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A MODEL FOR PREDICTION OF THE TIDAL CURRENTS IN THE ENGLISH CHANNEL

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ABSTRACT

A model for prediction of tidal currents in the English Channel is presented. It is based on the classical harmonic description of tides deduced from the spectral development of the luni-solar tidal potential. The spatial distribution of the characteristic parameters (intensity, phase, and direction of the maximum velocity vector, ellipticity of the hodograph) for the 26 harmonic constituents introduced in the prediction procedure are deduced from a numerical simulation of 1 month's duration for the entire English Channel.

Two kinds of documents can be produced from this model : instantaneous velocity fields over a given area, and time series of the intensity and the direction of the velocity vector at a given location, over a given period. Four examples of prediction are presented, corresponding to specific areas and over periods where tidal currents have actually been observed. The comparison between predictions and observations is very satisfactory.

1. INTRODUCTION

On the European continental shelf, the tidal effects dominate the currents; in some areas such as the English Channel they have such an amplitude that their prediction becomes necessary, not only for the safety of navigation but, in a more general sense, for everything related to the marine environment (maritime works, environmental studies, etc.). Usually, for these areas, the most complete and authentic source of information on tidal currents is provided by the nautical documents published by the Hydrographic Offices of the bordering countries.

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These documents give the amplitude and the direction of the currents for typical tidal cycles, usually for neap and spring tides, for a given number of points distributed throughout these areas. This information is obtained from averaged in situ observations representative of these typical tidal currents. This constitutes a very precious documentation, yet it does not enable a continuous and detailed prediction of the currents over long periods.

A very efficient prediction method is the harmonic method, which is commonly used to predict the variations in the sea level in ports. It allows for a prediction to be made at any time provided one knows the totality of the harmonic constituents characteristic of the phenomenon in a given area. Usually, these harmonic constituents are determined from in situ measurements. However, because of difficulties in analysis of these singals (related to the very peculiar form of the tidal spectrum whose lines are rather numerous and very close), the observations have to be made over a long period, spreading over several months. Because of the difficulty in carrying out observations at sea, the observation points available are very limited, even in the case of a well studied littoral sea.

LE PROVOST (1981) previously suggested a global model for the prediction of tidal levels in the Channel. At minimal cost it enables the computation of the variation in level of the surface of the open sea, at any time, with an accuracy of about 15 cm. The implementation of this model, based on the method of the harmonic analysis of tides, was possible due to the existence of a set of cotidal and isoamplitude charts of the main tidal constituents in the Channel, established by CHABERT d'HIERES and LE PROVOST (1979), with the help of a physical small-scale model. Tested with traditional coastal and offshore observations as well as with altimetric measurements by satellite (Seasat 78), this model has given excellent results.

Recent numerical modelling work (FORNERINO, 1982; LE PROVOST and FORNERINO, 1984) has resulted in a collection of harmonic constants of currents for the Channel equivalent to the collection of tidal levels established by CHABERT d'HIERES and LE PROVOST. We propose in this article a tidal current prediction model valid for the whole Channel area and developed according to the same principle as that used by LE PROVOST (1981) for the computation of levels and using that collection of characteristic constants of the currents.

2. DESCRIPTION OF THE COMPONENTS OF THE MODEL

2.1. The harmonic method

Generally speaking, one may describe the tide by means of its harmonic constituents; each of the parameters characterizing the phenomenon (sea level variation or constituents of the velocity field) can be approximated by a relation of the type :

$$S_{ap}(M, t) = S_o(M) + \sum_{i=1}^{N} f_i \, S_i(M) \cos[\omega_i t + (V_o + v)_i - g_i(M)] \qquad (1)$$

where :

$S_o(M)$	:	mean value of the signal at point (M)
N	:	number of constituents taken into account
$S_i(M)$	:	amplitude of the constituent having i as a subscript
$g_i(M)$	:	phase difference of this constituent in relation to the transit of the constituent at Greenwich Meridian
ω_i	:	pulsation of this constituent
V_{oi}	:	phase of the constituent in relation to the Greenwich Meridian at time $t = 0$
f_i and v_i		amplitude and phase nodal correction coefficients of this constituent

In order to validate this approximation (1), it is of course necessary to take into account all significant constituents : not only the ones resulting from astronomical generating potential, but also the ones induced by the non-linear hydrodynamic mechanism to be found in the littoral seas. The amplitude and phase of each of these harmonic constituents depend on the intensity of the generating forces as well as on the geometrical and hydrodynamical factors typical of the basins where they develop. The nodal correction coefficients result from the harmonic development of the generating potential; they allow for the long term variation of astronomical parameters (over one year) while limiting the number of significant constituents, N, to be retained (cf. SCHUREMAN, 1958).

The parameters ω_i, v_{oi}, f_i and v_i are defined as soon as the choice of the N constituents is made, and so the main problem related to the application of (1) lies in determining the quantities S_i and g_i, which depend on the position of the considered point M in the observed zone.

2.2. Aim of the model

Our aim is to develop a procedure for predicting tidal currents in the English Channel. It is a vectorial quantity varying in space and time : three functions are thus necessary to characterize it, such as, for instance, its projections on three axes of reference Oxyz (further, in this article we take the plane Oxy horizontal with Ox eastwards and Oy northwards). But the tide is typically a phenomenon of long waves and the velocity fields may, consequently, be considered as horizontal : so the problem comes down to the definition of two functions, u and v, for instance, projections of the speed vector on the Ox and Oy axes. On each point (x, y) the velocity vector varies on the vertical, between bottom and surface. When there are no surface constraints (i.e. when there is no wind) and if the density stratification can be disregarded (which is indeed generally the case for the English Channel) this vector is more or less constant, except near the bottom where a boundary layer exists : in this study we will restrict ourselves to the definition of this "mean" value of the velocity, valid for practically the whole of the fluid column. Therefore, using the harmonic formula, this current vector will be expressed as follows :

$$\vec{U}(x, y, t) = u\,\vec{i} + v\,\vec{j} \qquad (2)$$

with :

$$u = u_o + \sum_{i=1}^{N} f_i\, u_i(x, y) \cos [\omega_i t + (V_o + v)_i - g_{ui}(x, y)]$$

$$v = v_o + \sum_{i=1}^{N} f_i\, v_i(x, y) \cos [\omega_i t + (V_o + v)_i - g_{vi}(x, y)]$$

where $\vec{i}$ and $\vec{j}$ are unit-vectors according to Ox and Oy.

2.3. Basic data

In order to apply this formula (2) on a field $\mathcal{D}$ we need to know for each point the amplitude and the phase of the various tidal constituents : this data base is now available for the English Channel, following the work done by FORNERINO (1982). A group of networks specifying the characteristics of the significant constituents of the tidal currents over the entire Channel was produced from a numerical simulation based on a classical model with finite differences of the "predictor-corrector" type, of which only the main characteristics are mentioned here (cf. LE PROVOST and FORNERINO, 1984, for more details). The zone under consideration has two open boundaries (cf. figure 1) : the western one (Atlantic) goes from Devonport on the English coast to Roscoff, or thereabouts, on the French coast, and the northern one (North Sea) goes from Ramsgate on the English coast to Ostend on the Belgian coast; the area is divided into a 10 km grid mesh. The difference in level $\zeta(x, y, t)$ of the open sea surface is calculated at the centre of each grid and the velocity consituents u and v, respectively, on the east-west and north-south faces, as shown in figure 1. Along the solid boundaries the condition

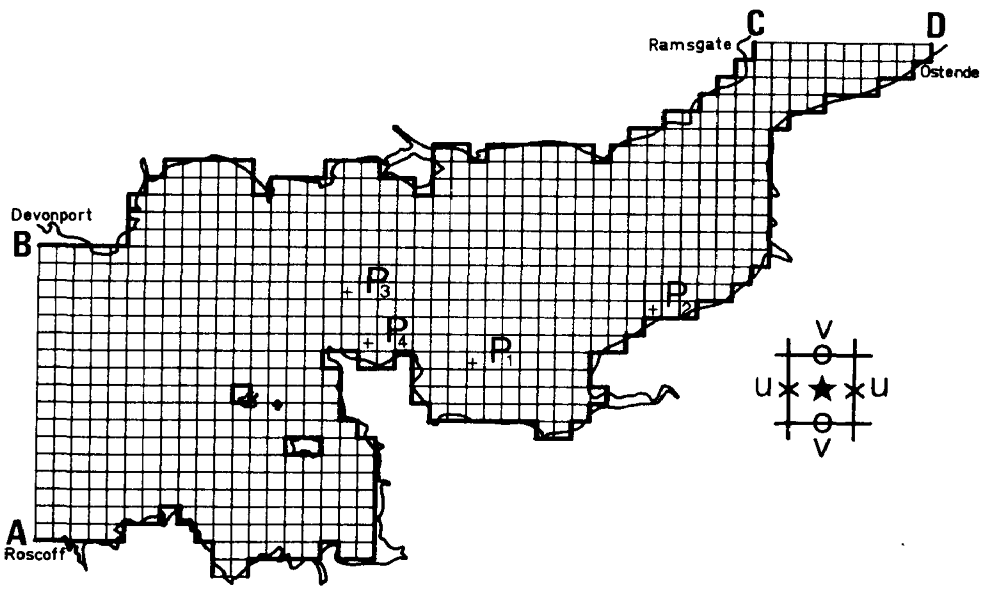

FIG. 1. — Spatial gridding of the modelled area, the English Channel, with location of the points of comparison between prediction and observation : P_1, P_2, P_3, P_4.

at the imposed limits is no normal flow; for the open boundaries on the Atlantic and the North Sea, the variations of level are prescribed at each moment and calculated according to type 1 formula using a distribution of the harmonic constituents obtained by CHABERT d'HIERES and LE PROVOST (1979). This numerical simulation reproduced the variations in level of the sea surface and the currents over one month in real time. Characteristic networks of the main harmonic constituents of the current were established for the whole of the gridded area (English Channel, Dover Strait, cf. fig. 1) after a harmonic analysis of the temporal series, computed at different points of the grid, had been made.

The harmonic constituents presented by FORNERINO (1982) number 22 : two long-period non-linear constituents MS_0 and MN_0; three diurnal constituents : K_1, O_1 and Q_1, six astronomical semi-diurnal constituents : M_2, S_2, N_2, μ_2, L_2 and ε_2, five non-linear semi-diurnal constituents : $2\,MS_2$, $2\,MN_2$, $2\,SM_2$, MSN_2 and MNS_2, three quarter-diurnal constituents : M_4, MS_4 and MN_4, and three sixth-diurnal constituents : M_6, $2\,MS_6$ and $2\,MN_6$. It should be noted that a certain number of constituents found in the real spectrum are not included in this list; this is a direct result of the actual conditions of the numerical experiment carried out in order to get these results : to reduce the cost of calculations, the numerical simulation was only done for one month and it was decided consequently not to take into account (for the definition of the boundary conditions) the waves close to the main constituents S_2, N_2, μ_2 and L_2 which cannot be separated from the latter over a one month period, i.e. K_2 and T_2, ν_2, $2\,N_2$ and λ_2.

In order to define each current constituent, one has to use four parameters : for instance, the amplitude and phase of each of the projections on Ox and Oy, i.e. μ_i, g_{ui}, v_i, g_{vi}, if formula (2) is used (these are the quantities which will be used later on in the prediction model). However, in order to visualize the current characteristics of these various constituents, it is easier to use another set of parameters based on a polar representation of these currents. The hodograph of an elementary harmonic constituent $\vec{U}_i$ of (2) :

$$\vec{U}_i(x, y, t) = u_i(x, y) \cos[\omega_i t - \varphi_{ui}(x, y)]\, \vec{i} + v_i(x, y) \cos[\omega_i t - \varphi_{vi}(x, y)]\, \vec{j}$$

is an ellipse (cf. figure 2); it can thus be characterized by three specific parameters :

- the amplitude of its semi-major axis A_i : this is the amplitude of the maximum current associated with this constituent;
- its ellipticity $R_i = \frac{a_i}{A_i} \times 100$, expressed as a percentage of the magnitude of the minor axis a_i to that of the major axis A_i. For $R = 0$, the current is rectilinear; for $R = 100$, the rose is circular;
- the direction of the major axis compared with a direction of reference (usually the North is used).

It then suffices to specify the maximum phase of the current in relation to the moment in time being used as a reference and the direction of rotation of the velocity vector to completely define the constituent characteristics. By giving a positive or a negative sign to the ellipticity according to the direct or reversed direction of rotation of the velocity vector, it is clear that the only fourth parameter required is : the *maximum current phase.*

This is the presentation that FORNERINO (1982) used for her results. To record here all the networks obtained would take up too much space; yet, in order really

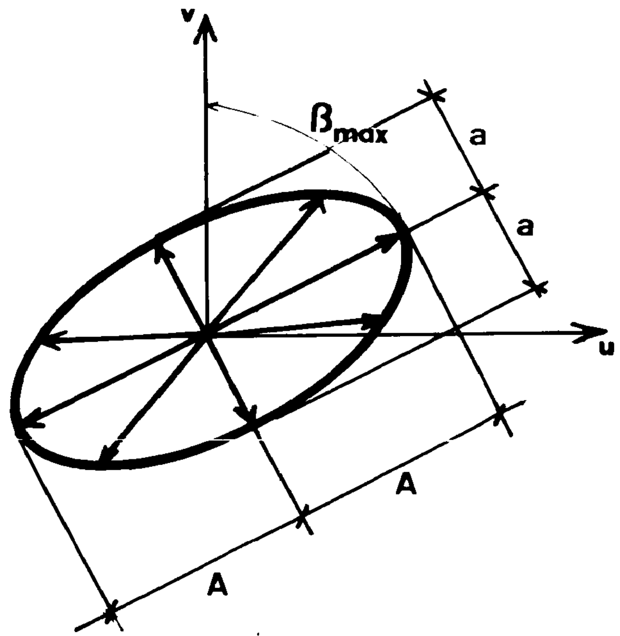

FIG. 2. — Parameters defining the velocity ellipse for any component i.
- semi-major axis A_i (modules of maximum velocity vector)
- ellipticity : $R_i = a_i/A_i \times 100\,\%$
- major axis orientation by reference to the North (β_i max) (direction of maximum velocity vector)
- maximum velocity phase $(\omega_i t)_{max}$.

to understand the essential characteristics of the current fields in the prediction zone under consideration, it is useful to be more specific about the salient features of the different groups of constituents in the spectrum.

2.3.1. The semi-diurnal astronomical constituents

We show in figure 3 the M_2 constituent (the most important one in the English Channel tide). The distribution of the current amplitude is typical of a Kelvin amphidromic tide : the maximum intensity zone is located in the central part of the basin, between Cotentin and the Isle of Wight, and coincides with the nodal zone of amplitude of the differences in open sea surface levels. This maximum current increases even more around the capes, mainly in La Hague, where the velocity vector of M_2 exceeds 2 m/s. On the other hand, at the Channel entrance, and in its eastern part, the velocity decreases to about 60 cm/s, and even less in certain bays (St.-Brieuc, Mont St.-Michel, Seine, Somme). A band of greater velocity is, however, noted between Bréhat and Guernsey. It can be interpreted as a ventral zone of current, to be associated with a nodal zone of the sea surface elevations at the entrance to the bay off Normandy and Brittany (Golfe normano-breton) in which the M_2 tide can exceed 4 m. Lastly, we should point out that the velocity vector also increases locally in the Dover Strait, due to the narrowing of the passage available for the propagation of the tidal wave in that area. The direction of the

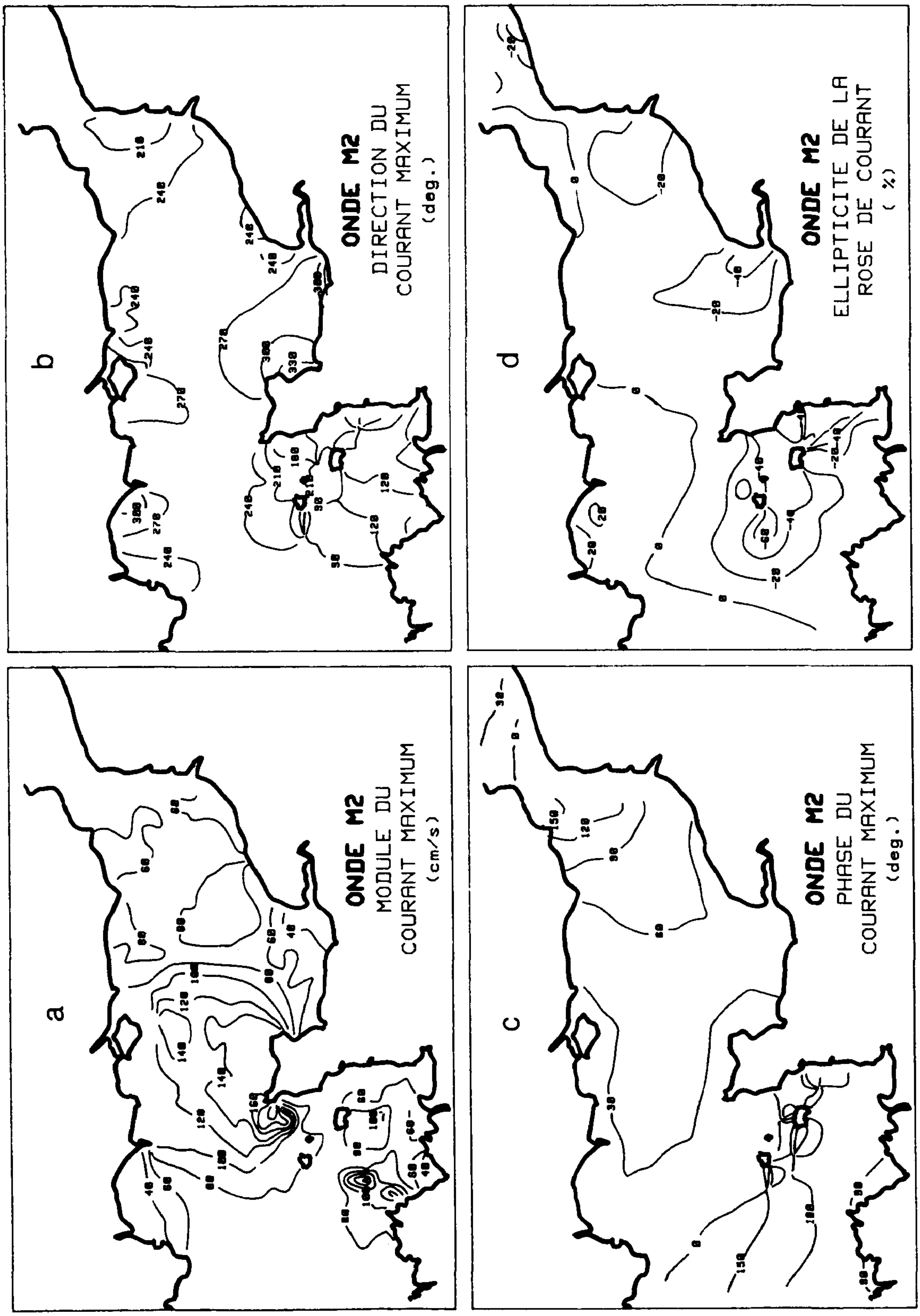

FIG. 3. — Characteristics of the semi-diurnal constituent M_2. Modules (cm/s) of maximum velocity vector; direction (°) of maximum velocity vector; phase (°) of maximum velocity vector; ellipticity (%).

maximum velocity vector is almost everywhere in the order of 240° to 270°, that is east-west, except in the Golfe normano-breton, where the network becomes very complex due to the very strong gyratory aspect of the currents in this area, with ellipticity values of 40 to 60 %. The increase in ellipticity of current roses in the eastern part of the Baie de la Seine is also to be noted.

The characteristic networks of the other semi-diurnal group of astronomical constituents (S_2, N_2, L_2, μ_2 ...) are very similar to those presented here for M_2 : the charts showing the direction and the ellipticity of the current roses are exactly the same; the phase networks are identical, given some phase shift; only the distributions of the velocity amplitudes are slightly different, but their networks are similar to that presented in figure 3 and may be deduced from it by simple affinity as a first approximation.

As these semi-diurnal constituents are the most important of the spectrum, their spatial characteristics, that we have just commented upon, determine the salient features of the actual current fields.

2.3.2. The semi-diurnal constituents of non-linear origin

The constituents 2 MS_2, 2 SM_2, MSN_2 and MNS_2 are the main ones of this group. It should be remembered that they result from the non-linear interaction effects between the main constituents M_2, S_2 and N_2 in shallow water areas. It is not necessary to reproduce here a typical example of their networks, since they show maxima and minima of the current in the same areas as the astronomical semi-diurnal constituents. The current directions are identical too; only the phases and ellipticity networks are a little different in the western part of the basin, mainly in the Golfe normano-breton where shoal depths, which cause considerable friction, induce energy transfers from the generating waves towards these semi-diurnal non-linear constituents (cf. LE PROVOST, 1976).

2.3.3. The diurnal constituents

Of course, the networks related to these constituents are completely different from the previous ones. The maxima of the currents are located exclusively in the Dover Strait area corresponding to their amphidromic points (cf. CHABERT d'HIERES and LE PROVOST, 1979). There, the K_1 constituent amplitude reaches, for instance, almost 13 cm/s (see figure 4); when we consider that in this area the M_2 current amplitude does not exceed 120 cm/s, we might a priori forecast that the real diurnal inequality in currents in the Dover Strait is appreciable. Also, on these networks one notes a minimum amplitude zone between 0° and 1° of longitude west which goes along with an increase in the ellipticity of the current rose; however, these details are negligible, given the very low amplitude of these constituents in this area.

2.3.4. The quarter-diurnal constituents

The wave length of these constituents (M_4, MS_4, MN_4) is half that of the semi-diurnal ones. As a result, the networks become more complex. To illustrate

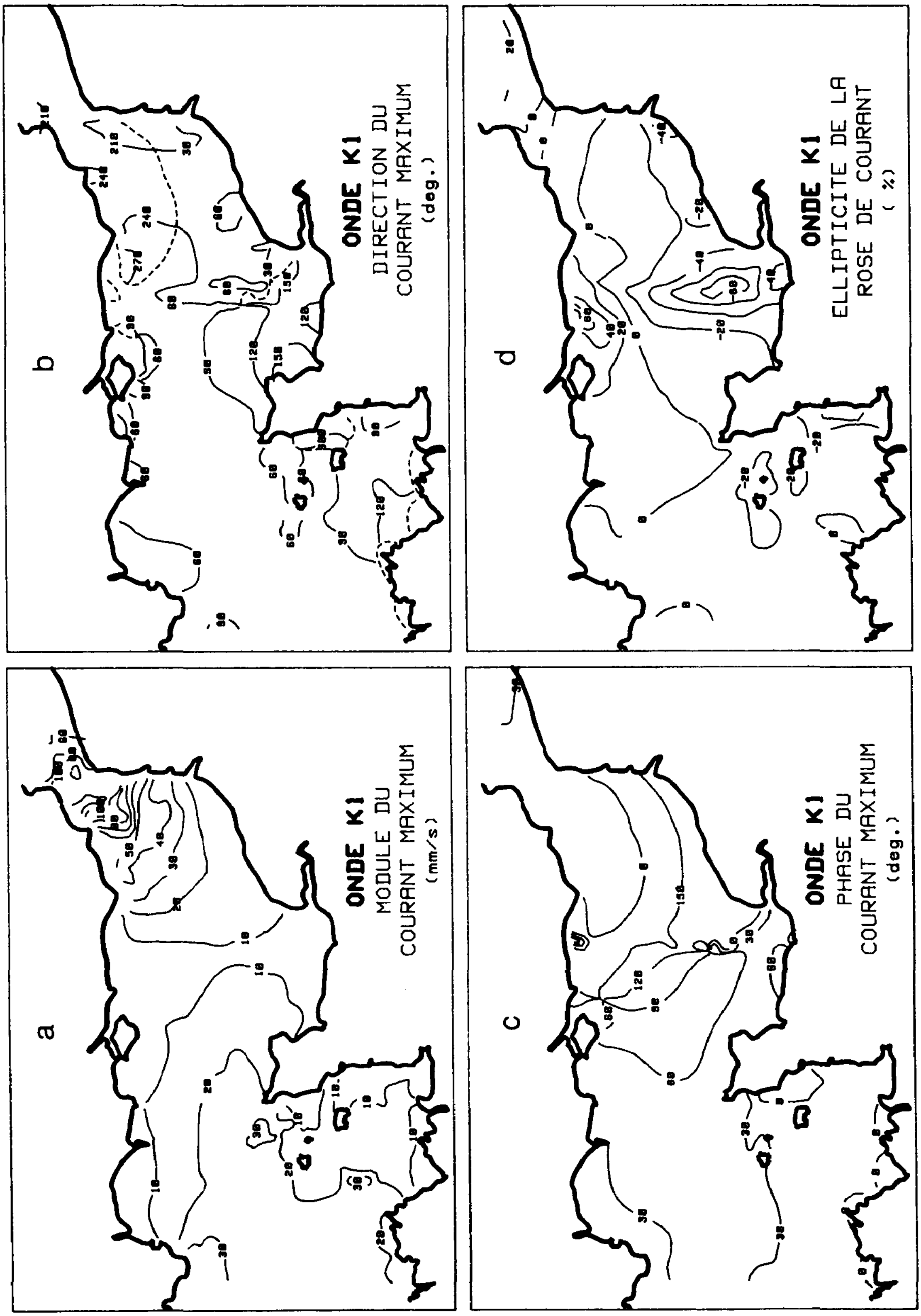

FIG. 4. — Characteristics of the diurnal constituent K_1. Modules (mm/s) of maximum velocity vector; direction (°) of maximum velocity vector; phase (°) of maximum velocity vector; ellipticity (%).

this point, we show the M_4 constituent in figure 5 : a maximum current amplitude can be noted in the centre of the eastern Channel, at the longitude of one of the amphidromic points typical of quarter-diurnal cotidal charts, and a minimum zone on either side which corresponds perfectly to the standard scheme of an amphidromic structure (one should note the marked ellipticity of the current roses in these areas of minimum current). Moreover, the existence of an area of maximum amplitude of the quarter-diurnal currents between Bréhat and Guernsey, at the entrance of the Golfe normano-breton and between Jersey and Mont Saint-Michel, in the very bay itself, should also be noted. The amplitude of these currents is significant in the Dover Strait as well.

The spatial distribution of these quarter-diurnal constituents is interesting because this introduces an asymmetry between flood and ebb in the global signal. An example of this is given later.

2.3.5. The sixth diurnal constituents

From CHABERT d'HIERES and LE PROVOST (1979) we know that the Channel is subject to sixth diurnal oscillations, mainly between the Baie de la Seine and the Isle of Wight. This characteristic is also found on the sixth diurnal current fields which are in this area of significant amplitude : M_6 and 2 MS_6 are of about 3 to 6 cm/s. Their presence in the global signal will thus appreciably distort the current roses.

The review of the salient features of these different categories of constituents already enables us to produce a rough description of what the tidal currents should be in the various zones of the Channel :

- maxima zones : central part, Cap de la Hague, Barfleur, St.-Catherine, Dover Strait, entrance to the Golfe normano-breton;
- strong ellipticity zones : eastern Baie de la Seine, Golfe normano-breton;
- significant diurnal inequality zones : Dover Strait;
- zone where there is a strong asymmetry between flood and ebb : between Fécamp and Newhaven.

The illustrations which follow will confirm some of these points.

2.4. Characteristics of the prediction model

With this collection of characteristic networks of the different significant tidal constituents we then have a base which will enable us to consider making predictions based on the harmonic formula (2).

The useful harmonic parameters (u_i, v_i, g_{ui}, g_{vi}) resulting from the numerical simulation are known at various intersection points of the grid : with a resolution of 10 km × 10 km, 716 data points provide accurate information on the spatial distribution of these parameters except, perhaps, in the coastal zones and in the zones with spatial variations of very important amplitude such as capes.

It is to be noted that FORNERINO's simulation (1982) did not provide for the determination of certain constituents which were not included, because the simulation period was limited to one month. This applies mainly to constituents T_2

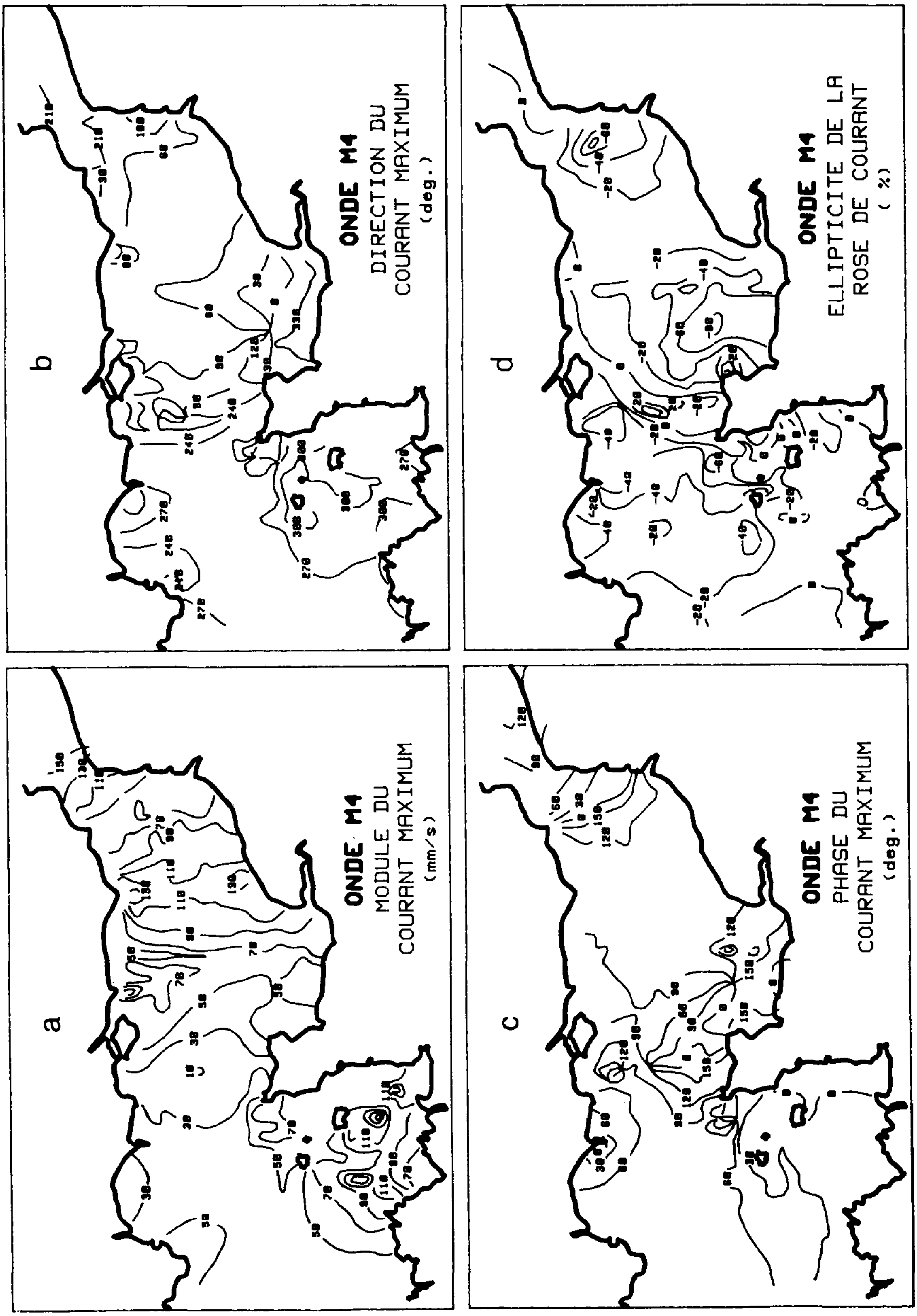

FIG. 5. — Characteristics of the quarter diurnal constituent M_4. Modules (mm/s) of maximum velocity vector; direction (°) of maximum velocity vector; phase (°) of maximum velocity vector; ellipticity (%).

and K_2, 2 N_2, ν_2, λ_2 whose cycles of separation are respectively one year with S_2, and six months with S_2, μ_2, ν_2, L_2. However, we have already mentioned in paragraph 2.3 the similarity between constituents of the same group and origin; this also applies to the above constituents. We can thus deduce their characteristic networks from those of the nearest known constituents by using the coefficients of proportionality between waves and the phase differences observed in the level constituents (cf. LE PROVOST, 1981).

One problem is, however, the choice of the number of constituents to be taken into account in formula (2). In the coastal zones, it is unavoidably high because the distortions due to the non-linear processes have to be reproduced. We have given in Table 1 the maximum amplitudes of the various constituents studied in FORNERINO's numerical simulation, as well as other significant constituents deduced from them by similitude. By limiting ourselves to the constituents, whose maximum amplitude exceeds 3 cm/s, we come to a number of 26 : it is precisely this same number that LE PROVOST chose for the equivalent model of level prediction which led to a mean square value rated at 20 cm in Le Havre, where the tide is reputed for its complex characteristics. For the tidal current prediction model we have in fact used 28 constituents, because the numerical simulation allowed us to establish the characteristics of two long-period constituents MS_0 (semi-monthly) and MN_0 (monthly) corresponding to the astronomical waves Ms_f and M_m, but resulting, in fact, from the non linear interactions between M_2 and S_2, on the one hand, and M_2 and N_2, on the other : these two constituents contribute in a significant way to the current fields around the capes (La Hague, Barfleur, Pointe Sainte-Catherine) and at the end of the Mont Saint-Michel Bay with a maximum amplitude of 6 cm/s and 3 cm/s, respectively.

The current prediction model thus formulated offers two types of products in practice :

— The prediction of a current field at any desired time t, accurately defined by its date (year, month, day) and its time (hour, minute, second) for a given group of points (x, y) which might very well cover the whole Channel : for each point the model predicts the module and the direction of the current. An example of this type of product is given in figure 6 : for the whole of the Channel a current pattern is established for different times during a tide of average amplitude.

— The prediction of the evolution in time of the current at a given point (x, y), for a given period between two dates t_1 and t_2. The model computes the module and the direction of the current vector at each moment $t = t_1 + k\Delta t$ between t_1 and t_2 with a time interval Δt specified by the user. Such examples are shown in figures 7, 8, 9, 10.

This model is easily adaptable to the micro-computers currently available on the market (with a memory of 16 Kbytes). This allows predictions to be made at an extremely low cost.

TABLE 1

List of constituents included in the prediction.

Maximum amplitudes : constituents 1 to 19 established from a numerical simulation; constituents 20 to 26 derived by similituc

No.	Cons-tituent	Angular velocity °/h	Maximum amplitude cm/s / Maximum amplitude area	No.	Cons-tituent	Angular velocity	Maximum amplitude cm/s / Maximum amplitude area
1	M_2	28.9841042	208 (A) 129 (B) 169 (C)	11	MN_4	57.4238337	8 (C) 5 (D) 4 (A)
2	S_2	30.0000000	63 (A) 38 (B) 63 (C)	12	$2\,MS_6$	87.9682084	7 (F)
3	N_2	28.4397295	33 (A) 12 (B) 29 (C)	13	μ_2	27.9682084	5 (A) 4 (C)
4	M_4	57.9682084	18 (C) 15 (D) 12 (B)	14	L_2	29.5284789	5 (A) 4 (C)
5	MS_4	58.9841042	16 (C) 9 (D) 8 (A)	15	MSN_2	27.4238337	5 (B) 3 (A)
6	$2\,MS_2$	27.9682084	15 (B) 14 (A)	16	MNS_2	30.5443747	4 (B) 4 (A)
7	K_1	15.0410686	13 (B)	17	$2\,SM_2$	31.0158958	3.5 (A) 3.4 (B)
8	O_1	13.9430356	12 (B)	18	Q_1	13.3986609	3.4 (B)
9	$2\,MN_2$	29.5284789	9 (A) 7 (B)	19	$2\,MN_6$	86.4079380	3.0 (F)
10	M_6	86.9523127	8 (F)				
	Area	A : Cap de La Hague B : Dover Strait		C Bréhat-Guernsey line D : Fécamp-Newhaven meridian			E : Cap de Barfleur F : Baie de la Seine
20	K_2	30.0821373	18 (A) 11 (B) 18 (C)	24	$2\,N_2$	27.8953548	4 (A)
21	ν_2	28.5125831	7 (A) 6 (C)	25	P_1	14.9589314	4 (B)
22	T_2	29.9589333	4 (A) 4 (C)	26	MK_4	59.0662415	4 (C)
23	$2\,MK_2$	27.8860712	4 (B)				

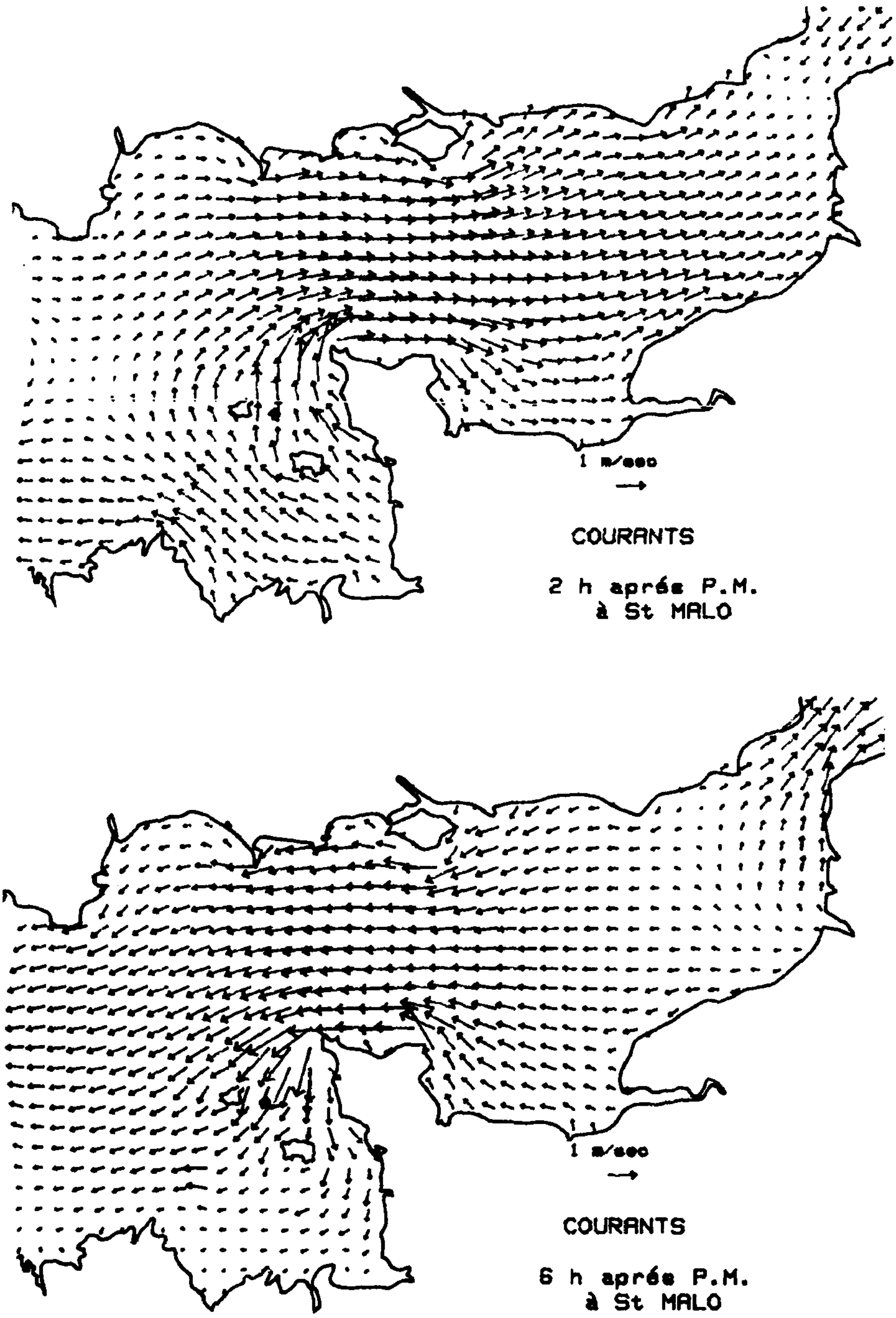

FIG. 6. — Maps of velocity field for a mean tide at t = 2 h and 6 h after high water at St.-Malo.

3. DISCUSSION — COMPARISON OF THE RESULTS WITH THE OBSERVATIONS

A useful collection of current observations in the Channel is available, in particular in the archives of the "Banque nationale des données océanographiques" (National oceanographic data center) (COB-CNEXO Brest). In order to assess the quality of the results of this model, we selected the measurement points giving the longest continuous series of observations for two reasons : first, so as to be able to assess the behaviour of the model over a long period of time, and second, because these long observed series can, a priori, be analyzed in terms of harmonic developments and thus enable us to understand any possible faults on some component of the prediction model. We have decided to give here four typical examples of such comparisons.

3.1. Point P_1 — Baie de la Seine

Observations of surface currents were made by the "Centre Océanologique de Bretagne" in 1979, over a period of 20 days (geographical location : 49°41′ N - 0°50′ W) and were analysed by Bertherat, Carcel and Le Provost (1981). Figure 7 shows a plot of the module and the current direction observed (limited to the first 15 days due to the page lay-out) and in Table 2 a list of some of the constituents computed through harmonic analysis of this signal. Over the measurement period, the maximum current is in the region of 1 m/s, its direction being alternately south-east at flood and north-west at ebb with a very low ellipticity (the current rose is almost rectilinear).

The predicted signal is plotted in dotted lines in the same graph. It can be seen that the differences between predicted and observed values are negligible; if one carefully studies the curve which gives the module difference, one can see that, for low coefficients, between the 13th and the 17th day, the maximum differences are not more than 10 cm/s and that, for the significant coefficients, these maximum differences are at most about 20 cm/s. It can be seen that the major deviations observed at the beginning of the recording are due to the malfunctioning of the current meter; except for the first three days, the average absolute value of the deviation is 4 cm/s and the mean square deviation is 6.6 cm/s. The predicted currents are, moreover, perfectly phased with the observed currents.

On the other hand, there is a major and systematic difference in the direction of about 23°, partly due to a difference of about 10° in the main direction of the current rose and partly due to a fault in the ellipticity. This difference results in a systematic error in the predictions clearly illustrated in figure 7 e which indicates the amplitude variations of the vectorial differences between prediction and observation.

These defects and qualities of the prediction are also clear if we compare the model and in-situ values of the main harmonic constituents, as shown in Table 2. The quality of the phase and amplitude parameters can be seen : there is only a difference of 4.2 cm/s for M_2, 0.1 cm/s for S_2 and 2.1 cm/s for N_2, and a few small inaccuracies with regard to phases. On the other hand, a discrepancy in the ellipticity of the constituents M_2 and N_2, as well as a deviation of about 10° in the direction of the maximum currents of M_2 and S_2 will be noticed. Besides, it will be noted that the parameters of the higher constituents (fourth and sixth diurnal) are quite well defined.

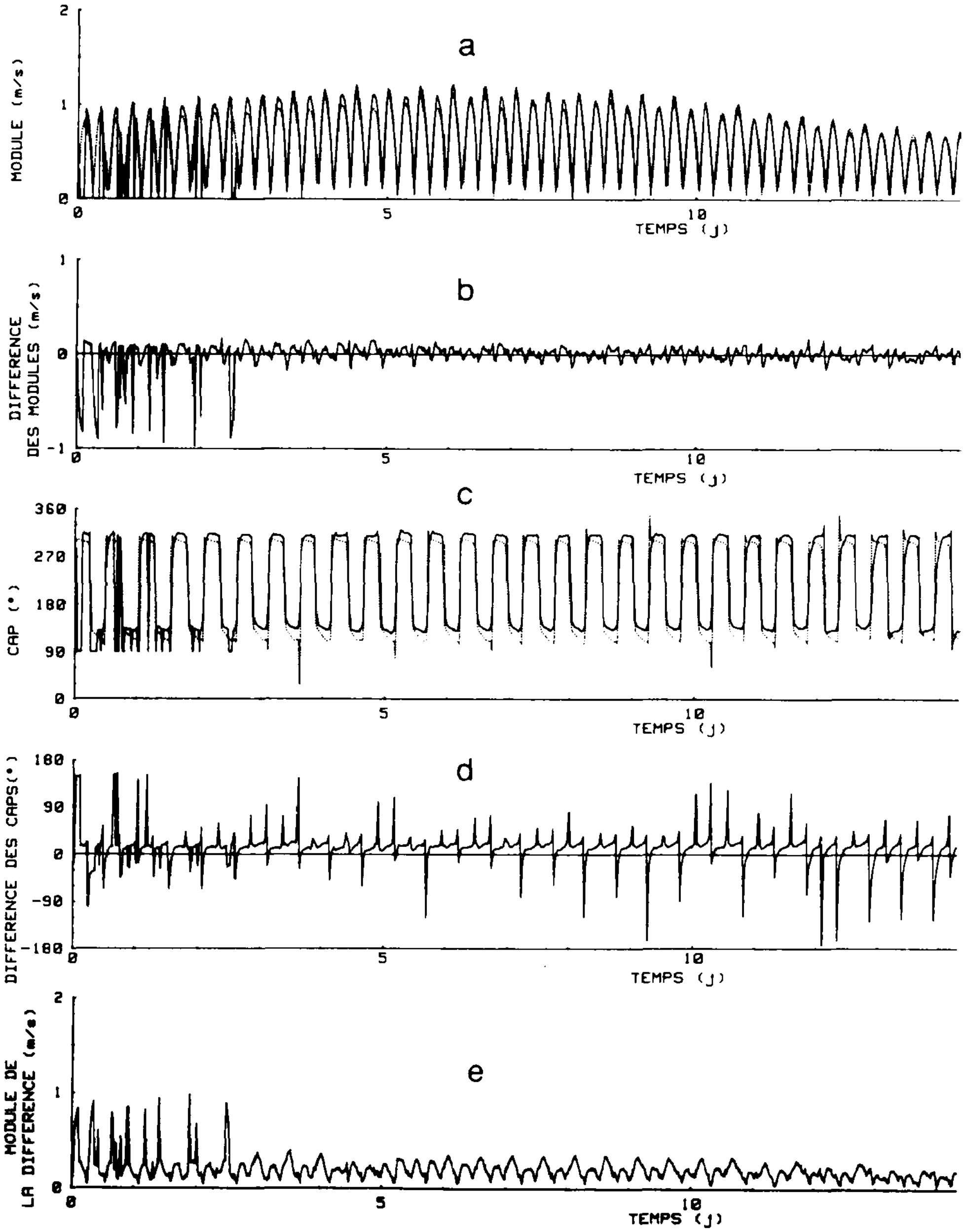

FIG. 7. — Observation and prediction of tidal currents at point P_1 (Baie de la Seine) since 19/6/79 at 19 h 20.

—— observation
········ prediction

TABLE 2

Harmonic constituents for tidal currents at point P_1.

Values observed in situ and computed from a numerical simulation over one month. Velocity in cm/s, phase in degrees related to the transit of the constituent at Greenwich meridian, direction in degrees related to the north geographical pole.

Cons-tituent	Maximum velocity		Max. current phase		Ellipticity		Max. current direction	
	Obs.	Comp.	Obs.	Comp.	Obs.	Comp.	Obs.	Comp.
O_1	1.3	1.5	42.8	176.	– 42.5	18.	45.	293.
K_1	2.0	1.4	32.5	62.	0.	– 21.	180.	133.
N_2	16.9	14.8	14.	15.	4.3	– 6.	298.	299.
M_2	96.2	92.	33.	33.	4.	– 6.	311.6	300.
S_2	28.9	29.	77.7	82.	– 8.2	– 8.	310.	301.
MSN_2	1.	1.5	12.5	79.	0.	– 9.	180.	116.
MN_4	2.15	1.7	34.	329.	28.	48.	112.	148.
M_4	6.25	5.	167.6	170.	– 57.4	– 52.	340.	326.
MS_4	4.04	3.5	32.	36.	– 20.	– 38.	171.	150.
$2\ MS_6$	7.2	5.	39.	24.	4.5	9.	326.	316.
M_6	5.6	5.7	173.	161.	14.	12.	135.	139.
$2\ MN_6$	2.2	2.6	5.6	323.	14.	16.	296.	315.
$2\ SM_2$	1.	1.5	105.	109.	0.	– 11.	90.	114.

3.2. Point P_2 — Paluel

A 40-day study is available for the area off Paluel. It was made by the EDF in 1976 (geographical location 49°46′ N, 1°40′ W) and an analysis was made by BERTHERAT (1981). This series is particularly interesting, since it shows a very marked asymmetry between flood and ebb. Figure 8 shows a plot of the velocity module amplitude and its direction from the 20th to the 35th day of observation.

As for the previous example, the predicted values given by the model are shown on the same diagram as dotted lines. First, we can see how well the directions are determined : the RMS error between observed and computed values is, over the 40 days available, only 9° !

The current module is also very accurately defined : the asymmetry between flood and ebb is very well reproduced between the 8th and the 31st day of observation; between the 2nd and the 8th, not shown here, and between the 32nd and the 38th day, the ebbs are still well reproduced, but a major deficiency in the flood leading to a difference of 25 cm/s is to be noted (see curve 8 b showing the module difference). This is most certainly due to meteorological effects (the observations were made in November and December), since any other interpretation is not logical. A comparison between the in-situ and the model values of the major harmonic constituents is indeed very favourable (cf. Table 3). One can notice the importance of the quarter-diurnal constituents, the sum of which corresponds to 19 % of that of the major semi-diurnal constituents, and which produces this asymmetry between ebb and flood.

In spite of these marked deficiencies over certain periods, one should keep in mind that the overall standard deviation over the 40 available days is only

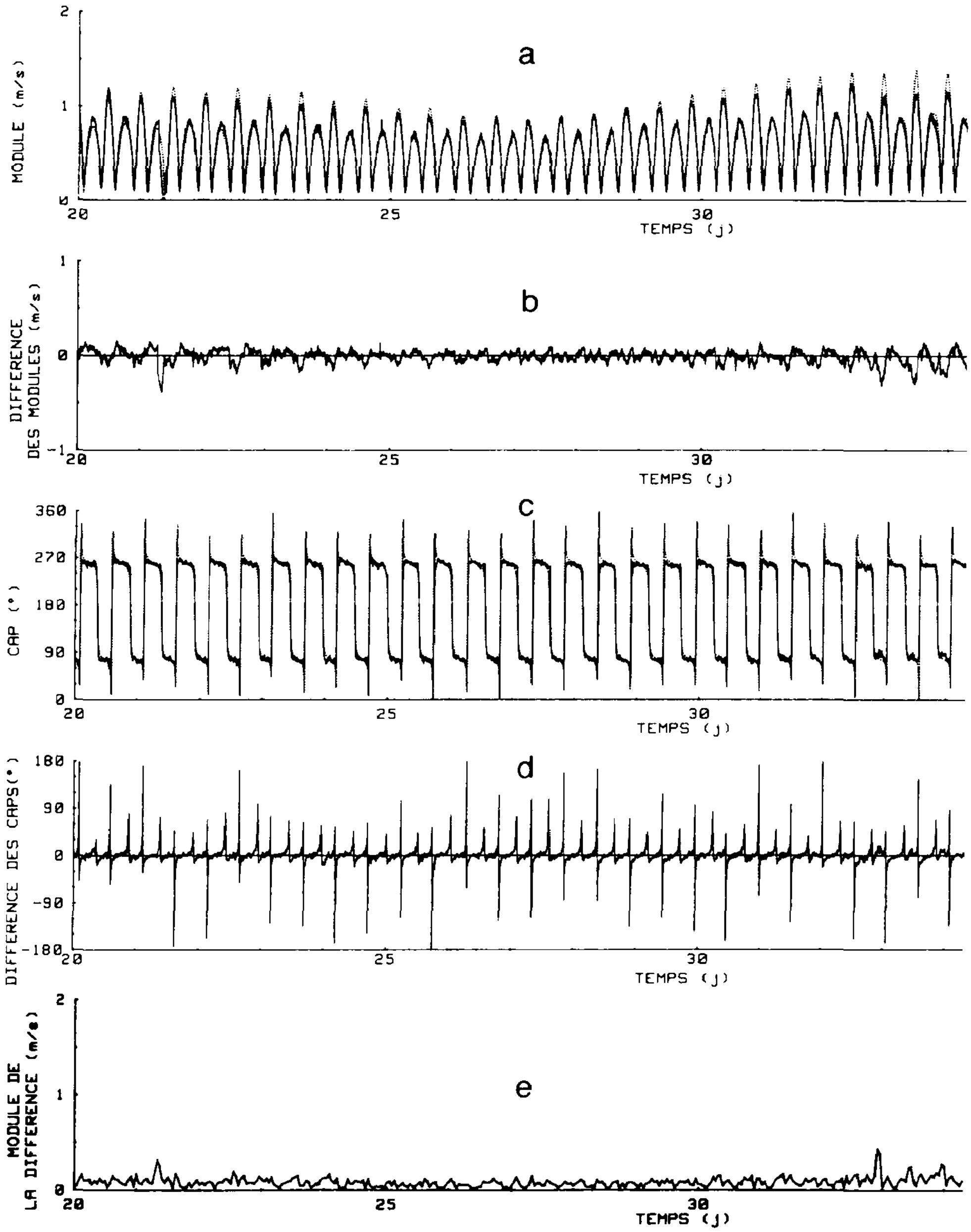

FIG. 8. — Observation and prediction of tidal currents at point P_2 (Paluel) from day 20 to day 35, since 18/11/76 at 22 h 20.

TABLE 3

Harmonic constituents for tidal currents at point P_2.

Values observed in situ and computed from a numerical simulation over one month. Velocity in cm/s, phase in degrees related to the transit of the constituent at Greenwich meridian, direction in degrees related to the north geographical pole.

Cons-tituent	Maximum velocity		Maximum current phase	
	Observed	Computed	Observed	Computed
M_2	81.6	83.0	59.1	58.0
S_2	23.4	25.9	285.0	288.0
N_2	13.3	13.6	218.0	216.0
M_4	11.4	12.1	114.0	98.0
MS_4	7.4	7.6	171.0	155.0
MN_4	3.8	4.2	74.5	79.0

6.7 cm/s and the mean overall deviation 8.9 cm/s. The agreement between the prediction at this point and the recorded values is all the more remarkable as it is situated near the coast where the grid is unavoidably coarse, given the 10 km grid of the simulation model.

3.3. Point P_3 — Central Channel

The behaviour of the prediction model in the central part of the Channel, where currents are very strong, is interesting. For this comparison we have selected point P_3 (coordinates : 50°01′ N - 1°47′ W) where the French "Service Hydrographique de la Marine" has completed a 16-day observation with a current-meter submerged at 29 m in depths of about 58 m. SHOM also made a harmonic analysis of this recording (Bessero, 1980).

The recorded current module and direction are shown in figure 9. One will notice the signal amplitude which exceeds 2.5 m/s during spring tides as well as the alternate east/west direction of the velocity vector. The prediction over this observation period gives relatively satisfactory results. We note a slight deviation in the direction (10° average) but, above all, a systematic error in the current amplitude due to a phase difference of the predicted signal producing an error of about 20 cm/s, to which is added a systematic deficiency of the ebb introducing a further 20 cm/s difference.

Referring to the observed and model values of the harmonic constituents relative to this point (cf. Table 4) we see that this phase difference is due to a fault of the semi-diurnal numerical solutions : M_2 is 10° too early, S_2 : 7°4 and N_2 : 11°7; a systematic deviation of 7° in the direction of the semi-diurnal constituents is to be found again in this table; the difference between flood and ebb is more difficult

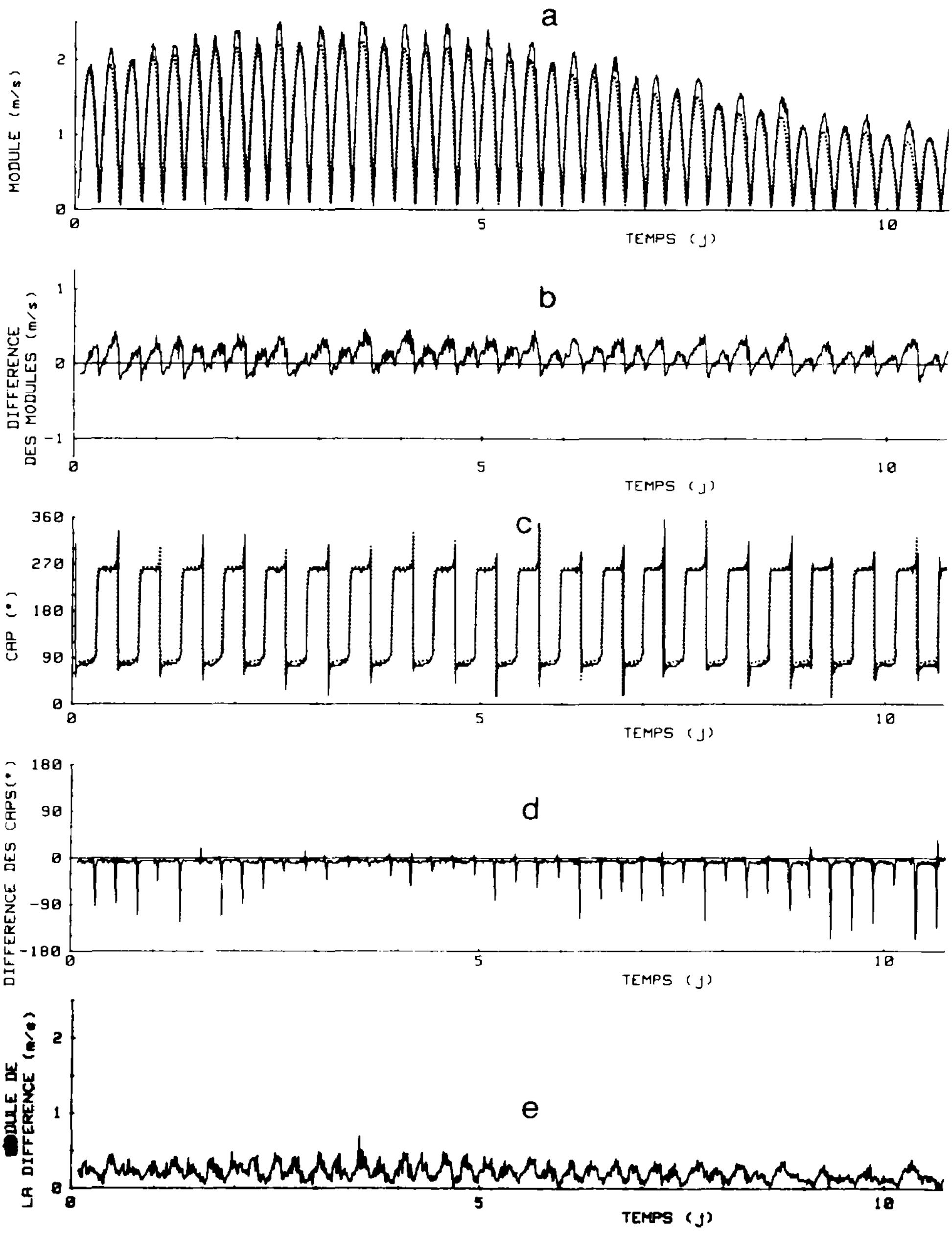

FIG. 9. — Observation and prediction of tidal currents at point P_3 (middle of the English Channel).

to interpret and no explanation can be found in the harmonic constituents given in Table 4.

In spite of these systematic faults, the mean deviation between predicted and observed values over the 16 available days is only about 14 cm/s for currents exceeding 2.5 m/s at certain periods. One can thus be reasonably satisfied with these results.

TABLE 4

Harmonic constituents for tidal currents at point P_3.

Values observed in situ and computed from a numerical simulation over one month. Velocity in cm/s, phase in degrees related to the transit of the constituent at Greenwich meridian, direction in degrees related to the north geographical pole.

Constituent	Maximum velocity		Max. current phase		Ellipticity		Max. current direction	
	Obs.	Comp.	Obs.	Comp.	Obs.	Comp.	Obs.	Comp.
O_1	2.5	2.9	17.8	2.0	4.0	2.0	69.5	84.0
K_1	2.6	2.7	45.6	63.0	7.7	1.0	78.2	83.0
MNS_2	1.6	1.9	154.8	91.0	0.0	1.0	75.4	83.0
N_2	18.5	25.8	186.8	198.5	2.2	1.5	77.3	84.0
M_2	155.2	157.5	226.1	216.0	3.2	1.5	78.7	84.0
S_2	47.5	50.0	271.4	264.0	2.9	1.5	77.5	84.0
M_4	2.8	1.9	279.5	329.5	35.7	4.0	112.4	52.0
MS_4	1.1	1.5	253.7	198.5	18.2	9.0	170.3	238.0
$2\ MS_6$	2.6	1.6	189.4	222.0	0.0	11.0	125.5	102.0
M_6	1.8	2.2	177.0	171.5	0.0	4.0	119.3	101.0
$2\ MN_6$	1.0	1.1	171.0	163.0	0.0	6.0	116.4	98.0

3.4. Point 4 — Off Cherbourg

However, this prediction model does not always provide the degree of accuracy found in the previous examples. We shall end our in-situ comparisons with the study of a point located off Cherbourg (location : 49°46′ N - 1°40′ W; 15 days' observation carried out by SHOM and analysed by BESSERO, 1980). The major deviations appearing in figure 10, in the module as well as in the directions, can be easily understood if one remembers the extremely coarse grid of Cotentin (cf. figure 1).

As regards the direction, a serious defect can be observed which corresponds in the predictions to a rotation of the current rose opposed to that of the observations. This results in a mean square error of 44° (with a mean absolute value of 25°). The significant deviations on the module seem mainly due to a systematic phase difference in the prediction, in advance, as for the previous point P_3, on the observation. A study of the harmonic constituents given in Table 5 shows that, in fact, these differences are not only the result of a phase difference of the constituent M_2 (17° or half an hour) but of an amplitude fault of 8.4 cm/s on M_2 and of 5 cm/s on S_2 and N_2 as well. On that table one notices the negative values of the semi-diurnal constituent rose ellipticity, in contradiction with the data inferred from observations. It is clear that the gridded division of the numerical model is not fine enough around Cotentin to give results as satisfactory as in the other areas studied.

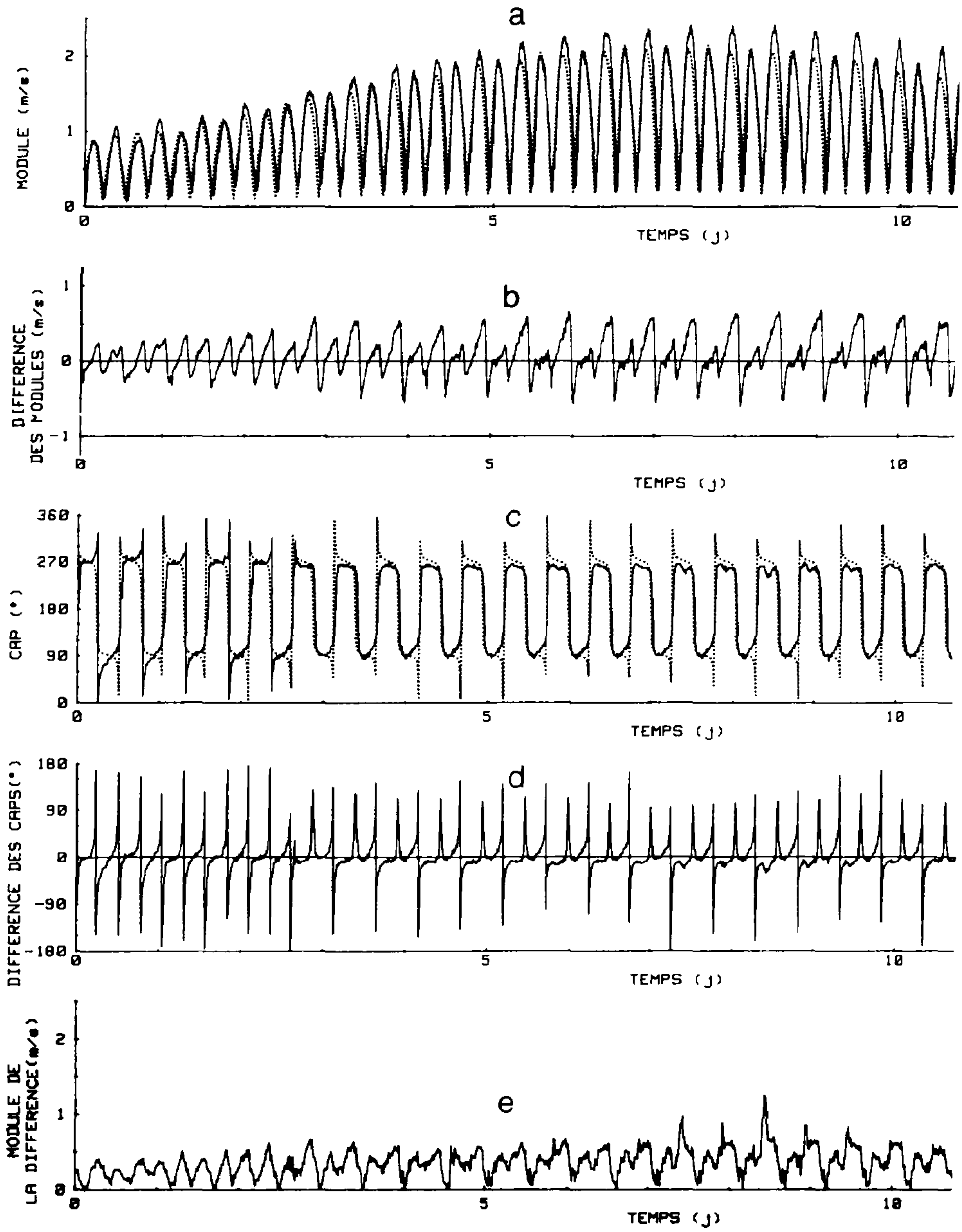

FIG. 10. — Observation and prediction of tidal currents at point P_4 (off Cherbourg).

TABLE 5

Harmonic constituents for tidal currents at point P_4.

Values observed in situ and computed from a numerical simulation over one month. Velocity in cm/s, phase in degrees related to the transit of the constituent at Greenwich meridian, direction in degrees related to the north geographical pole.

Constituent	Maximum velocity		Max. current phase		Ellipticity		Max. current direction	
	Obs.	Comp.	Obs.	Comp.	Obs.	Comp.	Obs.	Comp.
O_1	2.2	2.1	331.6	348.0	31.8	5.0	69.7	89.0
K_1	2.7	2.1	41.3	51.0	3.7	5.0	64.9	91.0
MNS_2	1.5	1.9	202.9	265.0	13.3	– 13.0	74.0	91.0
N_2	27.5	22.6	176.8	183.0	13.4	– 7.0	79.4	91.0
M_2	150.4	142.0	218.0	201.0	3.2	– 7.0	88.7	91.0
S_2	39.0	44.0	253.4	249.0	8.46	– 7.0	83.9	91.0
MN_4	2.2	1.3	274.8	123.0	18.2	– 5.0	24.8	85.0
M_4	10.2	3.5	349.2	323.0	3.9	– 2.0	42.8	85.0
MS_4	2.6	2.6	2.6	12.0	19.2	– 2.0	49.1	85.0
$2\ MS_6$	2.1	2.9	87.9	173.0	52.4	– 10.0	97.9	90.0
M_6	4.1	3.5	172.5	129.0	46.0	– 8.0	92.9	91.0
$2\ MN_6$	2.3	1.7	136.1	117.0	47.8	– 7.0	95.8	90.0

4. CONCLUSIONS

We have presented here a model for the prediction of the tidal currents in the English Channel. This model uses the results of a numerical simulation which had previously led to the production of a set of charts defining the characteristics of the major constituents of the tidal spectrum. With these harmonic constituents, reasonably precise predictions can be made which reproduce the signal modulations (semi-diurnal, diurnal, semi-monthly, monthly, etc.) as well as other typical aspects such as asymmetries between flood and ebb. Moreover, this method has an obvious practical advantage, because the computation equipment required is modest.

The model has been checked by comparing the predictions with some in-situ recordings. It is pertinent to note that these comparisons have been made using raw recordings, without filtering of some measured contributions not modelized, such as the effects of meteorological constraints; it should also be underlined that our results relate to the mean values of velocities on each vertical, and are thus not valid for the surface and the bottom. In spite of these shortcomings, the comparisons between predictions and observations are, in most cases, very favourable : about 10 cm/s should be noted as typical of the deviations on the modules and about 15° for the instantaneous value of inaccuracy in direction. These results are rather surprising given the low spatial resolution of the numerical model on which the calculation of the harmonic constituents used for the predictions is based. Passing on to regional models with finer grids would certainly give a better accuracy for the detail of the current patterns, particularly in coastal areas.

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