Tidal currents in the western Mediterranean Sea

Tidal currents
Western Mediterranean

Courants de marée
Méditerranée occidentale

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ABSTRACT

A large number of several-month current time series is now available in the western Mediterranean Sea, and harmonic and spectral analyses provide spatially coherent information about the major tidal (M2, S2, N2 and K1) currents in the region. When they are significant, these currents are generally barotropic, they mainly rotate clockwise and their ellipses have orientations that are strongly dependent on the local bathymetry. From the Alboran Sea to the Algerian Basin, the Ibiza Channel and as far as the Sardinian Channel, the velocities of the semi-diurnal components continuously decrease from a few 10^{-2} m/s in the west to 10^{-3} m/s and even less in the east. The phases increase eastward from the Alboran Sea to 3-4° E in the western Algerian Basin, and can then be considered as constant as far as ~9° E in the Sardinian Channel. Such a phase variation is consistent with numerical models and results from the presence of an amphidromic zone near 0-2° E. Eastward of ~9° E, the phases should increase again, under the influence of another amphidromic zone located in the Sicily Channel. In both the Gulf of Lions and the Ligurian Sea, the velocities are extremely low and the ellipse characteristics are erratic, again in agreement with the models. In the Corsican Channel, where relatively shallow depths induce an increase of barotropic currents, the semi-diurnal components have a phase roughly opposed to that in the southwestern part of the sea. Considering the amphidromic zone in the Sicily Channel, this out-of-phase relationship is consistent with the occurrence of a zone of maximum elevation in the eastern Tyrrhenian Sea. The K1 currents in the Corsican Channel are lower than the M2 ones, but much larger than any other tidal current. They are exactly in phase with the elevation in the whole sea. All these results also prove that low tidal currents can be discerned in records made by simple instruments.

RÉSUMÉ

Courants de marée en Méditerranée occidentale.

Un grand nombre de séries temporelles d'une durée de plusieurs mois est maintenant disponible en Méditerranée occidentale, et les analyses harmonique et spectrale fournissent une information cohérente spatialement sur les principaux courants de marée (M2, S2, N2 et K1) dans cette région. Lorsqu'ils sont significatifs, ces courants sont généralement barotropes, ils tournent principalement dans le sens rétrograde et leurs ellipses ont des orientations qui dépendent fortement de la bathymétrie locale. De la mer d'Alboran au bassin Algérien, en passant par le canal d'Ibiza et jusqu'au canal de Sardaigne, les vitesses des composantes semi-diurnes diminuent de façon monotone de quelques 10^{-2} m/s à l'ouest jusqu'à 10^{-3} m/s, voire moins, à l'est. Les phases augmentent vers l'est de la mer d'Alboran jusqu'à 3-4° E dans l'ouest du bassin Algérien, et peuvent ensuite être considérées comme constantes jusqu'à ~9° E dans le canal de Sardaigne. Une telle variation de la phase est en accord avec les modèles numériques et résulte de la présence d'une zone amphidromique à 0-2° E. À l'Est de ~9° E, les phases devraient de nouveau augmenter à cause d'une autre zone amphidromique située dans le canal de Sicile. Dans le golfe du Lion et la mer Ligure, les vitesses sont extrêmement faibles et les caractéristiques des ellipses sont incohérentes, de nouveau en accord avec les modèles. Dans le canal de Corse, où des profondeurs relativement faibles induisent une intensification des courants barotropes, les composantes semi-diurnes sont mises en évidence avec une phase à peu près opposée à celle de la partie sud-ouest de la mer. Considérant la zone amphidromique dans le canal de Sicile, cette opposition de phase est cohérente avec la présence d'une zone d'élévation maximale dans l'Est de la mer Tyrrhénienne. Les courants associés à K1 dans le canal de Corse sont plus faibles que ceux associés à M2, mais beaucoup plus forts que n'importe quel autre courant de marée. Ils sont exactement en phase avec l'élévation dans l'ensemble de la mer. Tous ces résultats prouvent aussi que de faibles courants de marée peuvent être extraits d'enregistrements obtenus avec des instruments de conception simple.

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INTRODUCTION

As first pointed out by Defant (1961), the tides throughout the Mediterranean Sea result from the interaction between the energy entering through the Strait of Gibraltar and the motions directly forced by the generating potential within the sea. Partly thanks to the relatively high accuracy of satellite altimeters, there has been a revival of interest in the characteristics of the tides in the Mediterranean Sea, and more fundamentally in the relative importance of the two above-mentioned mechanisms. There are different opinions, so that the main problem regarding the Mediterranean tides is still debated. We shall focus on the major components: the principal lunar M2 (period of 12.42 h), the principal solar S2 (period of 12.00 h) and the larger lunar elliptic N2 (period of 12.66 h) semi-diurnal tides and the luni-solar K1 (period of 23.93 h) diurnal tide.

Tidal currents have been known for a very long time to be important in specific parts of the western Mediterranean Sea, such as the Strait of Gibraltar, the Sicily Channel and the Strait of Messina, as well as through small channels that connect coastal ponds to the sea. They have also been observed in the interior of the Mediterranean, for example in the Alboran (Vangriesheim and Madelain, 1977; Viudez and Tintoré, 1994) and Tyrrhenian (Moen, 1984) seas, but comparisons between various data sets or between data and models have been done only in the specific places mentioned above. Up to now, most of our knowledge has come from coastal sea level data which do not constitute a homogeneous and fully significant data set (none of the numerous references will be referred to in this paper which deals only with currents in the interior of the sea). These data are assimilated into numerical models, such as the one of Canceill *et al.* (1995), which provides charts for several constituents and a global solution, fitting the data with an accuracy of ~ ± 3.10^{-2} m over the whole sea. Very similar solutions are provided by other models, with no data assimilation but taking into account earth tides and loading effects (Lozano and Candela, 1995). This general information is complemented by local analyses, such as those by Lacombe and Richez (1982) and Candela *et al.* (1990) in the Strait of Gibraltar (from current and sea level data), and Molines (1991) in the Sicily Channel (from a numerical model assimilating sea level data). Up to now, satellite altimetry (as processed by Sanchez *et al.*, 1992) has provided coherent but seemingly not more significant information.

These reference works show that the M2 tide in the western Mediterranean is the dominant one almost everywhere. At the western end of the Alboran Sea (Fig. 1), the M2 wave has a sea level amplitude of ~3.10^{-1} m and a phase of ~50° with respect to GMT. An amphidromic zone extends from Spain to Algeria near 0-2° E. Then, progressing eastward, the amplitude smoothly increases in the whole Algero-Provençal Basin, up to more than 10^{-1} m in the eastern Tyrrhenian Sea; the whole region has a phase of ~230°. Another amphidromic zone, centered on the middle part of the Sicily Channel, is associated with an amplitude of ~8.10^{-2} m in the northern part of the channel. Concerning the tidal currents, the most reliable observations were collected on the eastern side of the Strait of Gibraltar. In the following, this zone is referred to as "Gibraltar" and the phase of the current indicates the time of maximum flooding, *i.e.* eastward. There, the amplitudes

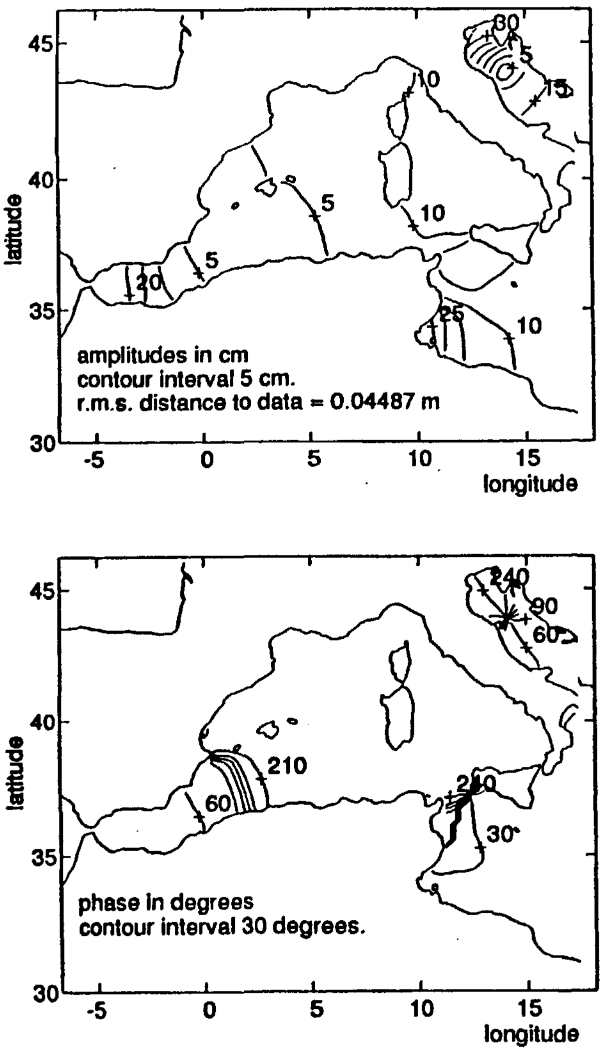

Figure 1

Cotidal chart for M2 according to Lozano and Candela (1995). Amplitudes (top) in 10^{-2} m and phase (bottom) in degrees with respect to GMT. According to Canceill et al. (1995), charts for S2 and N2 display very similar features.

and phases of the currents range between ~6.10^{-1} m/s and 130° at depth (200-300 m) and more than 1 m/s and 150° at the surface, which gives a mean phase of ~140° (Lozano and Candela, 1995). Therefore, the sea level having a phase of ~50° leads, as expected, the mean current by ~90°. Current measurements collected in the Sicily Channel have revealed relatively large amplitudes of the major tidal components, but harmonic analysis has not yet been performed. The available information in the Strait of Messina cannot be used directly since the tidal currents there depend strongly on the phase relationships between the Tyrrhenian and the Ionian seas. To our knowledge, no other harmonic analysis of current time series has been performed.

General features for S2 and N2 (charts not shown) are very similar, although less significant than for M2 (see Canceill *et al.*, 1995). For S2, the sea level amplitude and the phase at Gibraltar are ~12.10^{-2} m and ~75°. In the Tyrrhenian Sea and in the northern part of the Sicily Channel, the sea level amplitudes are ~5.10^{-2} and 3.10^{-2} m, respectively, associated with a phase of ~255°. For N2, the values range from ~5.10^{-2} m and 30° at Gibraltar to ~2.10^{-2} m in the Tyrrhenian Sea and ~$1.5.10^{-2}$ m in the northern part of the Sicily Channel, with a phase of ~210° in the two latter regions. The features for K1 (chart not shown) are very different (see Canceill *et al.*, 1995), with an amphidromic point only in the southern part of the Sicily Channel. The parameters are relatively homogeneous (~5.10^{-2} m and ~180°) throughout the western Mediterranean, although the amplitudes in the Tyrrhenian Sea are slightly lower than elsewhere (especially in the north of the Corsican Channel).

The amphidromic zones near 0-2° E and in the southern part of the Sicily Channel are the major characteristic of the cotidal charts of the main semi-diurnal components (as Fig. 1). Particular emphasis must be laid on these zones and especially on the first one, as several current time series are available in its vicinity (see Fig. 2). Note that the amphidromic point in Spain is virtual according to Lozano and Candela (1995, Fig. 1) and actual according to Canceill *et al.* (1995). If the anticlockwise rotation of the phase lines in

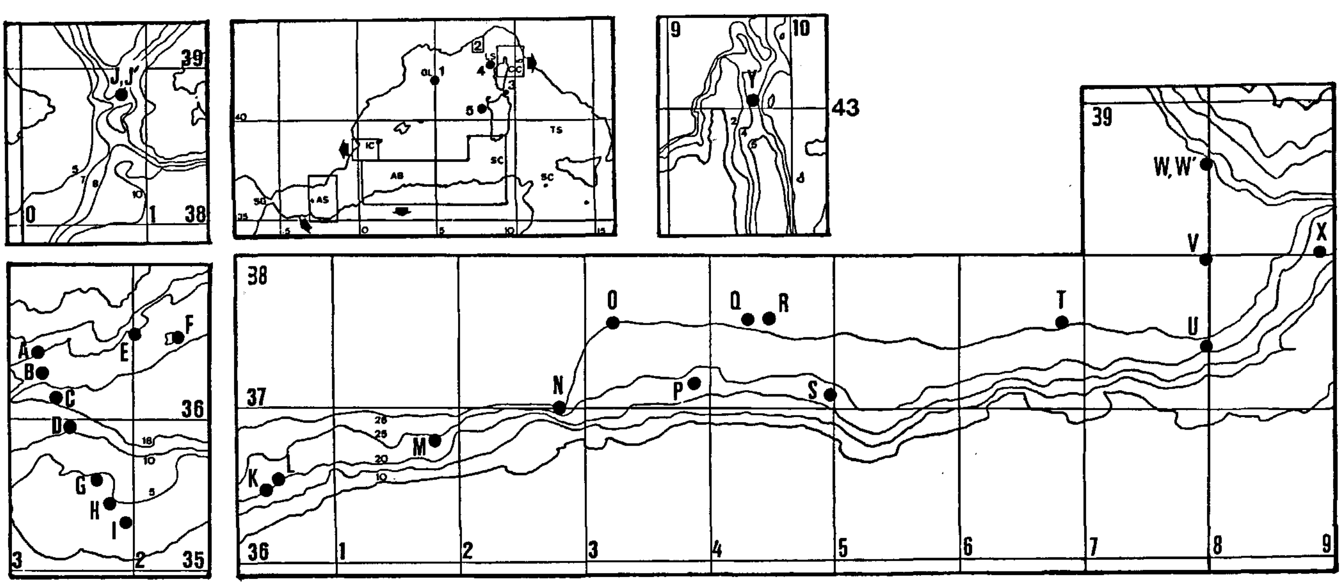

Figure 2

Location of the various experiments and points. Isobaths in hundreds of metres. Geographic zones defined by their initials (see text).

Fig. 1 is significant, the phases of the currents off Algeria slightly increase near 0-2° E as progressing eastward and are then more or less constant while, in the Ibiza Channel, they are expected to be more homogeneous. Otherwise, if there is no significant rotation, a nodal line of elevation can be considered, signifying roughly fully standing waves in the whole western Mediterranean Sea. The phase of the semi-diurnal currents will then be equal to the one of the sea level at Gibraltar + 90° (*i.e.* ~140° for M2, 165° for S2 and 120° for N2), especially in the vicinity of 0-2° E. Another point to be emphasized is that, according to both Lozano and Candela (1995) and Canceill *et al.* (1995), the phases of the semi-diurnal currents just inside the Ibiza Channel are expected to be roughly similar to those off Algeria near 4-5° E.

We will first present, in section 2, the details of the analysis and the data used for this study. The harmonic analysis of the current-meter time series, for the M2, S2, N2 and K1 components, is presented in sections 3 to 6. A discussion is provided in section 7.

METHODS AND DATA

Harmonic analysis has been performed following Foreman (1978) by considering only the major tidal components. The shortest record length to permit separation of the largest constituents, expected to be M2 and S2, cannot be shorter than two weeks. Nevertheless, computations with two- to three-week records (as A to I, see below) are not accurate and are obviously less significant than computations with several-month records (as J to Y); 60 and 18 constituents have been extracted, respectively, from the longest and shortest records. The shape of the ellipses will be characterized by their major (A) and minor (a, negative when the rotation is clockwise) semi-axes; the orientation (Θ) is defined with respect to East (increasing anticlockwise, mod. 180°) and the phase (G) is defined using the northern major semi-axis as reference. Some of our ellipses are oriented roughly north-south, so that the associated phases are clearly defined; but most of them are oriented roughly east-west, which induces a 180° uncertainty on the phase. In this case, and to be consistent with the literature (the phase corresponding to the eastward maximum), a Θ slightly lower than 180° has been replaced by Θ - 180° and the associated G by G - 180°.

The kinetic energy associated with the harmonic analysis ($K = A^2(1+r^2)/4$, $r = a/A$) has been compared with the value deduced from spectral analysis performed using the FFT and the 2-D formalism introduced by Gonella (1972). With several-month records, spectral estimates can be defined over frequency bands sufficiently small to separate the largest tidal components; the ellipses obtained with the two analyses are then very similar. Performing spectral analysis over several pieces permits definition of a stability coefficient as an estimate of the significance of both the spectral and harmonic computations. In such a way, it is clearly demonstrated that abnormal values of Θ and G correspond to quite unstable ellipses, and thus to non significant computations; this mainly occurs for records collected close to the surface due to the relatively low signal/noise ratio. The kinetic energy values are not reported here to avoid listing a large amount of numbers, but they can be found in an annex document (Rousseau, 1993).

Most of the data sets were collected with current meters for which the relationship between the velocity V and the number of rotations N is linear ($V = bN + c$), thus assuming a threshold velocity. Therefore, a fluctuating-tidal part of the current lower than the mean (almost constant direction) will be correctly estimated even if markedly low, whereas a larger one (alternating direction) will be overestimated. In most of the Mediterranean Sea, the subinertial currents are large with respect to tidal currents, so that the latter are expected to be discernible and accurate.

The data sets were collected with sub-surface moorings at various depths to the bottom, and during various seasons (Fig. 2 and Tab. 1). We will pay more attention to the longest data sets, because some records have just the minimum length required to perform significant analyses. Also to be noted is the fact that no significant results have been obtained for the analyses of the N2 and K1 components using records A-I, so that they are not presented. Moreover, although the major semi-axes computed from records K-P and R-S for K1 are often larger than for neighbouring frequencies (J1 and NO1), the orientations and the phases display large variability.

We have also analysed time series collected in both the Gulf of Lions and the Ligurian Sea, expected to be representative of the northern part of the western Mediterranean: two 5-month records collected at 300 and 800 m (point 1 in Fig. 2) from buoy BORHA-2 (kindly provided by C. Maillard of SISMER-Brest); twelve 7-month (PROLIG-2 experiment in 1985) and twenty-eight 5-month (PRIMO-0 experiment in 1990-1991) records collected by COM-La Seyne off Nice (zone 2); seven 2-week (in 1976-1977) records collected by SO-La Spezia in the Strait of Bonifacio (point 3); as well as three 9-month (THETIS-2 experiment in 1994) records collected by IFM-Kiel off western Corsica and Sardinia (points 4 and 5). Throughout the region, the tidal currents are extremely low (the computed major semi-axes are generally $<10^{-3}$ m/s) and the ellipse parameters highly variable, accounting for the non significance of the phase computations. These values are not reported in Table 1, even if the generally low amplitude of all the tidal currents in the whole northern zone, compared to other ones, is an important and significant fact.

Harmonic analysis of M2

The M2 characteristics vary in the Alboran Sea (A-I; Tab. 1). In the northern part of the sea, the ellipses at A-D have a large eccentricity (1-a/A) and are relatively similar in the vertical in both amplitude and shape; their orientation is closely related to the local bathymetry (see Fig. 2). The ellipses at E-F display some discrepancies in the vertical in amplitude, shape and orientation, which can be due to the time series being too short. Amplitudes larger at the bottom ($\sim 4.10^{-2}$ m/s) than at mid depth ($\sim 2.2.10^{-2}$ m/s) can result from uneven bathymetry contracting the streamlines, time-worn rotors or mooring swinging due to insufficient floatation. On the African continental shelf (G-I), the

Table 1

Major (A) and minor (a) (negative when the rotation is clockwise) semi-axes in 10^{-2} m/s, orientation with respect to East (Θ) and phase with respect to GMT (G) of the ellipses associated with M2, S2, N2 and K1 at points A-X.

Cruise	Serie	Bottom (m)	Period	M2				S2				N2				K1			
				A	a	Θ	G	A	a	Θ	G	A	a	Θ	G	A	a	Θ	G
Segamo	A360	950	late Aug.-late Nov. 1976	3.26	0.19	5	136	1.48	0.18	8	144								
	A940			3.03	–0.33	9	146	1.32	–0.26	16	149								
	B555	1 750	late Aug.-late Nov. 1976	2.58	0.19	–6	135	1.01	–0.15	-8	152								
	B1734			2.82	–0.06	0	133	1.22	–0.12	1	142								
	C200	1 850	late Aug.-late Nov. 1976	2.53	–0.03	4	148	1.08	–0.46	4	154								
	C1845			2.73	–0.25	–8	131	1.01	–0.02	4	145								
	D400	950	late Aug.-late Nov. 1976	2.80	–0.39	4	140	1.26	–0.29	2	149								
	D940			2.13	0.09	14	133	1.05	–0.16	–4	127								
FE90	E300	1 100	2-3 weeks in April 1990	2.14	–0.10	46	136												
	E600			4.42	–1.04	23	121												
	F300	860	2-3 weeks in April 1990	2.80	0.34	35	161	1.46	0.23	27	125								
	F800			3.89	–0.47	–2	117	1.84	–0.22	-37	116								
Segamo	G300	420	late Aug.-late Nov. 1976	3.08	–1.39	13	141	1.41	–0.43	-10	154								
	G395			2.35	–0.61	5	141	1.14	–0.23	-15	154								
	H115			3.63	–0.81	28	172	0.21	–0.06	49	287								
	H310	430	late Aug.–late Nov. 1976	1.69	–0.01	–2	129	1.43	–0.61	32	159								
	H421			1.51	0.09	5	140	0.95	–0.20	23	170								
	I62	250	late Aug.–late Nov. 1976	2.09	–0.79	61	218	0.24	–0.19	–31	241								
	I124			3.03	–0.55	64	234	1.29	0.21	121	179								
Ibiza	J90	870	mid Nov. 1990–mid Mar. 1991	1.27	0.22	104	138	0.55	0.07	64	181	0.57	–0.19	132	142	0.50	–0.06	110	49
	J115			1.56	0.30	93	145	0.80	–0.22	104	176	0.45	–0.14	89	110	0.41	–0.06	104	58
	J165			1.53	–0.21	102	144	0.89	–0.27	98	173	0.27	0.13	89	104	0.28	–0.03	175	175
	J265			1.83	–0.30	91	144	0.59	0.01	93	172	0.41	–0.03	89	112	0.28	–0.06	76	68
	J465			1.54	–0.26	93	145	0.63	–0.14	92	176	0.43	–0.15	106	112	0.24	0.02	80	101
	J715			1.45	–0.26	65	147	0.53	0.04	60	176	0.39	–0.09	82	120	0.35	–0.10	56	120
Ibiza	J'100	870	mid Mar.–late Jul. 1991	1.63	–0.38	96	147	0.59	–0.14	108	174	0.21	0.02	94	126	0.28	0.04	143	63
	J'125			1.63	–0.31	77	151	0.45	0.10	81	184	0.43	0.04	84	143	0.23	0.01	101	82
	J'200			1.64	–0.27	116	156	0.49	0.05	92	191	0.43	–0.13	116	157	0.44	–0.31	103	91
	J'250			1.85	–0.27	93	146	0.65	–0.17	84	163	0.51	–0.12	116	143	0.18	–0.01	70	39
	J'450			1.55	–0.20	95	150	0.52	–0.07	88	165	0.29	–0.07	99	131	0.22	–0.05	96	95
	J'700			1.55	–0.15	93	148	0.60	–0.10	88	176	0.30	–0.04	85	144	0.30	–0.07	103	81
Médi-prod 5	K100	2120	early Jun. 1986–late Mar. 1987	1.07	0.09	7	157	0.48	–0.11	12	197	0.17	0.07	–42	97				
	K300			1.05	–0.14	17	147	0.35	–0.03	17	177	0.18	–0.02	33	126				
	K1000			0.74	0.04	26	148	0.28	0.02	18	170	0.18	–0.01	27	140				
	K2000			0.99	0.11	22	150	0.38	0.03	23	175	0.21	–0.01	19	132				
	L1000	2 055	early Jun. 1986–late Mar. 1987	0.96	–0.03	35	148	0.42	0.09	28	168	0.20	–0.02	58	133				
	M100	2210	early Jun. 1986–late Mar. 1987	0.58	–0.01	4	138	0.39	–0.11	–24	214	0.31	–0.12	61	136				
	M300			0.56	0.03	8	156	0.19	0.08	0	167	0.11	–0.06	10	148				
	M1000			0.66	0.02	10	160	0.20	0.03	8	169	0.14	0.00	17	129				
Médi-prod 5	N1000	2 685	early Jun. 1986–late Mar. 1987	0.30	–0.01	–7	169	0.10	0.01	–17	172	0.10	–0.01	-9	186				
	N2000			0.63	0.00	–7	155	0.22	0.00	–10	191	0.14	0.03	–9	136				
	O100	2670	early Jun. 1986–late Mar. 1987	0.39	0.00	2	160	0.10	–0.02	13	162	0.15	–0.04	–18	128				
	O300			0.61	–0.04	16	161	0.20	0.05	26	193	0.07	0.01	–4	131				
	O1000			0.55	0.00	13	157	0.18	0.03	9	180	0.12	0.01	15	145				
	P100	2045	early Jun. 1986–late Mar. 1987	0.61	–0.19	27	187	0.16	0.13	55	275	0.21	–0.06	-32	161				
	P300			0.49	–0.05	10	153	0.14	0.01	–18	172	0.10	0.03	6	130				
	P1000			0.43	–0.02	1	156	0.16	0.00	-3	182	0.08	0.04	13	135				
Thétis–2	Q350	2 715	mid Jan.–end Oct. 1994	0.41	–0.20	2	161	0.15	–0.05	–1	208	0.07	0.00	8	193	0.13	–0.08	140	319
	Q2650			0.47	–0.02	7	159	0.17	–0.01	8	195	0.13	–0.04	11	132	0.05	–0.01	64	294
Médi-prod 5	R100	2690	early Jun. 1986–late Mar. 1987	0.35	–0.09	3	171	0.18	0.01	–21	176	0.02	–0.01	73	274				
	R300			0.46	–0.03	–1	152	0.13	0.03	–10	170	0.12	–0.05	–20	139				
	R1000			0.28	–0.03	4	151	0.09	0.01	–2	178	0.05	–0.01	–6	142				
	R2000			0.37	–0.02	7	158	0.15	–0.03	4	184	0.09	–0.01	12	135				

Table 1 (continued)

Cruise	Serie	Bottom (m)	Period	M2				S2				N2				K1			
				A	a	Θ	G	A	a	Θ	G	A	a	Θ	G	A	a	Θ	G
Médi-prod 5	S100	2410	early Jun. 1986–late Mar. 1987	0.40	0.04	57	206	0.35	0.05	10	150	0.16	–0.05	–26	103				
	S300			0.33	0.02	–15	162	0.13	0.05	60	236	0.11	–0.02	7	124				
	S1000			0.24	–0.01	–19	156	0.07	0.01	–6	176	0.06	0.01	26	134				
	S2000			0.16	–0.01	–7	152	0.07	0.01	12	197	0.04	0.02	–15	140				
Thétis–2	T2600	2 700	mid Jan.–end Oct. 1994	0.26	0.02	–1	160	0.09	–0.01	2	163	0.10	–0.01	0	111	0.08	0.01	–4	223
Primo-1	U2500	2 547	mid Nov. 1993–mid May 1994	0.19	0.01	17	160	0.06	–0.01	31	209	0.04	0.00	2	40	0.04	0.01	107	316
	U'450	2 547	mid May–mid Oct. 1994	0.07	0.01	1	148	0.04	–0.02	12	252	0.02	–0.01	76	348	0.04	0.02	28	245
	V200	2 705	mid May–mid Oct. 1994	0.12	–0.01	25	209	0.03	0.01	70	230	0.04	0.01	8	126	0.06	0.01	141	36
	V2655			0.10	0.01	–32	328	0.04	0.00	–9	322	0.02	0.00	152	347	0.08	–0.01	–6	115
	W1000	2 185	mid Nov. 1993–mid May 1994	0.10	0.00	0	201	0.03	–0.01	48	246	0.02	0.01	20	102	0.07	0.01	–6	275
	W2155			0.23	–0.02	–12	154	0.04	0.01	–5	236	0.10	–0.01	15	134	0.15	0.04	124	64
	W'300	2 185	mid Feb.–end Oct. 1994	0.17	–0.06	–32	184	0.05	0.02	36	341	0.12	–0.03	–9	154	0.17	0.03	2	289
	W'1000			0.22	0.01	–17	194	0.10	–0.02	41	217	0.04	–0.03	73	57	0.12	0.03	157	75
	W'2000			0.18	0.04	–23	188	0.05	0.01	2	224	0.06	0.00	88	299	0.09	0.00	72	292
	X1795	1 835	mid Nov. 1993–mid May 1994	0.24	–0.03	20	161	0.10	–0.02	32	214	0.03	0.01	25	145	0.18	0.01	30	292
Corsica	Y42	420	mid Nov. 1990-mid Apr. 1991	1.42	-0.05	104	306	0.57	-0.12	98	348	0.37	0.02	76	258	1.10	-0.60	76	83
	Y92			2.18	-0.10	97	313	0.96	-0.10	96	12	0.66	-0.22	90	239	1.60	-1.09	85	71
	Y192			1.88	0.10	98	303	0.79	0.06	133	7	0.65	-0.11	108	280	1.20	-0.29	66	134
	Y294			2.21	-0.15	92	337	0.71	-0.08	84	15	0.44	0.02	103	324	1.88	-0.21	88	164
	Y400			2.40	-0.13	95	348	0.77	-0.12	93	29	0.65	0.01	84	318	2.66	-0.18	95	194

eccentricities are mostly smaller than in the northern Alboran Sea; the variations with depth are also noticeable but the relationship with the local bathymetry is less definite. These differences are certainly due to general topographic features: the steeper the slope the greater the constraint on the streamlines. Also to be noticed is the fact that most of the meters on the shelf were immersed at shallow depths, so that relatively large currents in lower and higher frequency bands, as well as tidal harmonics generated in shallow water, might degrade the accuracy of the computations. Representative values for the amplitude and phase of M2 throughout the Alboran Sea should be ~3.10^{-2} m/s and ~140°. Note that this phase value is exactly that expected for the current (140°) at Gibraltar, in the case of a standing wave.

At ~0° 50' E in the Ibiza Channel (J-J'), the signal appears relatively barotropic, with ellipses having a mean amplitude of $1.5\text{-}1.7.10^{-2}$ m/s, a mean phase of ~145° with no significant variation with depth, and a mean orientation of 91-95° (Tab. 1). Therefore, the mean amplitudes are lower (roughly by a factor of two) and the mean phase is slightly larger (by a few degrees) than in the Alboran Sea. It is important to notice that the relatively shallow depth (maximum ~900 m) in the Ibiza Channel might induce an intensification of a barotropic current coming from the interior of the sea; therefore, the M2 current amplitude, just outside the channel, could be relatively low. Moreover, the north-south mean direction of the channel is quasi-perpendicular to the west-east mean direction of the tidal currents in the open sea (see below K-T), so that only a small part of the flow would proceed through the channel. Most of the rotations are clockwise, except during the first period (J) at the two upper levels where the signal/noise ratio is relatively low. As shown in Figure 2, the local isobaths cannot be easily defined, but the mean orientation of the ellipses roughly corresponds to the direction of the channel.

From the western Algerian Basin (K-T) to the Sardinian Channel (U-X), the amplitudes of the M2 currents are noticeably smaller and decrease significantly and continuously eastward, from ~10^{-2} m/s (~0° 30' E) to ~2.10^{-3} m/s (~9° E). The ellipses have major semi-axes and orientations that are relatively similar over the whole depth (Tab. 1), especially in the western Algerian Basin (Fig. 3). Moreover, the local isobaths there are well defined, since the location of each mooring was accurately chosen from a bathymetric map specifically drawn before deployment, and display small but noticeable deviations with respect to an overall east-west mean orientation. The orientations of the ellipses are roughly parallel (especially the deepest ones) to these local isobaths. On the whole, the tidal currents are east-west in the whole region. Note that the relatively large length of the records (6-9 months) allows a clear separation of the various semi-diurnal components. Considering that the tidal velocities are relatively low, with respect both to the overall velocities (several tens of 10^{-2} m/s at ~100 m and several 10^{-2} m/s at depth) and to the instrument capabilities (expected accuracy ~ $\pm 10^{-2}$ m/s), we conclude that the instruments are efficient, that the harmonic analysis is accurate and that both the barotropy of the signal and the eastward decrease are significant.

Some parameters (O100 velocity, S100 orientation and phase, V2655 phase) will not be considered in the statistics, due to technical problems or low signal/noise ratios. Considering the whole set from west to east, some two-thirds of the ellipse rotations are clockwise and the mean phases range within 150-175° (Tab. 1); the overall mean is ~155°, thus ~10° (resp. 15°) larger than that of ~145° (resp. 140°) found in the Ibiza Channel (resp. at Gibraltar). It appears from Table 1 that the phase significantly increases in the west and is almost constant in the east of the zone. The increase in the west was estimated by computing a linear relation, using an increasing number of points as progressing eastward, until the best correlation was obtained; the remainder of the points were used to estimate the homogeneity of the phase in the east. Between ~0 and 4° E, the phase G noticeably increases with the longitude (X); the relation estimated from the mean values at each point is G ~ (4.78X + 146)° with a correlation coefficient r^2 ~ 0.88 (Fig. 4a). According to such a relationship, the phase differences with the value expected for a fully standing wave (~140°) would range between ~6° at ~0° E to ~25° at ~4° E, which appear to be significant values. Between ~4 and 9° E, the relation is G ~ (–0.68X + 161)° with r^2 ~ 0.01 (Fig. 4a), indicating a non significant variation with longitude of the phase, which can thus be considered as constant (~158° at ~4° E to ~155° at ~9° E).

In the Corsican Channel (Y), the M2 signal is relatively barotropic with an amplitude of $1.4\text{–}2.4.10^{-2}$ m/s and a phase of 303-348°, and the ellipses have an orientation of 92-105°; the means are $\sim 2.0.10^{-2}$ m/s, ~320° and ~97°, respectively. The Y records are long enough to permit a complete analysis of the tidal signal, thus these characteristics can be significantly compared with those noted further to the west, especially in the Ibiza Channel (J, J'). The variations with depth are larger in the Corsican Channel, so that the mean amplitude and phase are probably slightly less representative than in the Ibiza Channel; note that the phase seemingly increases with depth. Due to the small depth (~400 m), the barotropic currents are probably intensified. The mean velocity is larger than in the Ibiza Channel, but the maximum depth is lower and the section smaller, hence the differences can be partly due to topographic effects. In both channels, most of the rotations are clockwise and the ellipses are oriented in the roughly north-south direction of the channel, but the major difference concerns the nearly out-of-phase relationship between both channels. Indeed, the tidal currents are northward (with G~145°) in the Ibiza Channel, whereas they are roughly southward (with G~140° = 320°-180°) in the Corsican Channel; at that time (G~145-155°), they are roughly eastward off western Algeria as well as in the Sardinian Channel. Therefore, the elevation maximum occurring in the Tyrrhenian Sea might result from currents flowing, from the Alboran Sea throughout the whole Algero-Provençal Basin, along both the northern and southern continental slopes.

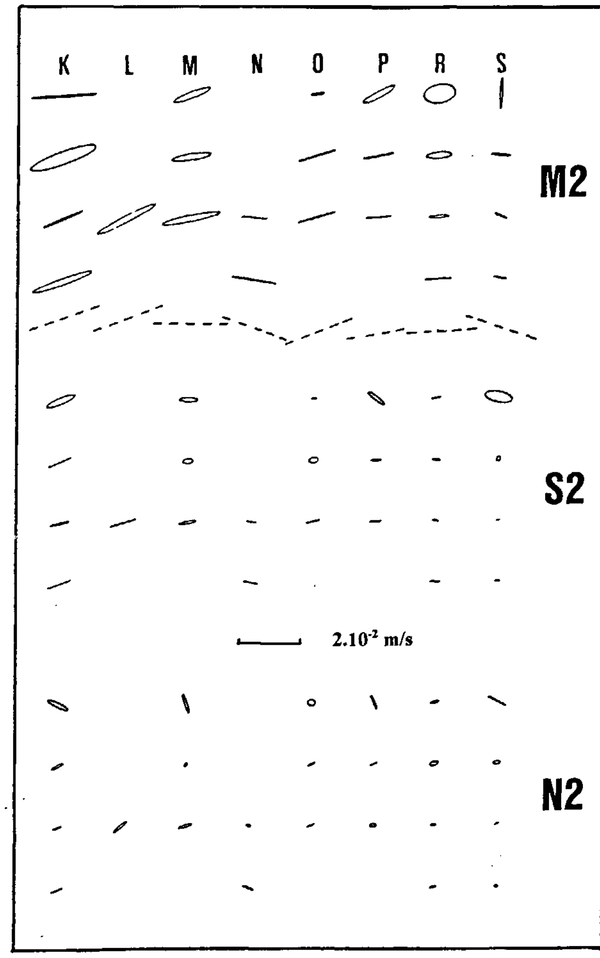

Figure 3

Ellipses at the 4 nominal depths at points K-P and R-S (see Fig. 2) for M2, S2 and N2, oriented with respect to North (upwards); the direction of the local isobaths is indicated by the dashed lines.

Harmonic analysis of S2

The S2 current amplitudes are generally relatively low, usually less than 50 % of the M2 values. Some features similar to those observed for M2 can be discerned.

In the Alboran Sea, especially at A-D and G-I, the S2 characteristics appear to be homogeneous. The amplitude is $1.0\text{-}1.5.10^{-2}$ m/s and the ellipses have a roughly east-west orientation over the whole depth, clearly related to the local isobaths. Most of the phases range within 140-160°, since some values markedly out of this range are clearly associated with extremely low amplitudes and then are not significant. The mean phase of ~150° is lower than that expected for a standing wave from its value at Gibraltar (~165°). It is difficult to validate the significance of this difference, due to the combination of both the relatively short length of these records and the relatively low amplitude of S2. For the same reasons, the larger amplitude ($1.5\text{-}2.0.10^{-2}$ m/s) of S2 in the eastern Alboran Sea (F, E records are too short) and the mean phase of ~120° cannot be considered as significant.

In the Ibiza Channel (J-J'), the S2 currents have amplitudes of $5\text{-}9.10^{-3}$ m/s, with a mean of $\sim 6.10^{-3}$ m/s, which is half the value in the Alboran Sea. Most of the rotations are clockwise and the ellipses have similar orientations over the whole depth, giving means of ~88°. The phases range within 160-190°; the means are ~175° during both periods and are thus larger than the value of ~165° at Gibraltar. Note that the ~10° phase difference between Ibiza and Gibraltar is close to the ~15° one computed in the Alboran Sea. The ~5-month length of records J-J' is sufficient to

(a)

(b)

(c)

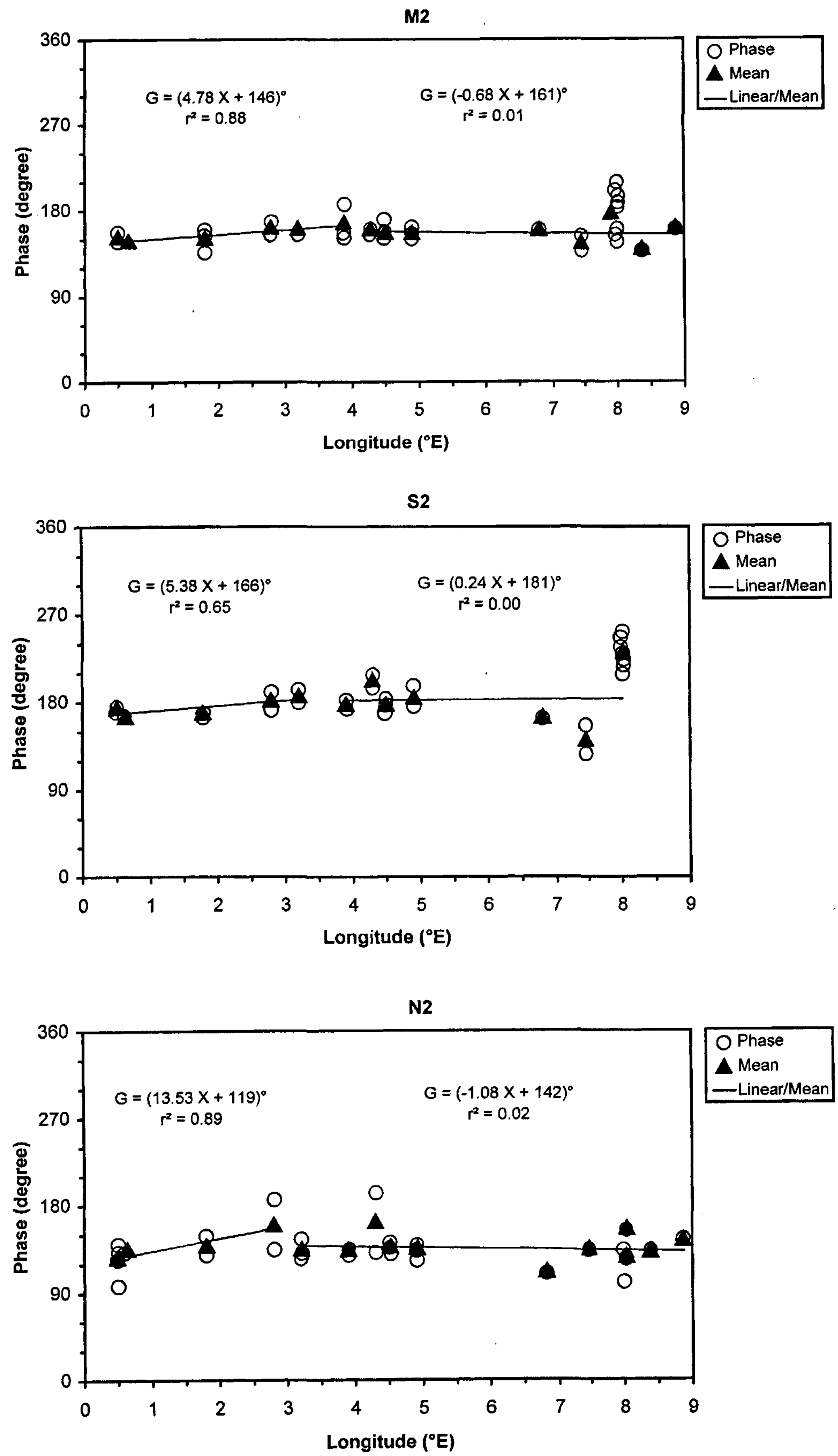

Figure 4

Linear relations computed from the mean phases (horizontal scale in degrees of longitude) from the points beween ~0° E and ~9° E off Algeria and Tunisia for M2 (a), S2 (b) and N2 (c).

provide accurate computations. The results are consistent with those obtained in the Alboran Sea.

From the Algerian Basin (K-T) to the Sardinian Channel (U-X), features similar to those for M2 are evidenced. The S2 currents decrease continuously eastward from 3-5.10^{-3} m/s (~0° 30' E) to less than ~10^{-3} m/s (~9° E) (Tab. 1). In the Algerian Basin, most of the ellipses are similar over the whole depth and are again, especially the deepest ones, roughly parallel to the local isobaths (Fig. 3).

Due to an especially low signal/noise ratio, the S2 phases are less significant near the surface and in the east of the area (as for M2), so that some records giving values clearly too large (K100, M100, P100, S300, V2655, W'300) or too low (O100, S100) have been excluded from the statistical analysis. The mean phases at each point range within 175-240° (Tab. 1, Fig. 4b), the overall mean being ~185°; this mean phase is ~20° larger than the one (165°) at Gibraltar. Between ~0 and 4° E, the linear relation is G ~ (5.38X + 166)°, r^2 being ~0.65 (Fig. 4b). According to this relationship, the phase differences with the value expected for a fully standing wave (~165°) would range between ~1° at ~0° E to ~25° at ~4° E. This relation is similar to that estimated for M2. Between ~4 and 9° E, the relation is G ~ (0.24X + 181)° with r^2 ~ 0.00 (Fig. 4b). This relation is in good agreement with the one estimated for M2 and indicates significantly no variation with longitude of the phase which can be considered as constant (~182° at ~4° E to ~183° at ~9° E).

In the Corsican Channel (Y), the S2 signal has an amplitude of 6.10^{-3}-10^{-2} m/s and a phase of 348-29°, the means being ~8.10^{-3} m/s and ~10°. The ellipse orientations are relatively similar at most of the levels and range within 84-133°, *i.e.* roughly north-south, and the rotations are generally clockwise. Note that the S2 amplitudes are generally ~3 times less than the M2 ones and are roughly similar to those encountered in the Ibiza Channel. In agreement with the M2 characteristics, the most interesting result concerns the mean phase of ~10° which is nearly opposed to that computed in the Ibiza Channel (~175°), indicating a quasi out-of-phase relation between both channels. Therefore, as for M2, the S2 currents are roughly southward in the Corsican Channel, while they are roughly northward in the Ibiza Channel and eastward from western Algeria to the Sardinian Channel.

Harmonic analysis of N2

In the Ibiza Channel (J-J'), the N2 currents have significant amplitudes of 3-5.10^{-3} m/s, slightly lower than the S2 ones. The signal is also barotropic and the ellipses display no significant variation with depth, their mean orientation being that of the channel, during both periods. An unexplained feature is that the phases are not very variable during each of the two periods, but significantly differ from each other, the means being ~117° and ~141°, respectively. This discrepancy in comparison with the computations for M2 and S2 is due to computational rather than experimental errors. Nevertheless, we will consider that an overall mean of ~130° is a representative value.

From the Algerian Basin (K-T) to the Sardinian Channel (U-X), features similar to those described for both the M2 and S2 currents are observed, although they might be less significant. The N2 amplitudes decrease continuously eastward from 2-4.10^{-3} m/s (~0° 30' E) to less than ~10^{-3} m/s (~9° E) (Tab. 1); note that these values are in the same range as those computed for S2. Despite the extremely low amplitudes of the major semi-axes, it still appears that the ellipses are similar over the whole depth and that the deepest ones are roughly parallel to the local isobaths (Fig. 3).

As for the M2 and S2 phases, a linear relation can be estimated from the mean phases at each point. Some visibly non significant phases (K100, P100, R100, S100, U2500, U'450, V2655, W'1000 and W'2000) have again to be excluded. Thus, the mean phases at each point range within 125-160° (Tab. 1, Fig. 4c), and the overall mean is ~140°. This value is ~20° larger than the one (120°) at Gibraltar and the difference is equal to that computed for the S2 wave. Between ~0 and 3° E, the phase increases as G ~ (13.53X + 119)°, r^2 being ~0.89. From this linear relation, the phase differences with the value (120°) of a fully standing wave would range within ~ –1° at ~ 0° E to ~ 40° at ~3° E. Between ~3 and 9° E, the relation is G ~ (–1.08X + 142)° with r^2 ~ 0.02. According to this relation, the phases would range within ~139° at ~3° E to ~132° at ~9° E and, although the variation is a little larger than for M2 and S2, the phases can be considered as constant. Therefore, these relations confirm those computed for M2 and S2, so that the phase of all the semi-diurnal waves varies linearly as progressing eastward from ~0° E to 3-4° E, and is then constant at least as far as ~9° E.

In the Corsican Channel (Y), the N2 amplitudes are relatively weak (3-7.10^{-3} m/s) and slightly lower than the S2 ones. The ellipses have orientations relatively similar over the whole depth, with a mean of ~92°, corresponding roughly to the channel direction. The N2 currents have relatively variable phases ranging within 239-324°, with a mean of ~285°. Therefore, the N2 currents are northward (~130°) in the Ibiza Channel roughly when they are southward (~105°) in the Corsican Channel. Even if less clearly than for M2 and S2, the out-of-phase relation between both channels also seems significant for N2. The N2 currents off western Algeria (0-3° E) and from eastern Algeria to the Sardinian Channel (3-9° E) are eastward roughly at the same time (119-160° and 132-139°, resp.). Despite the scatter in these values, all the maxima occur simultaneously, as for M2 and S2.

Harmonic analysis of K1

In the Ibiza Channel (J-J'), the K1 signal has amplitudes of 2-5.10^{-3} m/s, comparable to the N2 ones. The ellipses are relatively similar over the depth and, although their orientations appear more variable during the first period (56-175°) than during the second one (70-143°), the mean orientations of ~100° and ~103°, respectively, are roughly that of the channel and are thus representative. The rotations are generally clockwise. The K1 phases are more variable than the N2 ones, especially during the first period, and also display different mean values from one period (~95°) to the other (~75°), the overall mean being ~85°. The phase seemingly decreases (from J to J') for K1, whereas it increases for N2 and is almost constant for M2 and S2. This is obviously due to computational errors so that, for simplicity and coherency with what follows, a mean phase of ~90° will be considered as a representative value.

In the Corsican Channel (Y), the K1 currents have relatively large amplitudes of ~10^{-2} m/s near the surface to more than $2.5.10^{-2}$ m/s close to the bottom. These amplitudes are lower than the M2 ones over most of the depth, except close to the bottom, but they are much larger than any other semi-diurnal and diurnal (especially O1 and Q1) components. The ellipse orientations and the phases are variable within 65-95° and 71-194°, respectively, and thus prevent the computation of significant means from all records; all rotations are clockwise. Nevertheless, the eccentricities are relatively low only at the upper levels, so that the associated orientations and phases are inaccurate while, at the two deeper levels, the eccentricities are large and the orientations are well in the direction of the channel. The two phases of ~164° and ~194° provide a mean (~180°) which could be representative, furthermore as the elevation has also a phase of ~180° in the whole sea. This could be explained by considering that, according to Canceill *et al.* (1995), the amplitude of the elevation in the north of the Corsican Channel (the Ligurian Sea) is larger than in the south (the Tyrrhenian Sea), and that the narrowness of the channel controls the north-south exchanges, the current being maximum when the elevation, and thus the difference between the Ligurian and Tyrrhenian seas, is maximum.

DISCUSSION

Cotidal charts of the main semi-diurnal components, provided by theoretical models, describe basically a simple standing mode, with one node of elevation [either actual (Canceill *et al.*, 1995) or virtual (Lozano and Candela, 1995)] in Spain near 0-2° E and another in the southern part of the Sicily Channel, and maxima at Gibraltar and in the eastern Tyrrhenian Sea. The currents are hence expected to be basically in phase throughout the sea. Due to the large difference between the volume of water in the Alboran Sea compared to that in the remainder of the western Mediterranean, the currents in the west are expected to be larger than in the east. This is strongly supported by the eastward decrease of the semi-diurnal amplitudes, from the Alboran Sea to the Sardinian Channel, as well as by the significantly low values in the Liguro-Provençal Basin. It appears that enhanced semi-diurnal currents in the Corsican Channel result from the constriction of the streamlines due to the bathymetry. This is not the case for the currents in the Ibiza Channel, because the mean direction of the channel is perpendicular to that of the currents in the open sea; even if the latter are relatively large, only a small part of the flow would proceed through the channel, so that such a bathymetric effect will be less efficient.

This "in-phase relationship associated with a simple standing mode" has to be qualified. According to this relation, the flooding transport is generally eastward in the interior of the sea, and is mainly along the continental slope on the edges. Therefore, this means according to our definitions that if the phase of the elevation is Ge at Gibraltar (and thus Ge + 180° in the eastern Tyrrhenian Sea), the phase of the current (Gc) is Ge + 90° (eastward) from Gibraltar to the eastern Tyrrhenian Sea, Ge + 90° (northward) in the Ibiza Channel and Ge + 270° (southward) in the Corsican Channel. The phases Ge for the semi-diurnal components M2, S2 and N2 are 50°, 75° and 30°, respectively. The phases Gc, expected from these relations, can be compared with the mean phases (Gm) computed from the current measurements in the various regions (Tab. 2). The agreement is good for M2, but differences of 5-15° are noted in the Ibiza Channel and from Algeria to the Sardinian Channel. The agreement is also rather good for S2 and N2, considering their relatively low amplitudes, but similar differences of 10°-20° and 10°-15° are noted in the same regions. These disparities consequently require further investigation.

Indeed, the mean phases of the M2, S2 and N2 currents computed from relatively long records, are larger off Algeria (155°, 185°, 140°) than in the Ibiza Channel (145°, 175°, 130°) and, in both places, they are larger than the values (140°, 165°, 120°) at Gibraltar. Giving a smaller weight to the Alboran Sea values (140°, 150°, ?) which are less significant than the others, the mean phases thus appear to increase from Gibraltar to Ibiza (by 5-10°) and Algeria (by 15-20°). This general eastward increase has to be considered together with the increase roughly estimated from ~0° E to 3-4° E off Algeria, for M2 (150° to 165°), S2 (170° to 180°) and N2 (130° to 160°). These variations are consistent for the three semi-diurnal waves, so that they might be significant. This would mean that the phase of the current in the Ibiza Channel should be roughly similar to the one near 0° off Algeria. Considering Figure 1, this would account for an amphidromic point, either actual or virtual, located in the north (instead of the south, as suggested mainly by Canceill *et al.*) of the Ibiza Channel, and for phase lines radiating towards the Algerian coast.

The comparison of the ellipses, computed for the semi-diurnal components off Algeria (Fig. 3), provides an estimate of the accuracy of the velocity measurements with respect to the significance of the computations and to the effect of the bathymetry constraining the streamlines. To be emphasized is the fact that deep measurements in the

Table 2

Phase of the current (Gc) computed from the phase of the elevation at Gibraltar (Ge; Gc = Ge + 90°) compared to the mean phase (Gm) computed from the current measurements for the semi-diurnal components in the various regions.

	Gc/Gm for the semi-diurnal components		
	M2	S2	N2
Eastern Alboran Sea	140°/140°	165°/150°	–
Ibiza Channel	140°/145°	165°/175°	120°/130°
Off Algeria to the Sardinian Channel	140°/155°	165°/185°	120°/135°
Corsican Channel	320°/320°	345°/10°	300°/285°

western Mediterranean have evidenced currents of several 10^{-1} m/s, especially near the foot of the continental slope. This phenomenon has been observed in the northern Ligurian Sea (Albérola *et al.*, 1995; Sammari *et al.*, 1995), as well as off Algeria (Millot, 1994), so that it is perhaps a characteristic of the whole western Mediterranean. The tidal currents are strongly influenced by the bathymetry, as indicated by the orientations of the ellipses similar to those of the local isobaths, especially at depth and in the Algerian Basin where a detailed bathymetry was available. When ellipses are available at both 1000 m and 2000 m (K, N, R, S), the former are smaller than the latter for all components, and such an intensification is most apparent at point N where the bottom slope is one of the steepest in the whole sea. Therefore, the intensification at depth is clearly a general feature that is ascribed to a bathymetric effect.

Another result is that no significant phase variation with depth has been derived. Although the space and time variations of both the orientation and the phase of the ellipses can be relatively large, our feeling is that these variations are due to computational rather than experimental errors.

For each of the semi-diurnal waves, it has been demonstrated that the phase of the currents increases linearly eastward off Algeria between ~0° E and 3-4° E, and can then be considered as constant as far as the Sardinian Channel (~9° E). This result is in agreement with an amphidromic zone near 0-2° E and a zone of constant phase between 3-4° E and ~9° E, as indicated by the elevation in Figure 1. Farther than ~9° E, the phase should vary again eastward, due to the other amphidromic zone located in the southern part of the Sicily Channel.

Energy density spectra have been computed in the eastern Alboran Sea, off Algeria and in the Corsican Channel. At least in these specific regions, it appears that tidal currents are relatively large, especially at depth, compared to inertial currents. This is especially true in narrow channels, where the rotation of inertial currents is hindered by the topography, as well as in winter when the stratification is reduced.

The relatively long records analysed here have permitted a statistical analysis of the amplitude and phase of the major tidal currents. It has been demonstrated that amplitudes of the order of 10^{-3} m/s could be accurately computed, as well as phases with accuracy of a few degrees. This also validates the performance of simple current meters. Moreover, considering that some regions, which are crucial from a tidal point of view, are –for political reasons– not at present accessible, getting current time series there should be more feasible than getting sea level ones. In view of the contemporary interest in the Mediterranean tides, reflected in the use of current and sea level data, satellite altimeters and numerical models, there is no doubt that our understanding of these tides will be improved very soon.

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