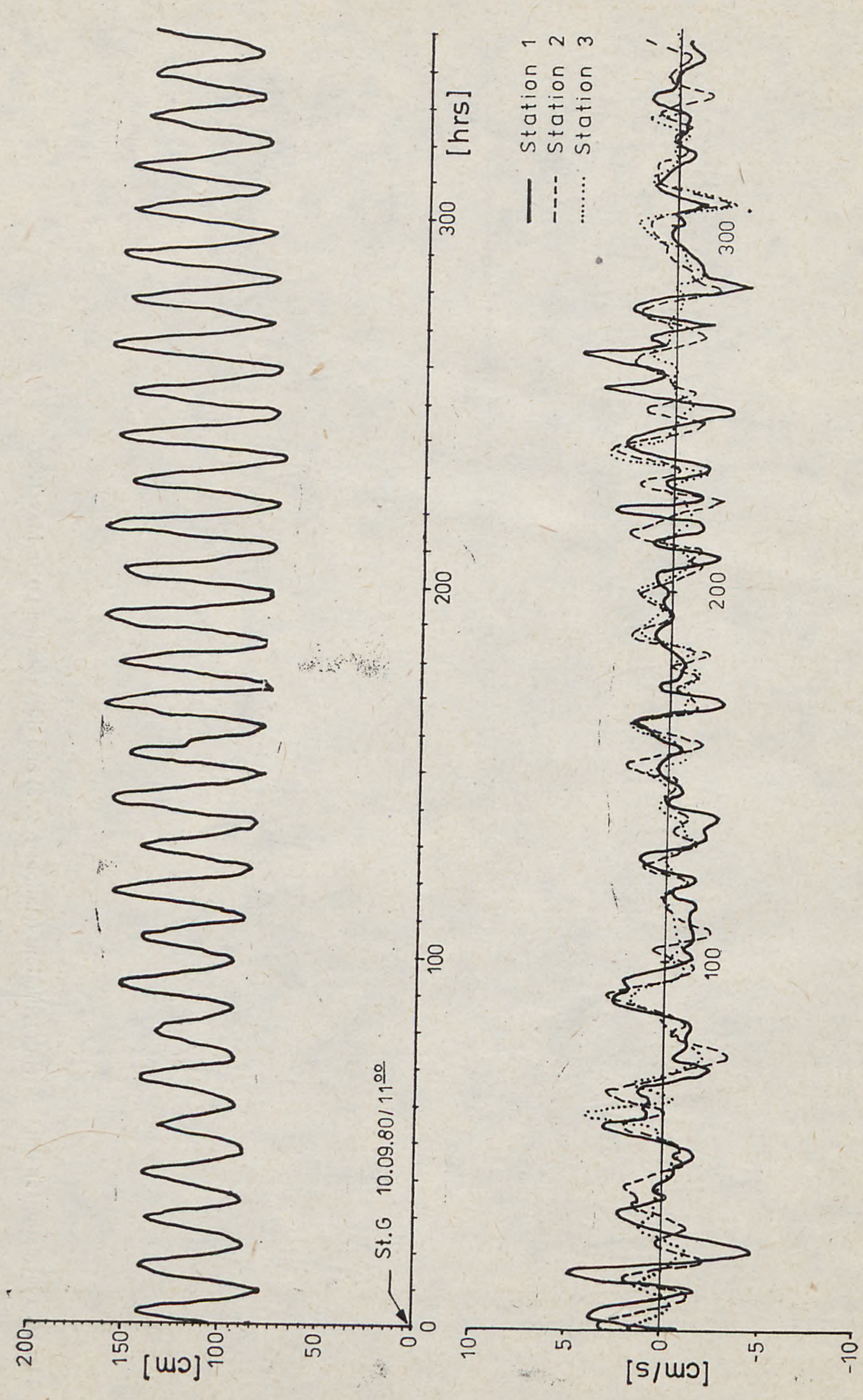

Fig. 11. Fluctuations in tidal current oscillations (stations 1, 2, 3) and tides (station G) in September 1980

most representative for further analysis. The values of constant tidal components M2 and S2 at stations Cah. and 1 are comparable; they differ considerably from the values determined at the stations on the river Senegal, where a substantial underestimation of the amplitudes and a large phase shift may be observed.

On the basis of the known dependence $F=(K1+O1)/(M2+S2)$, the type of tides was determined. At all stations, the values $F \leqslant 0.25$ were obtained, which means that in the investigated area regular semi-diurnal tides occur. The large share of energy maxima in the spectra of currents with tidal periods made us separate these components from the remaining signals. In order to do this, time series of currents were subjected to filtration by means of a band cosine filter with the characteristics $7 < T_0 < 14$ hours.

Fluctuations of tidal currents against the background of tides are presented in Figures 10 and 11. Figure 10 shows the changeability of tidal currents for the along--shore component v (stations 1, 2, 3), as well as tides at station G in May, when large activity of the north-easterly trade-wind is observed. Figure 11 presents the situation for September, when the conditions are different from those in May.

Table 2 presents mean amplitudes and phases of tidal currents for the four main tidal components (M2, S2, K1, O1). These characteristics were calculated by means

Table 2. Mean amplitudes and phases of tidal currents

Tidal components	Amplitudes and phases	Stations 1	2	3
	A_v	1.67	1.43	0.62
	G_v	261	217	193
M2	A_u	0.61	0.79	0.47
12.42 h	G_u	148	179	152
	A	1.78	1.64	0.80
	A_v	0.54	0.85	0.19
	G_v	354	287	232
S2	A_u	0.31	0.59	0.15
12.00 h	G_u	233	290	275
	A	0.63	1.04	0.24
	A_v	0.74	0.28	0.20
	G_v	333	266	177
O1	A_u	0.26	0.29	0.17
25.82 h	G_u	17	295	296
	A	0.79	0.40	0.30
	A_v	0.99	0.60	0.29
	G_v	208	297	336
K1	A_u	0.36	0.26	0.19
23.93 h	G_u	208	209	191
	A	1.06	0.66	0.35

$A_{v,u}$ – current component amplitudes,
$G_{v,u}$ – current component phases,

$A=\sqrt{A_u^2+A_v^2}$

of a harmonic analysis for several 29 day long divisions. The analysis of data from Table 2 shows the diversification of mean amplitudes and phases at individual stations. The largest amplitudes are at station 1, the smallest—at station 3. There is also a distinct phase shift between particular stations. Mean values of tidal currents (semi-diurnal) determined from the dependence 2(M2+S2) equal: 4.82 cm/s—station 1, 5.36 cm/s—station 2, 2.08 cm/s —station 3. For diurnal currents, mean values determined from dependence 2(K1+O1) are: 3.70 cm/s—station 1, 2.12 cm/s—station 2, 1.30 cm/s—station 3.

Next, dependence $F=(K1+O1)/(M2+S2)$ was used to determine the type of tidal current for this area. The values of F are: 0,77—station 1, 0.40—station 2, 0.62—station 3. The value of F contained in the interval $0.25<F\leqslant 1.5$ indicates the occurrence of a semi-diurnal-irregular type of currents. It can be seen that the value of F is different for tides and currents of this area. Regular semi-diurnal tides, characteristic for the fluctuations of the sea level, become irregular semi-diurnal tides for currents under the influence of many factors typical of this area. Tidal currents at station 2 are closest to the regular semi-diurnal type. On the shelf off Mauritania ($\varphi=21°06'$N, $\lambda=17°14'$W, and depth $z=45$ m), the same regularity in tidal phenomena was observed. For water level fluctuations F equalled 0.11, for tidal currents $F=0.33$ at a depth $z=18$ m and $F=0.5$ for $z=38$ m [7], The irregularity of the semi--diurnal tidal current is caused by the turbulent mixing on the shelf, especially in its shallow part. The proximity of the bottom also disturbs the phase value of tidal currents.

The values of tidal current amplitudes on the shelf off Cap Blanc and in the river Senegal estuary area are approximate [5, 7, 11]. According to Hagen, the mean amplitude fluctuates between 1.1 and 2.5 cm/s for component v and between 1.4 and 4.5 cm/s for component u for the whole vertical profile ($z=10$, 20, 40, 60 m). According to Mittelstaedt *et al*, amplitude (M2+S2) equals about 5 cm/s for component v and 3 cm/s for component u. For the measurement profile north-east of the river Senegal estuary, a station was located at a depth of 103 m [11]. Amplitudes of the semi-diurnal current were: 5.9 cm/s for v and 8.8 cm/s for u at the surface; 1.6 cm/s for v and 1.8 cm/s for u at the bottom. The short period of measurements (about 3 days) probably influenced the value of amplitudes in this profile.

All long, filtered time series of the recorded currents for the along-shore component v were subjected to spectral analysis and then the spectra were averaged for the whole investigated area. In this way a general amplitude distribution was obtained; it is presented in Figure 12. The differences in the values of mean amplitudes in Table 2 and Figure 12 resulted from the averaging of unequal time divisions. The values of mean amplitudes in Figure 12 are more representative because they present the situation for almost the whole period of measurements. These values undergo deformations at individual stations due to the changes in depth in the coastal shelf zone. It may be seen that tidal amplitudes reach the greatest values at station 2 (about 1.45 cm/s). The occurrence in this place of a well-pronounced peak causes a visible increase in the current velocity according to the well-known laws of hydrodynamics [4]. It may be added that the specific configuration of the coast line

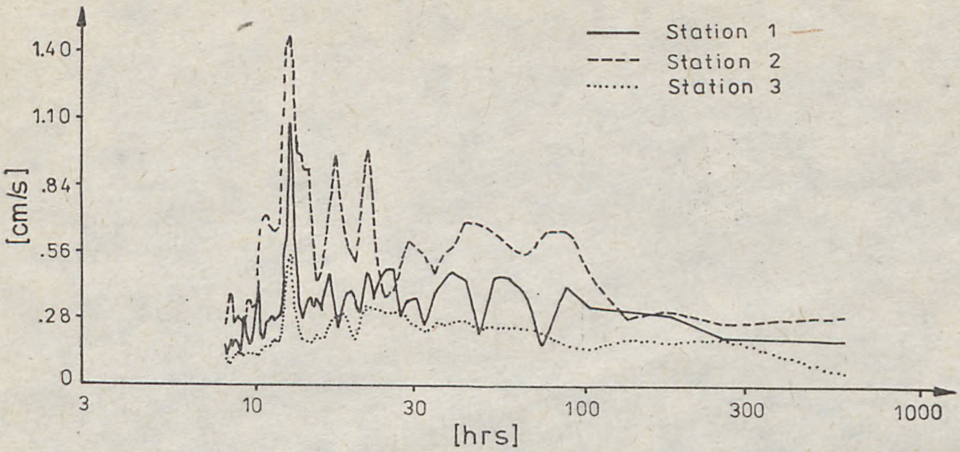

Fig. 12. Spectrum of averaged amplitudes for current along-shore component *v* (averaged for the whole period of measurements)

and the changes in depth cause the phenomenon of transformation of tides. The periodicity of tidal current phases is also disturbed. It should also be stressed that in nature we are faced with a complex system of tides and currents, with the process of interference, which are a universal and very significant phenomenon in the coastal zone.

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