DETERMINATION OF MEAN LEVEL OF ARGENTINE SEA

Influences of Oscillations of the Sea not Caused by the Tide

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Note by Directing Committee of I.H.B.:

The « Argentine Sea » mentioned in the following article is stated to include:

« The whole of the continental shelf from the shore to the slope determined by the Argentine Atlantic Trench in the East and Drake Passage in the South ».

This area has not however been listed in the Bureau's Special Publication No. 23 « Limits of Oceans and Seas », nor has the name « Argentine Atlantic Trench » been so far adopted by the International Committee on Ocean Bottom Features.

Introduction.

Mean sea level is defined in principle as the surface where the tide is zero, and is determined by integration of the tide curve.

Integration of the tide curve may be accomplished mechanically and simultaneously by recording the tide by means of an « integrating tide-gauge », or by computation, i.e. by determining the arithmetical mean of hourly heights of the tide, previously obtained over an extensive observational period.

The tide curve, however, is not only the graphical expression of oscillations in sea-level due to lunisolar action, since it likewise totalizes all the effects of disturbing agents unrelated to the tide proper, and principally the action of the enveloping atmosphere.

Integration of the recorded tide curve will therefore not represent the « zero-tide surface », since the character of random action cannot be attributed with accuracy to influences of factors unrelated to the tide, even when a long series of observations is analysed.

It will therefore be necessary to establish the range and type of such unrelated influences in order to enable the accurate determination of the desired ideal surface.

In order to eliminate all sea-level variations produced by lunisolar action, it will suffice to consider complete oscillatory periods representing well-defined astronomical cycles. Such cycles are in part as follows:

Mean solar day	=	1	mean	solar	day
Lunar day	=	1.035	»	»	»
Anomalistic month	=	27.554	»	»	days
Synodical month	=	29.531	»	»	»
Tropical month	=	27.332	»	»	»
Nodical month	=	27.212	»	»	»
Evectional period of moon	=	31.812	»	»	»

Tropical year	= 365.242 mean solar days
Period of revolution of lunar perigee	= 3232.591 » » »
	= 8.85 years
Period of revolution of ascending node of moon	= 6793.459 mean solar days
	= 18.61 years
Metonic cycle (Repetition of moon's phases)	= 19.00 »
Saros cycle (Repetition of eclipses)	= 18.03 »

From this set of values, it has been deduced that a series of observations covering a period of 19 years may be considered as best adapted to a first-order determination of mean sea-level.

Experience has so far shown that mean sea-level determinations in one place over such periods have not coincided, whence it appears that all disturbances unrelated to the lunisolar tide have not been eliminated in spite of the long series of observations taken.

Such disturbances are largely of atmospheric and seismic origin, although longer-period variations of temperature, density and salinity of sea-water are likewise of relative importance.

Geographical irregularities of the particular location and the nature of the adjacent depths determine the tidal characteristics at in the area and may alter the « normal zero-tide surface ».

It will accordingly be necessary, before any determination of mean sea-level, to make an exhaustive study of local tidal conditions, in order to reject those which at first sight show the largest number of disturbing factors.

DYNAMIC ASPECT OF ARGENTINE SEA

The Argentine Sea extends over the whole of the Argentine continental shelf, from the shore to the slope determined by the Argentine Atlantic Trench in the East and Drake Passage in the South.

Owing to its shape and the distribution of isobaths in a direction parallel to the coast, the Argentine Sea is a large trough open to the ocean basins which surround it and in which the lunisolar waves propagated into it are formed.

These are refracted on the continental slope, are then propagated towards the coast, and are subjected to a series of transformations due to the gradual rise of the sea-bottom and to meteorological influences which, combined with the effect of the earth's rotation on the moving masses of water, cause the amplitude of the oscillations to increase so that upon their arrival on the coast they attain tremendous values.

The tide in the Argentine Sea accordingly takes on widely different forms and amplitudes, depending on whether the tide wave is of a progressive, stationary oscillating and amphidromic nature, combined with tidal currents having corresponding characteristics, i.e., of a reversing or rotary character.

These various types and amplitudes follow the topographic pattern of the area (extent of the shelf, depths, nature of bottom, etc.), proceeding from the mixed type with a two-foot range opposite Mar del Plata to the semi-diurnal variety with a 40-foot range opposite the section of the Patagonian coast adjacent to Puerto Gallegos.

The tidal pattern in the Argentine Sea may be observed in Figure 1. Co-tidal lines (of equal time of the tide) and lines of equal amplitude, corresponding to the principal lunar wave M_2, have been drawn, the latter wave being the most representative of the semi-diurnal group in the Argentine Sea.

The co-tidal lines are based on tidal observations carried out directly offshore and in the open sea; they are also derived from determinations obtained by computing the mathematical expressions connecting the tidal currents with the surface gradients, i.e.:

$$(1) \qquad \frac{\delta u}{\delta t} = -g \frac{\delta y}{\delta x}$$

in which:

u = horizontal velocity of current

g = acceleration of gravity

y = vertical displacement of the surface.

In the diagram appear two amphidromic points located on the Argentine continental shelf and which were predicted by Harris in 1904 as theoretically necessary, since at that time the requisite observations were not available for its determination on a more solid basis.

From a study of the co-tidal line chart (Fig. 1), we may assume the existence of two strong tide-waves of a preponderant semi-diurnal type. One is progressive, resulting from the meeting of the Atlantic with the Pacific, and runs into the Argentine Sea between the mainland and the Malvine Islands, whence it is propagated within 24 hours all along the coast as far as Rio de la Plata; the other is stationary, and is generated by the wave coming from the Atlantic, whereupon it is refracted by the continental slope. Interference with this wave occurs simultaneously over the entire length of the continental shelf, ending in the formation of two amphidromic systems: one off Puerto Deseado and the other opposite San Blas.

If the Atlantic-Pacific wave coming from the South did not exist, the stationary wave would be propagated freely in a direction parallel to the isobath delimiting the continental shelf, and would thus reach the entire coastline at the same time, even though the influence of the earth's rotation were to interfere with its development. It would not be possible to explain satisfactorily the extraordinary case of successive « port establishments » recorded along the Argentine coast.

The stationary wave's existence is not only proven by the great amplitudes recorded at Bahia Grande and San Matias, but by the generation of the amphidromic points, lacking which it would not be possible to explain the development of the co-tidal lines upon arrival at the Argentine Atlantic Trench.

The charts showing co-tidal lines and equal amplitudes (Fig. 1) are supplemented by others showing equal levels, or the topography of the sea surface at a given instant. In plotting the latter, the following expression is used:

$$(2) \qquad h_{M_2} = A \cos 30° \, (t - H)$$

in which:

h = height of water above mean sea-level

A = semi-amplitude of the wave considered

t = time

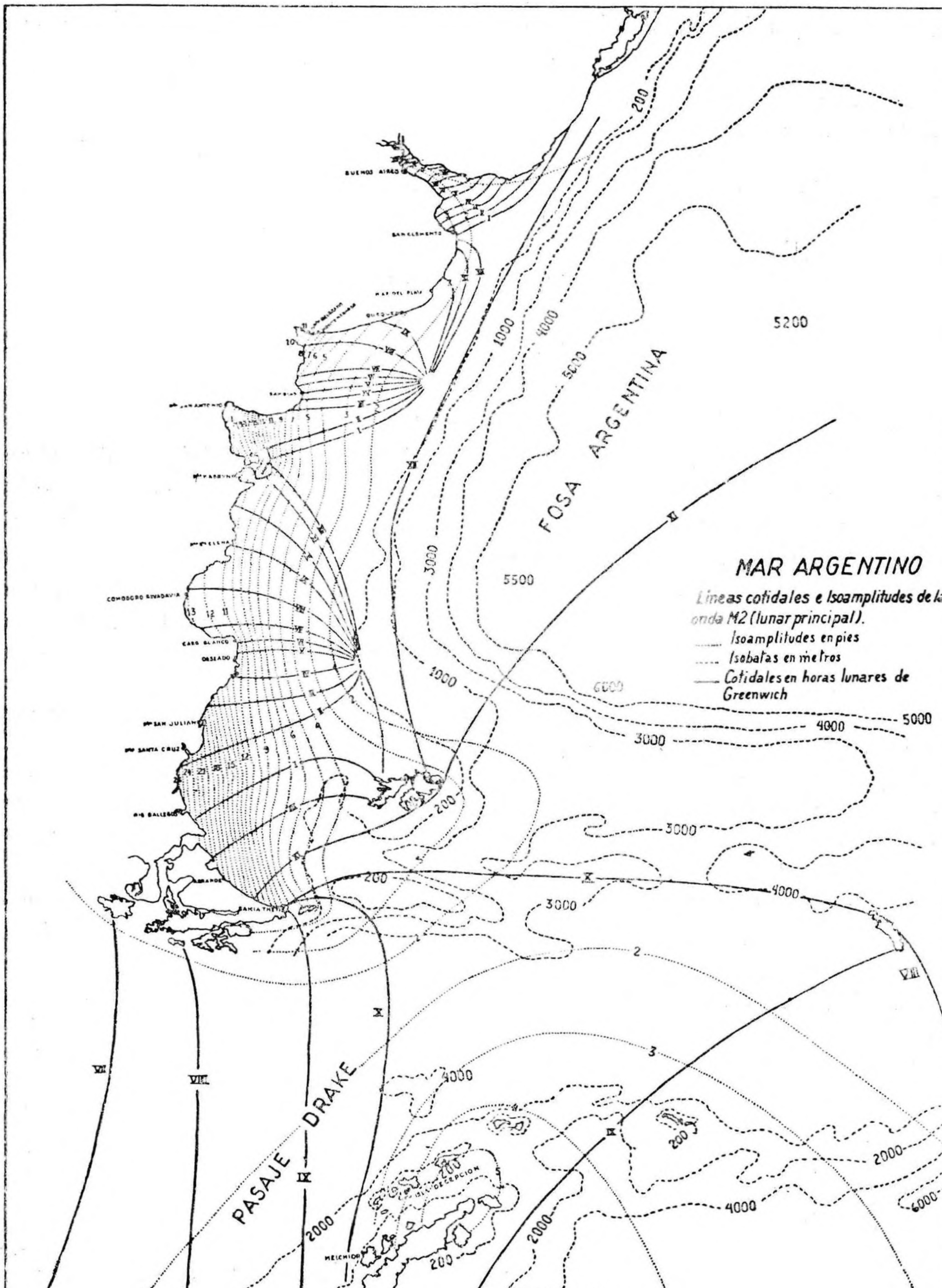

MAR ARGENTINO
Líneas cotidales e Isoamplitudes de la onda M2 (lunar principal).
Isoamplitudes en pies
Isobatas en metros
Cotidales en horas lunares de Greenwich
FOSA ARGENTINA
PASAJE DRAKE
ANTARTIDA ARGENTINA
5200
5500
6000
5000
4000
3000
2000
1000
200

Fig. 1.

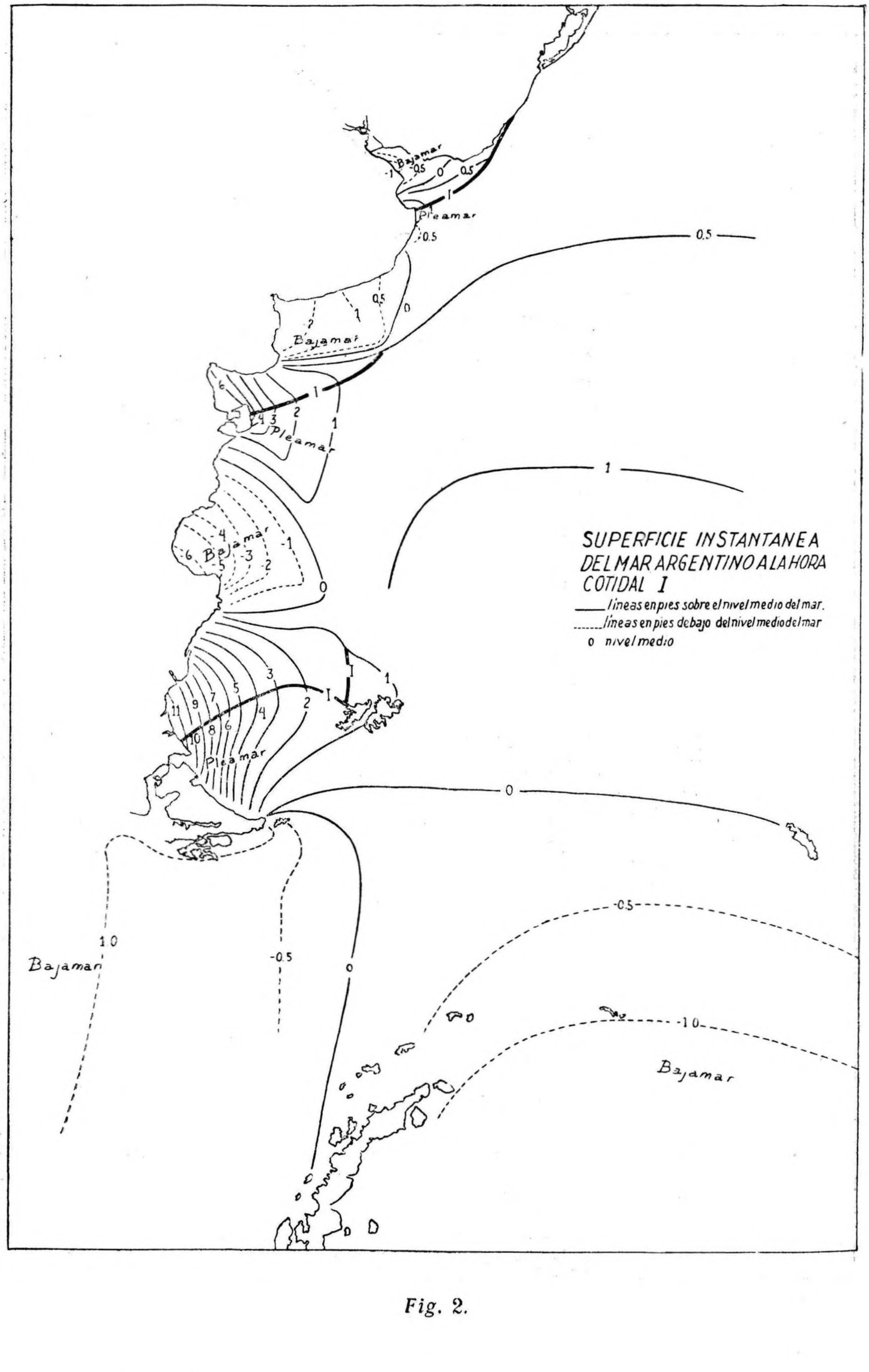

SUPERFICIE INSTANTANEA
DEL MAR ARGENTINO A LA HORA
COTIDAL I
____ líneas en pies sobre el nivel medio del mar.
...... líneas en pies debajo del nivel medio del mar
0 nivel medio
Bajamar
Pleamar
Bajamar
Pleamar
Bajamar
Pleamar
Bajamar
Bajamar

Fig. 2.

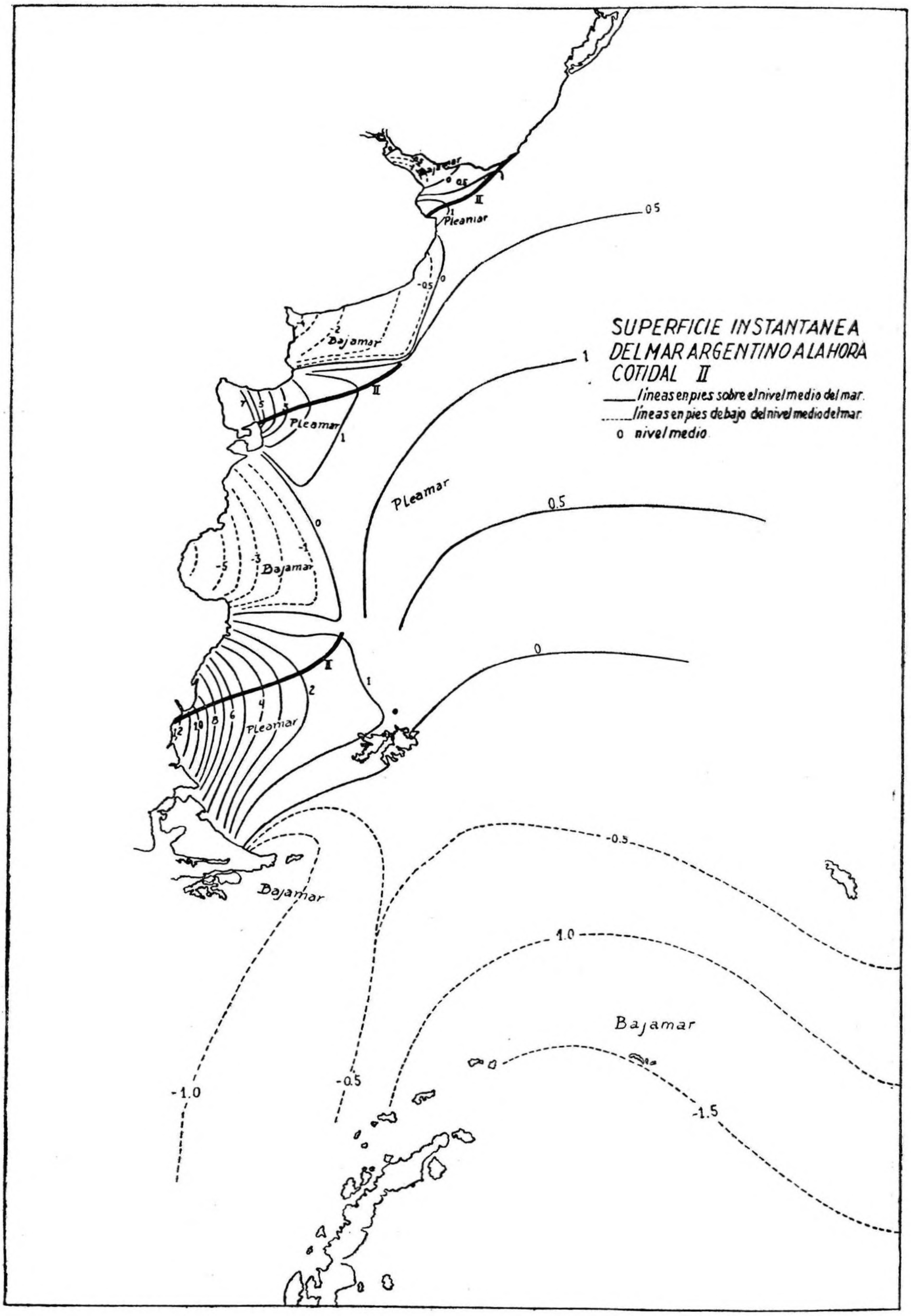

SUPERFICIE INSTANTANEA
DEL MAR ARGENTINO A LA HORA
COTIDAL II
líneas en pies sobre el nivel medio del mar.
líneas en pies debajo del nivel medio del mar.
o nivel medio
Pleamar
Bajamar
0.5
1
0
-0.5
-1.0
1.0
-1.5

Fig. 3.

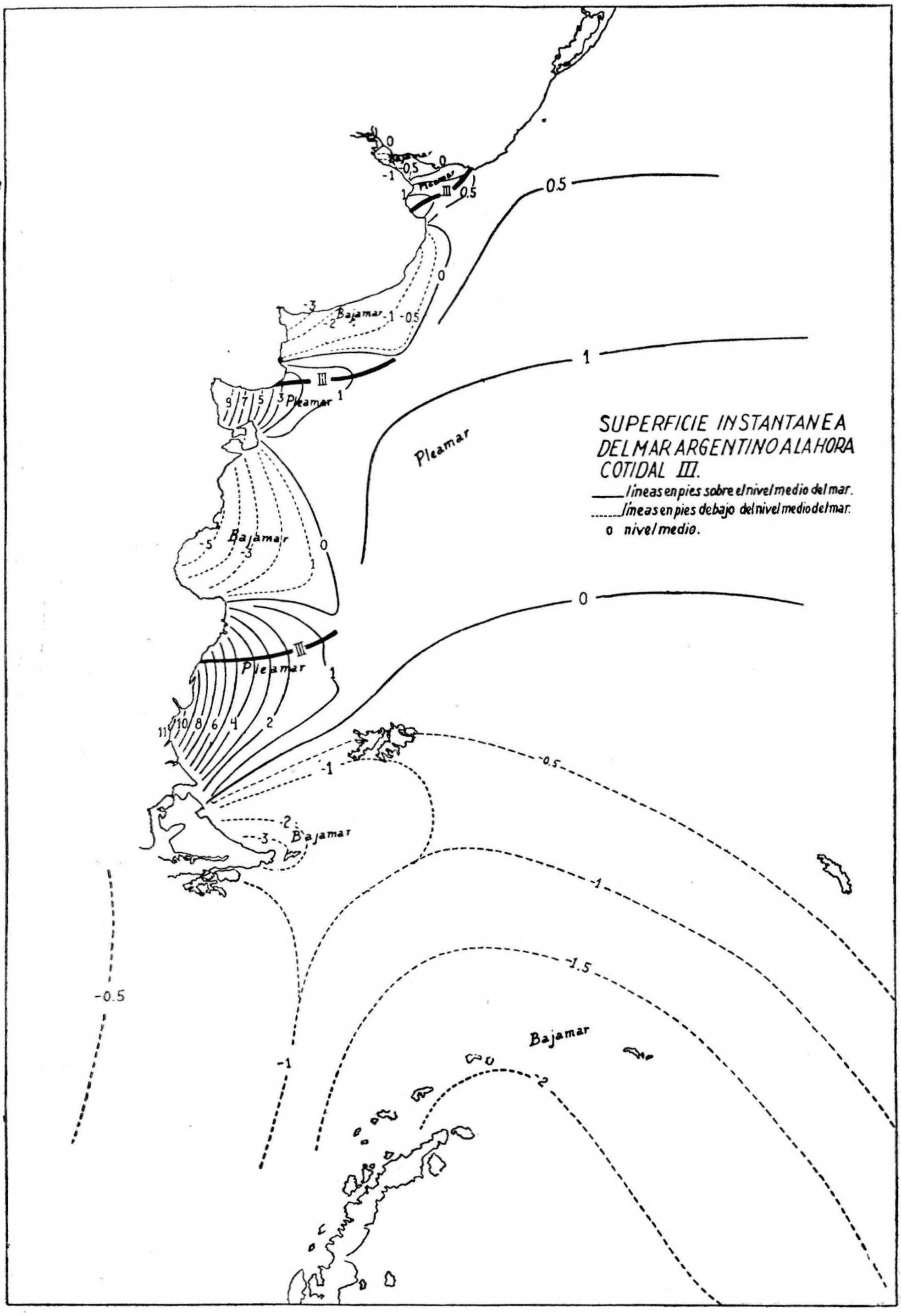

SUPERFICIE INSTANTANEA
DEL MAR ARGENTINO A LA HORA
COTIDAL III.
líneas en pies sobre el nivel medio del mar.
líneas en pies debajo del nivel medio del mar.
o nivel medio.
Pleamar
Bajamar
0.5
1
0
-0.5
-1
-1.5
-2

Fig. 4.

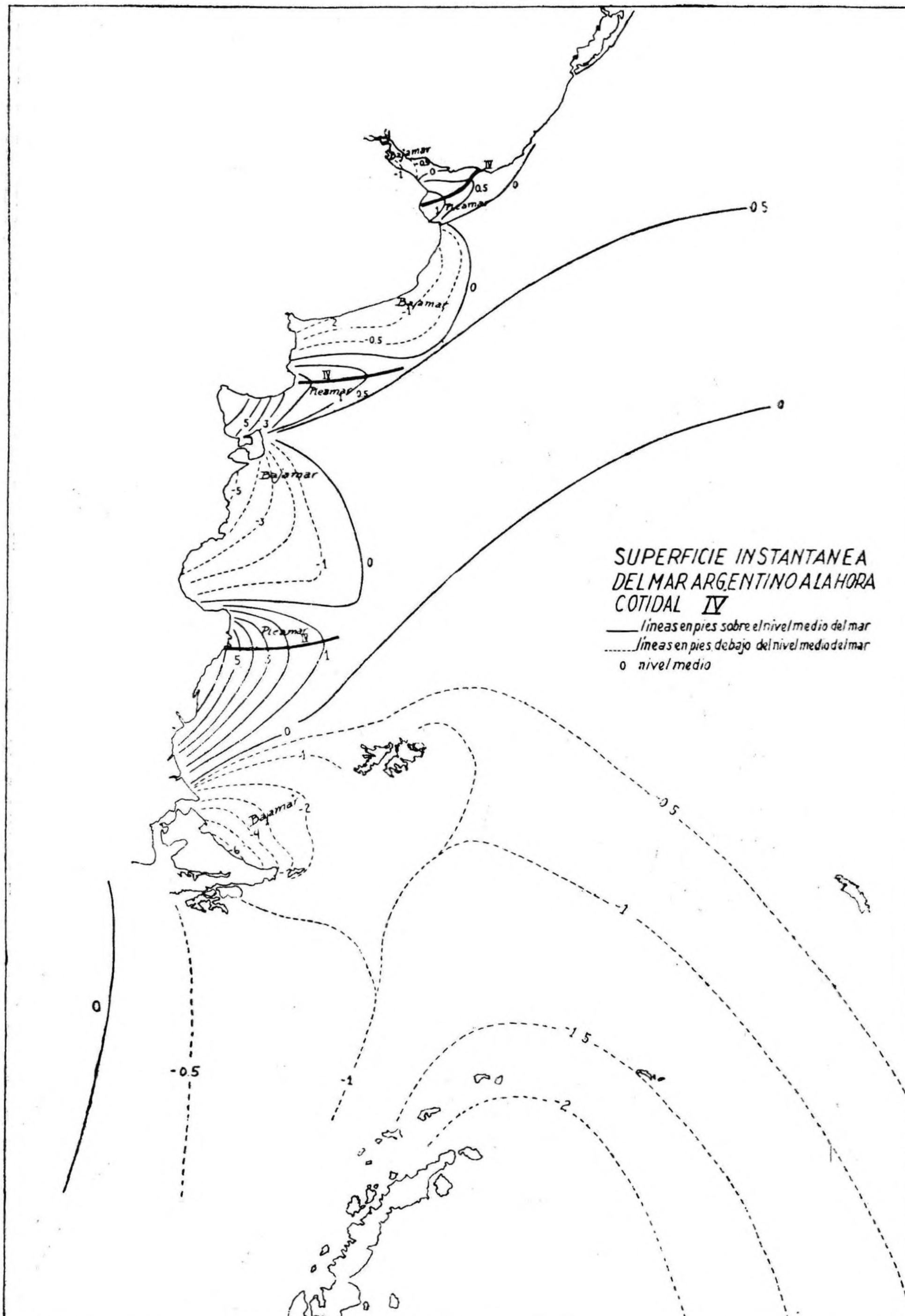

SUPERFICIE INSTANTANEA DEL MAR ARGENTINO A LA HORA COTIDAL IV
líneas en pies sobre el nivel medio del mar
líneas en pies debajo del nivel medio del mar
0 nivel medio
Bajamar
Pleamar
Bajamar
Pleamar
Bajamar
Pleamar
Bajamar
IV
IV
IV
0.5
0
-0.5
-1
-1.5
-2

Fig. 5.

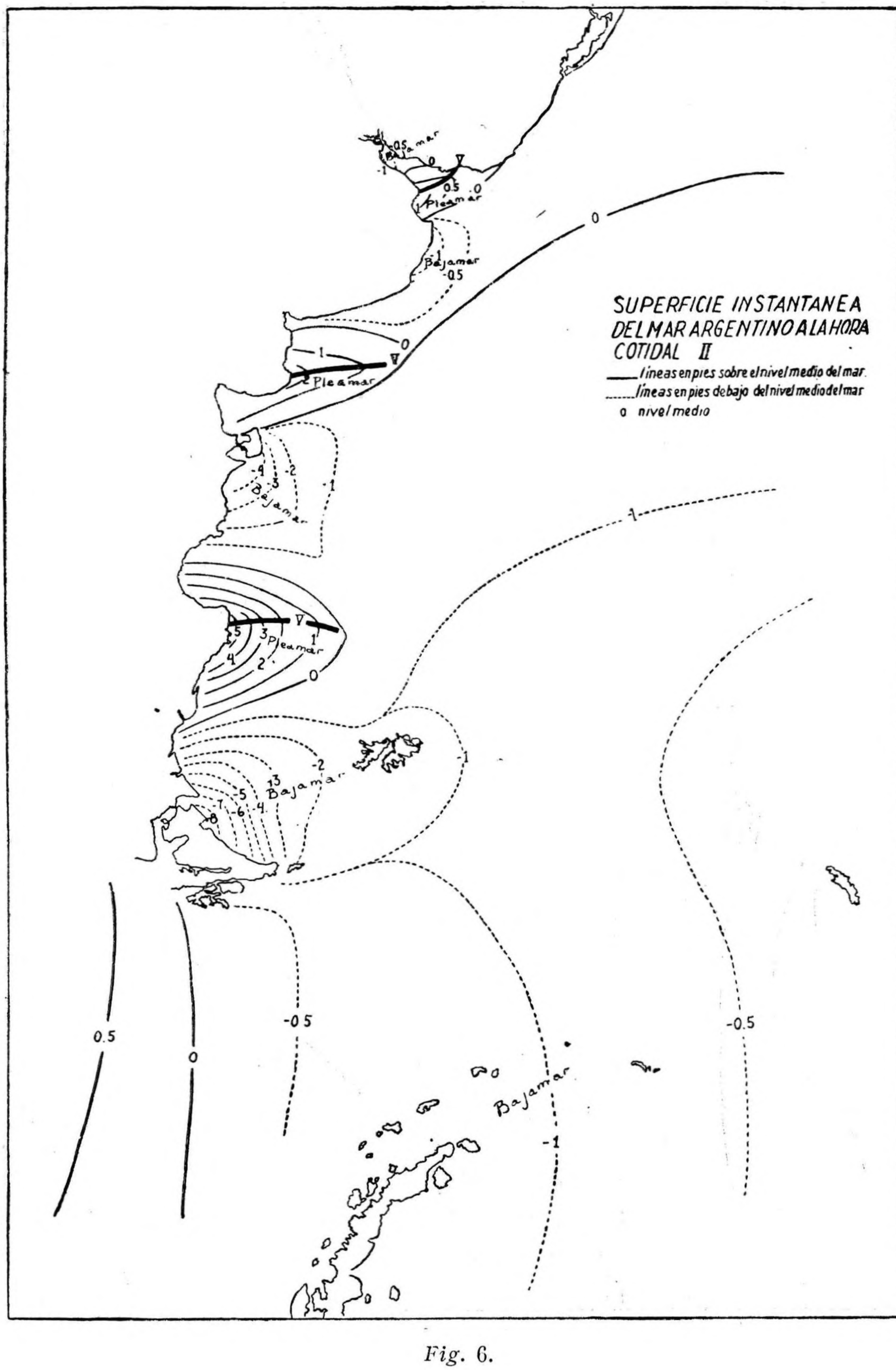

SUPERFICIE INSTANTANEA
DELMAR ARGENTINO A LA HORA
COTIDAL II
líneas en pies sobre el nivel medio del mar.
líneas en pies debajo del nivel medio del mar
0 nivel medio
Pleamar
Bajamar
-0.5
0.5
0
-1

Fig. 6.

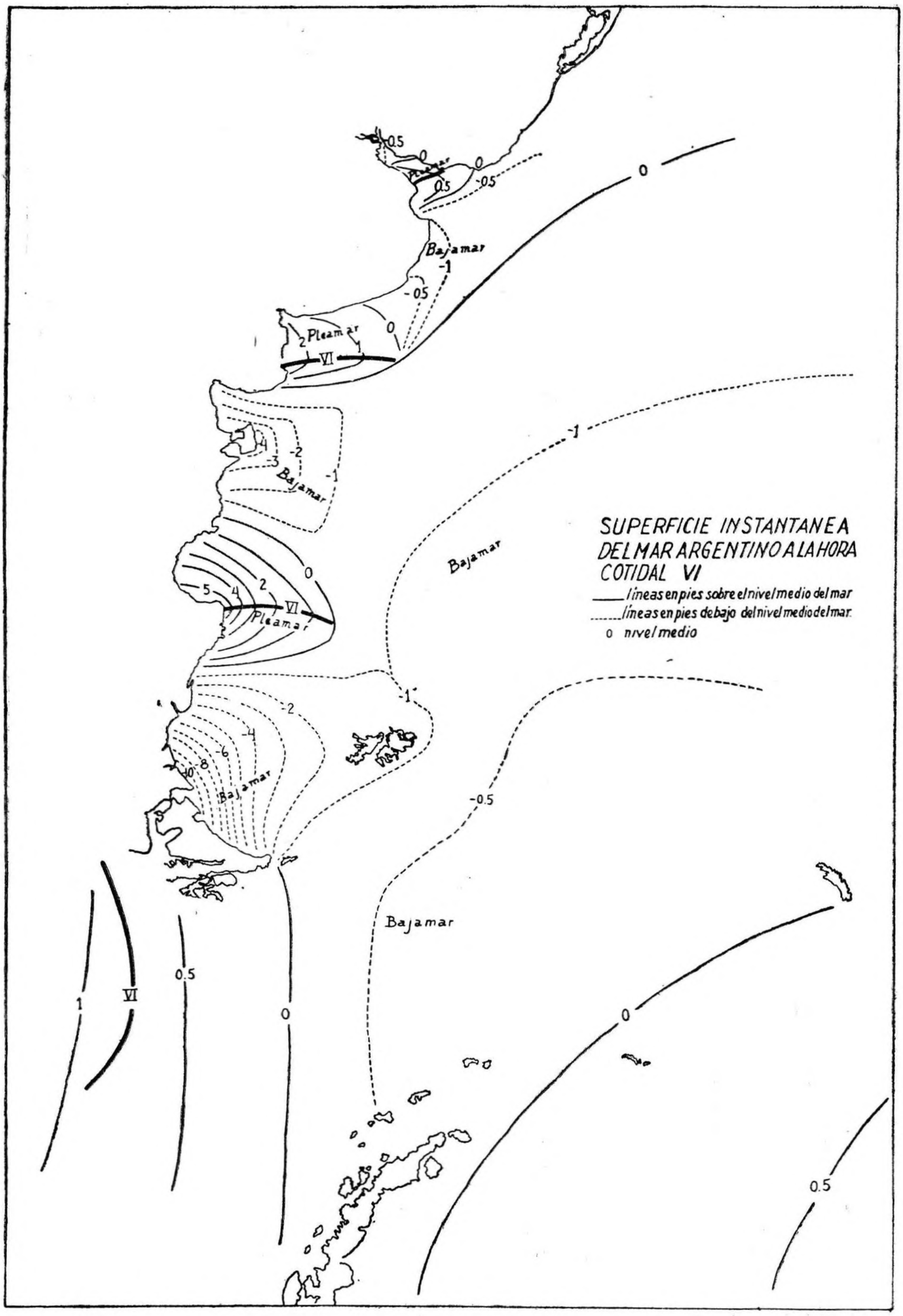

SUPERFICIE INSTANTANEA
DEL MAR ARGENTINO A LA HORA
COTIDAL VI
____líneas en pies sobre el nivel medio del mar
......líneas en pies debajo del nivel medio del mar
0 nivel medio
Bajamar
Pleamar
VI

Fig. 7.

$$H = \text{co-tidal time of } M_2 = \frac{K_{M_2}}{30} \pm G \text{ in Greenwich lunar time.}$$

Charts have been plotted corresponding to the co-tidal times I, II, III, IV, V and VI, which represent successive variations of the instantaneous topography of the sea corresponding to a half-cycle of wave M_2 (Figs. 2, 3, 4, 5, 6 and 7).

From observation of these charts, it may be deduced that the tide in the Argentine Sea is not produced as a wave propagated along the coast, but as an accumulation resulting from concurrent fronts in the successive places where it is formed. The tide continuously evolves in a direction resulting from its northward progression, and this in turn simultaneously gives rise to various directions and strengths of tidal currents, of such a complex nature that in nearby areas currents of different directions and magnitudes may be recorded.

ACTION OF THE ATMOSPHERE ON THE ARGENTINE SEA

The study of the dynamic topography of the sea surface, when the disturbing astronomical factor is alone considered, is frequently rendered invalid owing to the effect of meteorological action, which in certain areas of the Argentine Sea, reaches considerable proportions.

Therefore, and in order to obtain the range and effect of meteorological influences on mean sea-level, it will be necessary to clarify the tidal record curve which corresponds to the astronomical tide, characterized by its periodicity and amplitude, by separating from the marigram the residual curve, produced by atmospheric disturbances.

Such residual curves, which represent « storm waves », must be determined at the largest possible number of points, interconnected by altimetry in such a way as to bound extensive areas so that the actual effect of the atmospheric disturbance can be established.

Two types of oscillation should preferably be analysed. First, those having a very short period (from 2 to 25 minutes in the open sea), called « seiches »; and secondly, long-period oscillations (from 2 to 4 days) defined as « storm surges ».

Both types of oscillation are of great significance where the Argentine Sea is concerned (along the coast of the Province of Buenos Aires).

SEICHES: The short-period oscillations are recorded on the marigrams (in the open ocean) with the following main characteristics:

(a) 2-to-5-minute tooth-shaped oscillations with almost constant amplitudes of from 6 to 10 cm. (Fig. 8), coincident with the presence in the marine area of strong wave trains of irregular amplitude.

It appears that such short-period oscillations, which can occur alone or combined with other longer-period oscillations, result from an inordinate elevation of mean-sea level on the coast, due to the variable action of the wave trains.

For each wave train, the mean level passes alternately through a maximum and minimum, owing to the unequal amplitude of the trains, thus giving rise to a complex oscillatory motion of the mass of water adjacent to the coast.

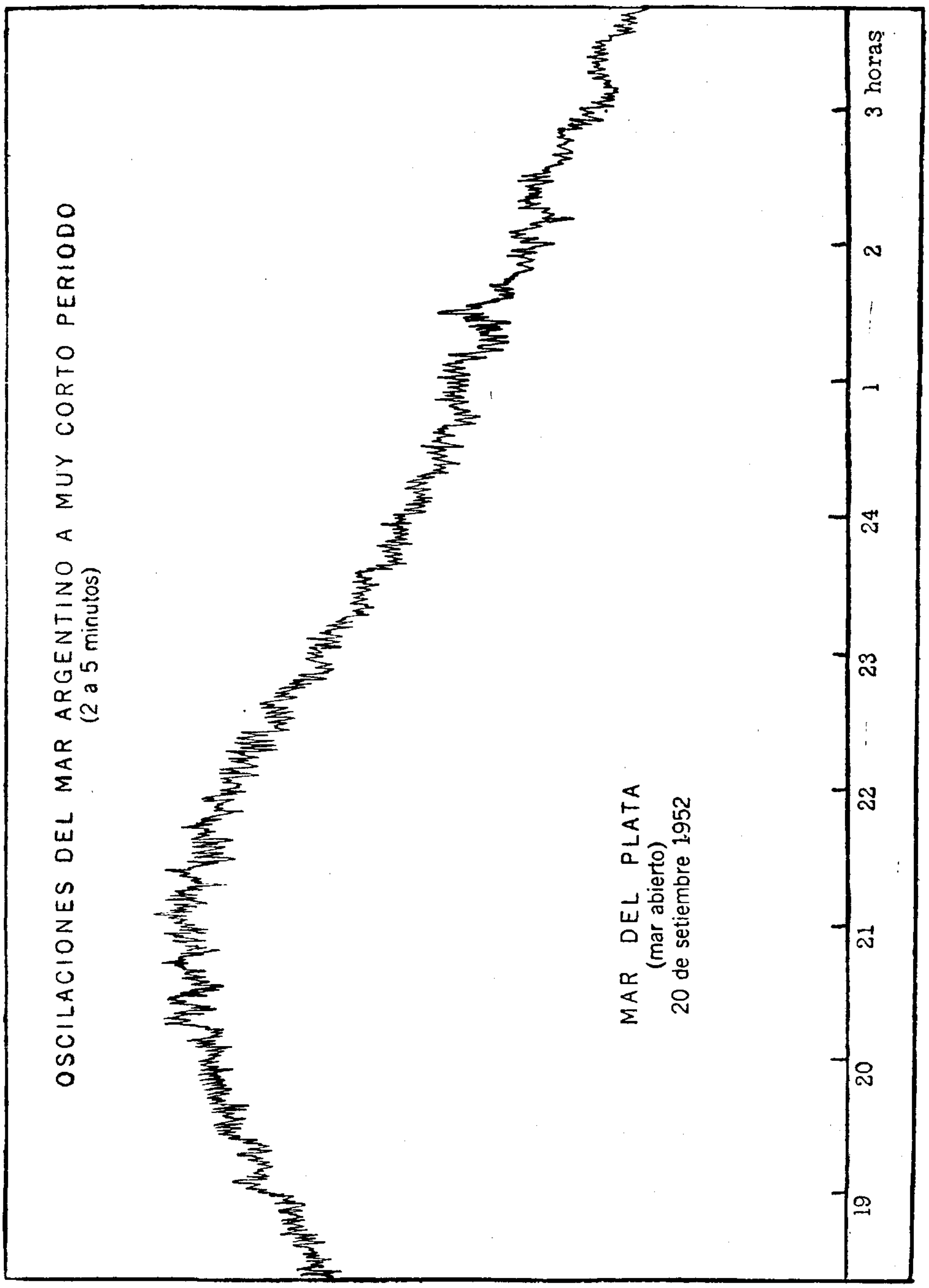

OSCILACIONES DEL MAR ARGENTINO A MUY CORTO PERIODO
(2 a 5 minutos)
MAR DEL PLATA
(mar abierto)
20 de setiembre 1952
19
20
21
22
23
24
1
2
3 horas

Fig. 8.

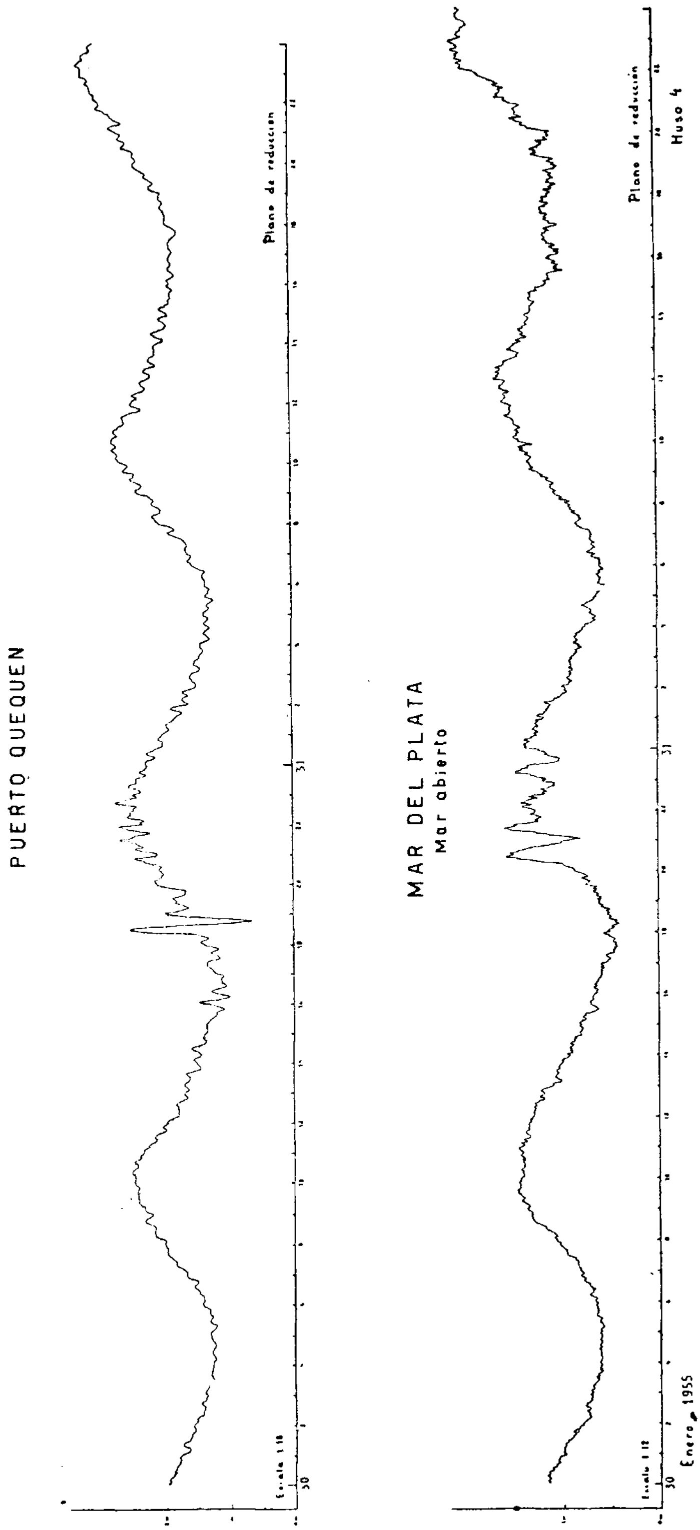

PUERTO QUEQUEN
Plano de reducción
MAR DEL PLATA
Mar abierto
Plano de reducción
Huso 4
Enero 1955
30
31

Fig. 9.

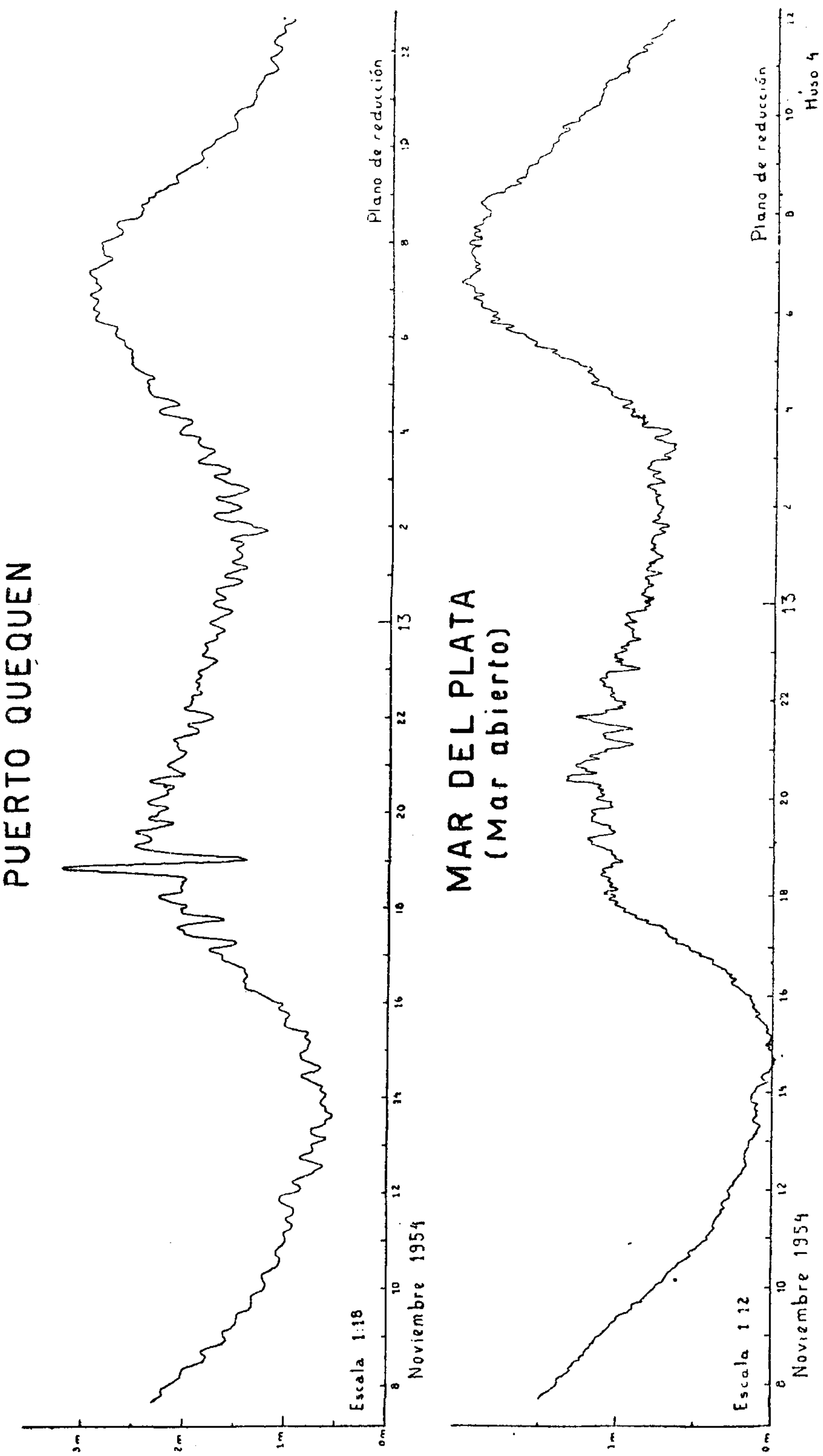

PUERTO QUEQUEN
Escala 1:18
Noviembre 1954
Plano de reducción
MAR DEL PLATA
(Mar abierto)
Escala 1:12
Noviembre 1954
Plano de reducción
Huso 4

Fig. 10.

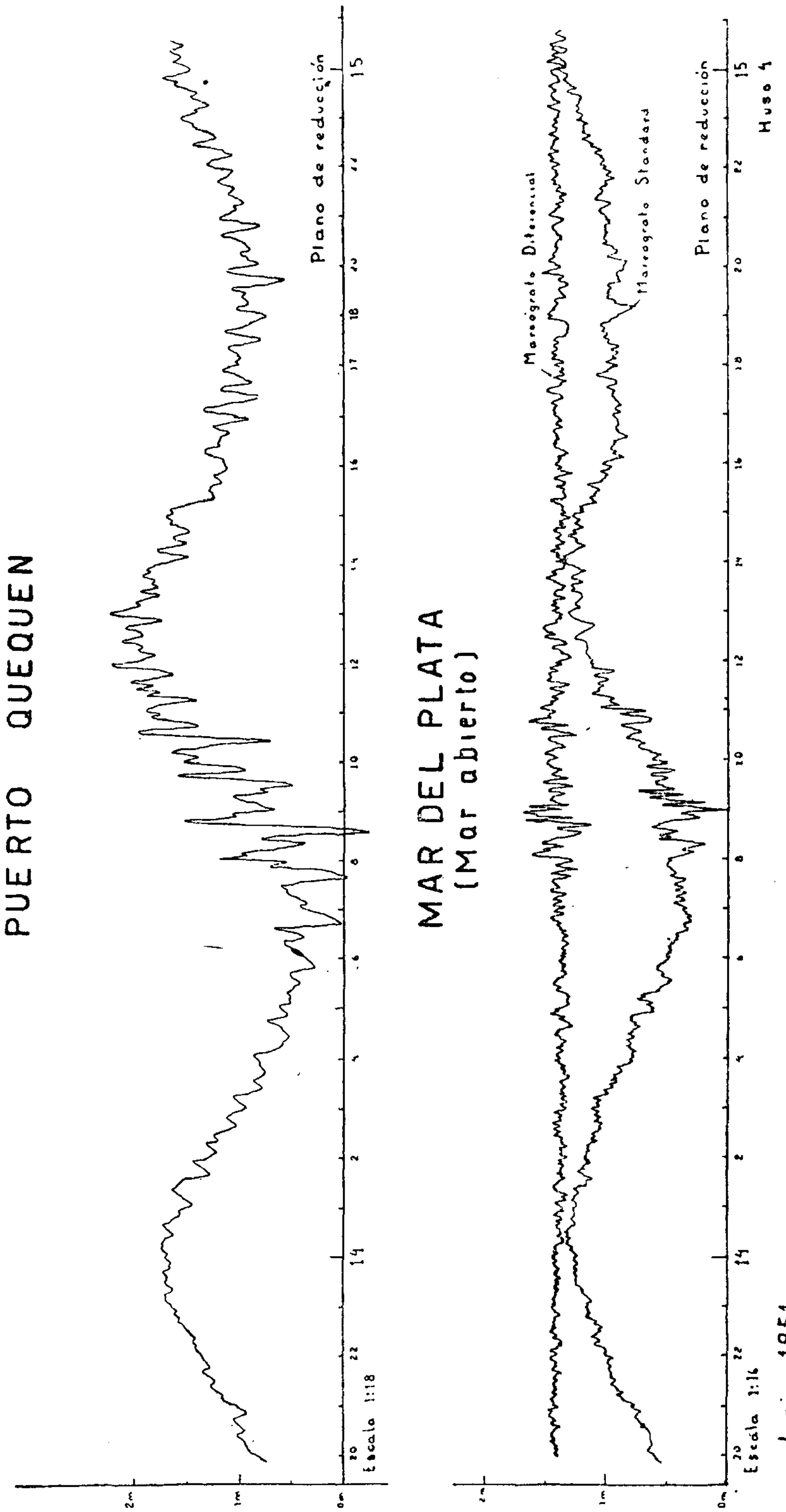

PUERTO QUEQUEN
Plano de reducción
Escala 1:18
MAR DEL PLATA
(Mar abierto)
Mareógrafo Diferencial
Mareógrafo Standard
Plano de reducción
Escala 1:16
Huso 4
Junio 1951

Fig. 11.

The amplitude of this oscillation may be determined by the following expression:

$$A = \frac{\pi}{4\,L}\,(h^2 - h'^2)\cot gh\,\frac{2\,\pi\,H}{L}$$

where:

L = length of oscillation

h and h' = maximum and minimum amplitudes of a series of waves

H = depth of water

Opposite the Mar del Plata coast (Tide Station) the mean value of this expression is A = 8 cm.

(b) 5-to-25-minute oscillations, of irregular shape and variable amplitude (15 cm. to 90 cm.). They suggestively occur during the passage of cold fronts in the maritime zone of influence.

When these oscillations are propagated within the harbours of Quequén and Mar del Plata, they increase up to 150 cm. due to the action of resonance, with a change in period and amplitude in accordance with the dimensions of the surrounding mass of water.

Figures 9, 10 and 11 reproduce the marigrams abtained at the Tide Stations of Mar del Plata (open sea) and Quequén (harbour).

The occurence of such « seiches » coincides with the passage of the cold fronts associated with the corresponding storm centres for the zone.

It has been observed in a great number of cases that prior to the occurrence of the « seiches » the level of the sea remains below the values corresponding to those determined for the prediction of the astronomical tide, carried out on the basis of various long-period harmonic analyses and totalizing 42 constituents.

During the phenomenon under reference, the weather situation which prevails over Argentine territory and the sea is as follows:

(1) A semi-permanent cold anticyclone from the Pacific, of wide extent and which in the shape of a wedge enters the territory at Lat. 38° S.

(2) A cold anticyclone of wide extent from the Atlantic which approaches the territory and of such range as to cover areas of Uruguay and Brazil.

(3) An almost permanent low-pressure area surrounding the Antarctic continent.

More or less pronounced low-pressure troughs in the eastern zone of Patagonia, ascending northwards to Lat. 42° S. A more pronounced pressure gradient towards the higher latitudes.

(4) A thermal depression between the Atlantic and Pacific anticyclones, descending to Lat. 36° S.

A cold air mass enters by way of Patagonia and extends towards the NE, displacing the warmer air over the land and giving rise to an extensive cold front.

It may be stated that the basic feature of the front is a wind shift from the northern sector to the southern sector.

In accordance with this standard synoptic case (Figs. 12, 13, 14), the prevailing winds over the south coast of Buenos Aires Province will be those in the north and northwest sectors, which will drive the waters out to sea and give rise to a change in level occurring over a wide area, determined by the dynamic equilibrium as between wind action and gravity.

When the opposite synoptic situation arises, involving the formation and displacement of the cold front and associated cyclones (Figs. 12, 13, 14), the latter will give rise as they advance to a corresponding change in sea-level due to the dynamic action of the distribution of pressure gradients.

This change in sea-level will give rise to an oscillation in combination with the previous one, which will already have begun to regress towards the coast, since the resultant wave will considerably increase the amplitude of its oscillation and will travel at even greater speed, owing to the favourable conditions it will then encounter.

This wave, upon its arrival on the slope represented by the coast of Buenos Aires Province, will be reflected upon itself, causing a sudden rise in sea-level (Fig. 9) followed by a rapid as the oscillatory cycle develops, until the logical dissipation of energy through gravity action, interference and friction brings about a decrease in amplitude and a gradual increase in periodicity, and it either disappears or becomes combined with a new phenomenon, then ending as « seiches » of an extremely complex aspect (Fig. 11).

Off Mar del Plata, in the open sea, the « seiches » that have been recorded have an average period of 12 minutes and an average amplitude of 15 cm.

For a mean depth of 90 m., which is the estimated figure for the maritime zone of influence, the result is a « seiche » 20 km. long (11 miles) and a propagation velocity of 30.6 metres per second (60 miles per hour), since:

$$L = T\sqrt{gH} \tag{4}$$

$$V^2 = g\frac{L}{2T'}\operatorname{tgh} 2\pi\frac{H}{L} \tag{5}$$

Since displacements of the fronts and associated storm centres in this zone reach a mean velocity of 30 miles per hour, in some instances seiches will occur several hours before the actual presence of the original atmospheric disturbance.

Analysis of atmospheric distributions generating « seiches » on the maritime coast of Buenos Aires Province.

January 30, 1955. At 0900, an Atlantic anticyclone was observed on the Uruguayan coast. At Mar del Plata, northwesterly and westerly winds and subnormal atmospheric pressure (1009 mb) were recorded (Fig. 12).

On the 2000-hours charts, pressure centres were observed at the previously described standard position, with the exception of an undefined warm front penetrating into Córdoba Provnice. The wind is from the NE sector, with a velocity varying between 19 and 26 km. per hour, and the pressure is 1010 mb.

At 0900 on the 31st, a cold front formed located at the level of Mar del Plata. The electrical storm which took place shows the lack of stability of the air mass. Upon the passage of this front a change in the direction of the wind

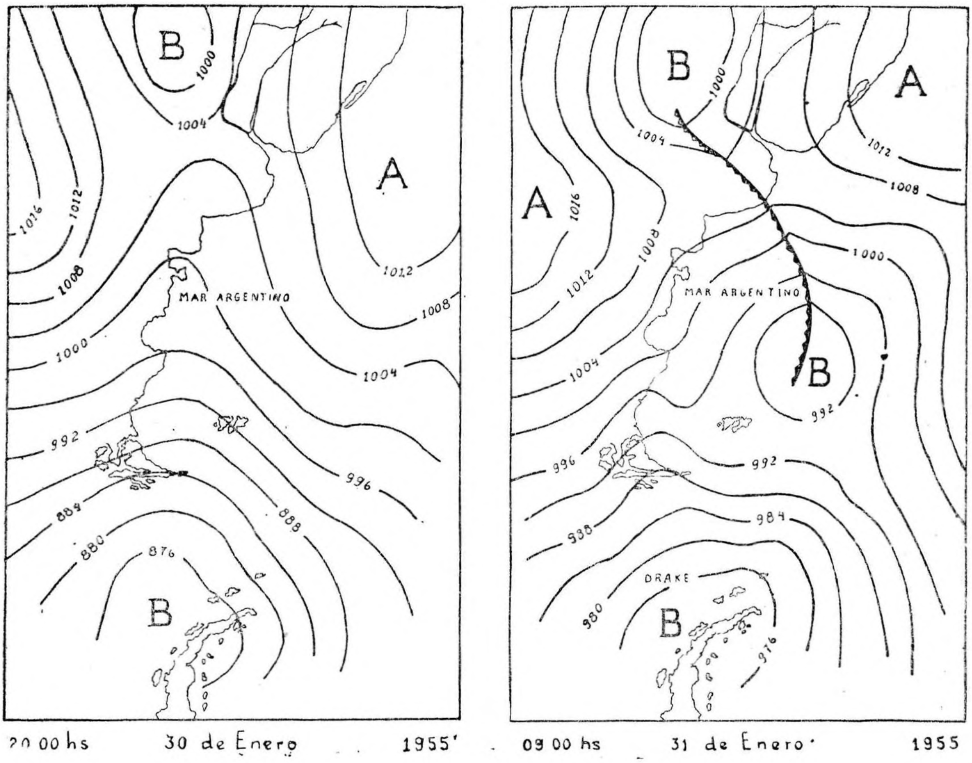

MAR ARGENTINO
DRAKE
20 00 hs 30 de Enero 1955
09 00 hs 31 de Enero 1955

Fig. 12

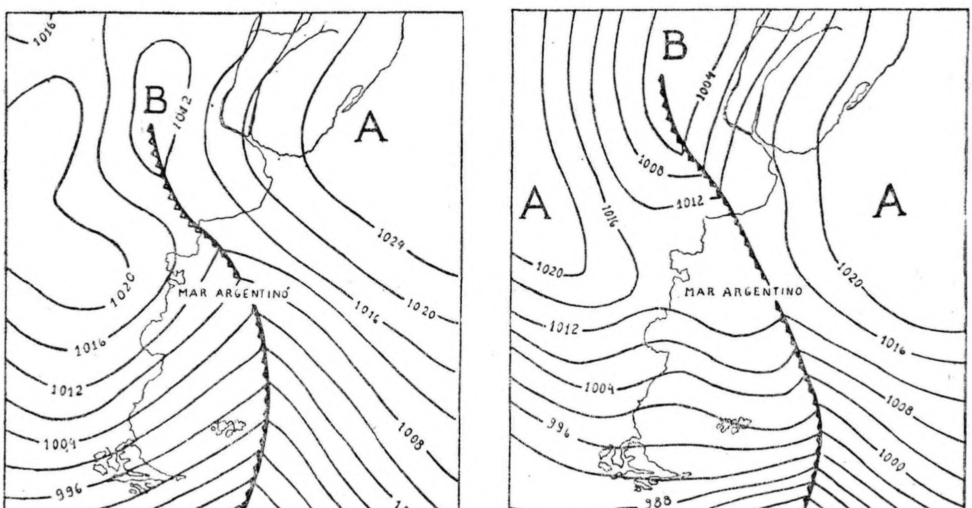

MAR ARGENTINO
DRAKE
09 00 hs 12 de Noviembre 1954
20 00 hs 12 de Noviembre 1954

Fig. 13

was observed which appeared to come from the southeast. Coinciding with the passage of this front at Mar del Plata, the « seiche » was recorded on the marigram of the Tide Station (Fig. 9).

November 12, 1954. An unusual seiche was observed at Mar del Plata and Puerto Quequén. On the 0900-hours weather-chart of this particular day, the Atlantic and Pacific anticyclone cover extensive areas which enter Argentine territory in the shape of a wedge; the formation of a closed cold front was observed which occured over the land at the altitude of Bahía Blanca. Winds at Mar del Plata came from the northwestern sector and had a velocity of 7-12 km. per hour (Fig. 13).

At 2000 hours, the anticyclone centre moved eastward, along the Buenos Aires coast. The cold front moved to the northeast, giving rise during its passage to intermittent electrical storms. At Mar del Plata the wind shifted to the east. Coincident with the passage of the front a Mar del Plata between 2000 and 2400 (time-zone 3), the seiche was recorded on the Station marigram (Fig. 10).

June 14, 1951. The weather-chart for this date shows a tropical air mass over the northern part of the country with a temperature of 10 to 15 degrees above normal. The southwestern sector of Buenos Aires Province, Eva Péron, the Cuyo and Patagonia areas are slightly covered by a colder air mass (Fig. 14). Both air masses determine an extensive frontal surface of the occluded type where the cold air mass displaces the warm air mass. A depression is moreover noted at the level of Necochea which extends to the western part of Buenos Aires Province. The weather conditions at Mar del Plata were as follows: a north wind with a velocity of 7 knots, and in the southern part of Buenos Aires Province slight precipitation.

On the 14th, between 0800 and 1000 hours, seiches were observed on the marigram of Mar del Plata and Puerto Quequén as coinciding with the passage of a cold front (Fig. 11).

On the 15th at 0900, the cool air front arrived as far as Río de la Plata and south of Santiago del Estero, and remained in the northern and central sectors of the country, as well as southeast of the coast, which were still covered by tropical air. At Mar del Plata the wind shifted to the south quadrant, giving rise moreover during passage of the cold front to precipitation and a decrease in temperature.

STORM SURGES: The long-period oscillations commonly known as « storm surges » occur in the Argentine Sea with great force and with relative frequency.

In March 1950 a « storm surge » with marked characteristics as regards amplitude, period and extent was recorded. Its action was felt all along the coast from Comodoro Rivadavia to Palermo (in Río de la Plata), and it reached maximum amplitude opposite Mar del Plata and Quequén.

It raised the mean sea-level above its normal value during the 3 days it lasted by as much as 68 cm. at Comodoro Rivadavia; 75 cm. at Madryn; 143 cm. at Puerto Belgrano; 145 cm. at Puerto Quequén; 140 cm. at Mar del Plata (in the open sea); and 18 cm. at Palermo (Río de la Plata) (Fig. 16).

The period covered was 3.4 days. The atmospheric distribution responsible for such a rise in mean sea-level was the following (Fig. 15):

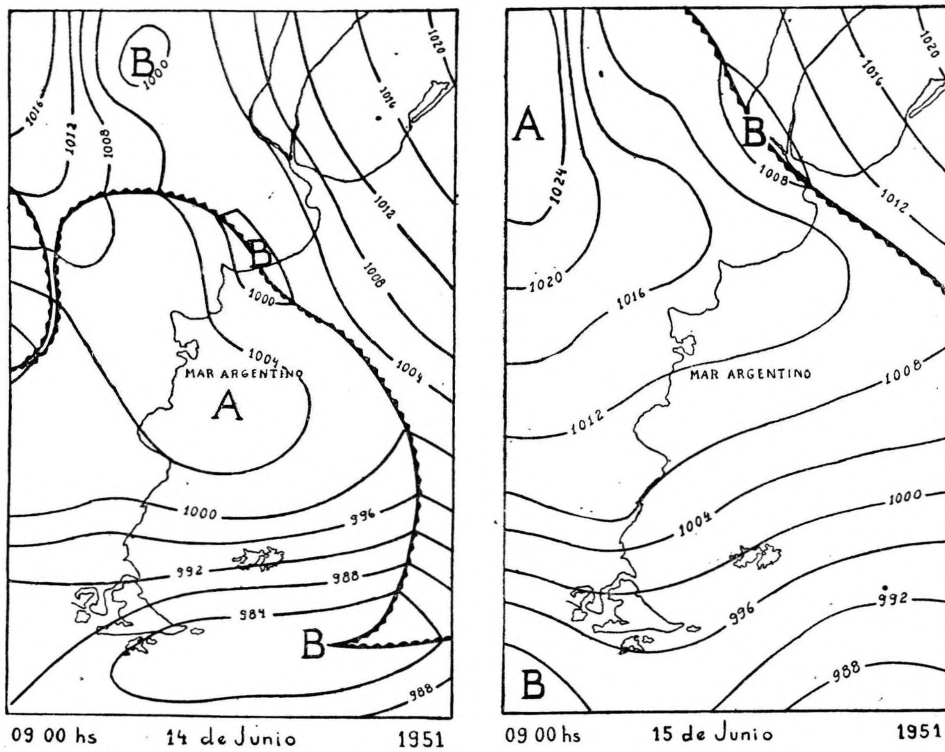

MAR ARGENTINO
A
B
09 00 hs 14 de Junio 1951
MAR ARGENTINO
A
B
09 00 hs 15 de Junio 1951

Fig. 14.

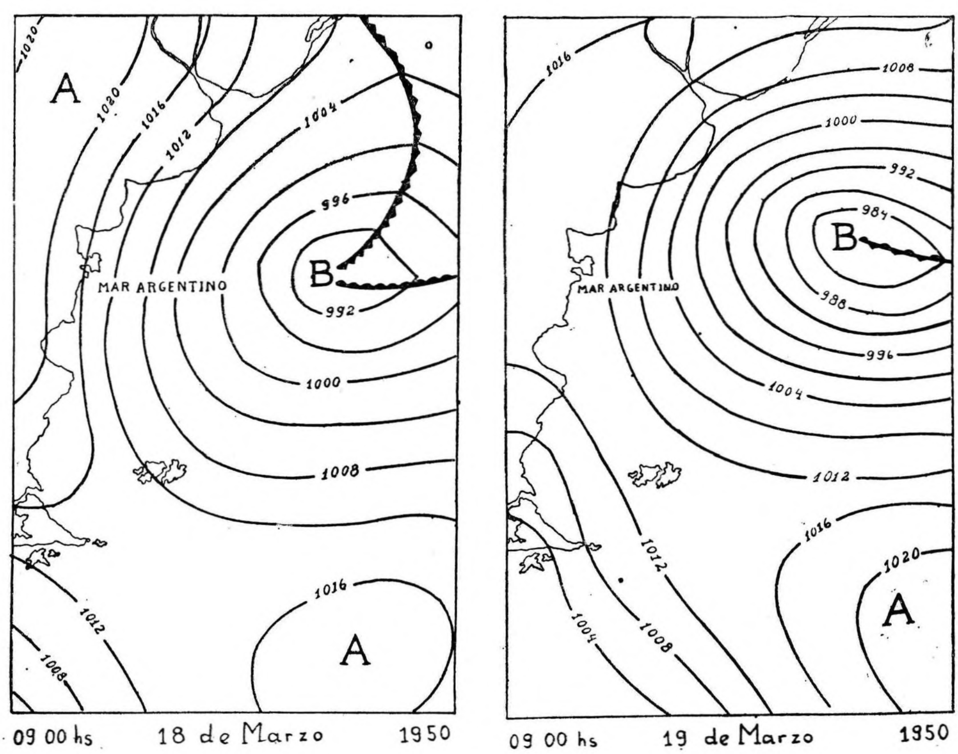

MAR ARGENTINO
A
B
09 00 hs 18 de Marzo 1950
MAR ARGENTINO
A
B
09 00 hs 19 de Marzo 1950

Fig. 15.

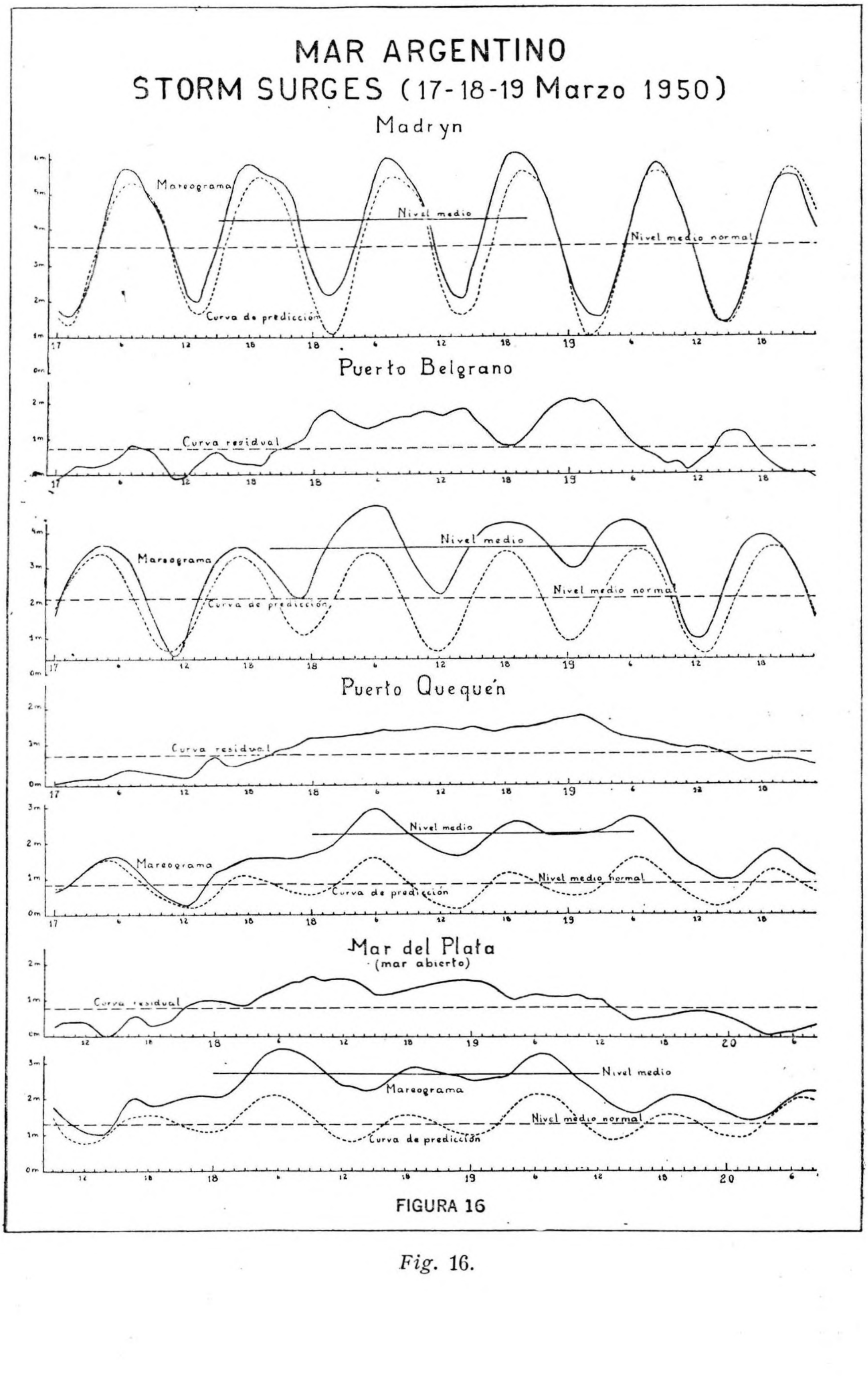

MAR ARGENTINO
STORM SURGES (17-18-19 Marzo 1950)
Madryn
Mareograma
Nivel medio
Nivel medio normal
Curva de predicción
Puerto Belgrano
Curva residual
Nivel medio
Mareograma
Nivel medio normal
Curva de predicción
Puerto Quequén
Curva residual
Nivel medio
Mareograma
Nivel medio normal
Curva de predicción
Mar del Plata
(mar abierto)
Curva residual
Nivel medio
Mareograma
Nivel medio normal
Curva de predicción
FIGURA 16

Fig. 16.

March 17, 1950: The weather chart shows a cyclone in the northwest, a cold front centred on Buenos Aires and heading out to sea where it joined up with an Atlantic cyclone 400 miles east of San Jorge.

The Pacific anticyclone is intense and is displaced in the higher latitudes; there is an anticyclone above Georgias and another east of Uruguay.

March 18, 1950: The chart shows that the anticyclone has entered the country, after meeting the front and associated cyclones over the Atlantic. A cyclone over the Argentine Sea has moved during the previous twenty-four hours approximately 300 miles towards NNE., decreasing slightly in strength, but approaching the SE coast of Buenos Aires Province, giving rise to very strong winds in the south and southwest sectors.

March 19, 1950: The anticyclone over the mainland increases in intensity. The Argentine Sea cyclone moves very slowly in a north-easterly direction, blocked by the anticyclone located farther east, moving approximately 250 miles during 24 hours and meeting its centre 300 miles ESE of Mar del Plata.

The extraordinary action of this atmospheric distribution over the sea was due to the slowing down of the cyclone blocked and worn down by the anticyclones to the West, North and East.

The associated winds moreover gave rise to surface currents headed in a northerly direction, and to a mass flow of water to the Northwest.

This mass flow meant a piling-up of water off the coast between Cabo Blanco and Río de la Plata, which produced the extraordinary rise in the mean sea-level as recorded on these days.

Action of atmospheric pressure over the sea.

It is known that a pressure system considered from the dynamic aspect, travelling at a given speed, will act on the level of the sea as a tractive force, and generate an oscillation whose period and elevation will largely depend on the dimensions of the zone of disturbance, as well as on its depths and shape.

It has been ascertained that the elevation at a certain place of the sea-level due to a pressure system is defined by the following expression:

$$y = \frac{13\,(760 - p)}{1 - \dfrac{C^2}{gh}} \tag{6}$$

in which:

y = elevation of the sea-surface in mm.
C = velocity of the atmospheric disturbance in m/s.
p = atmospheric pressure in mm.
h = mean depth of water in m.

The formula expresses the fact that when the velocity C of the atmospheric disturbance approaches gh, which is the velocity of propagation of a free oscillation, a phenomenon of « resonance » may occur, and the elevation in sea-level may largely exceed the value corresponding to the static effect determined by the « equilibrium ratio » 13 : 1.

The following tables show the change in level that would be caused by the dynamic action of displacements of low-pressure centres over the Argentine Sea.

Elevations in mm. for C = 20 miles per hour.

Depth in metres	Velocity of wave in miles per hour	Shift from mean pressure of 760 mm. 10	20	30	40
		Dynamic effect in mm.			
15	24	465	930	1394	1859
25	30	229	458	687	916
50	43	166	332	498	663
100	61	146	291	437	583
200	86	137	275	412	550
Static effect for equivalent shift		130	260	390	520

Elevations in mm. for C = 30 miles per hour.

Depth in metres	Velocity of waves in miles per hour	Shift from mean pressure of 760 mm. 10	20	30	40
		Dynamic effect in mm.			
25	30	4607	9213	13820	18427
50	43	253	506	759	1011
100	61	172	343	515	687
200	86	148	296	444	592
Static effect for equivalent shift		130	260	390	520

The underlined values correspond to extreme theoretical conditions for which the formula loses its actual significance.

The tractive force of the wind associated with the pressure centres is partially governed by the relationship between the viscosity of the air and the water determining friction between the two fluids. This force was determined by Rossby, in accordance with the dynamics of fluids, by the following expression:

$$T_0 = 2.26 \times 10^{3} \rho \ V^2 \tag{7}$$

where:

ρa = density of the air (1.25×10^{3})

V = velocity of wind (m/s)

The effects of the wind's tractive force over the sea vary principally with depth, and the extent and shape of the mass of water exposed to its action.

From (6) and (7) are derived the extraordinary effect of the dynamic action of displacements of the pressure centres and the winds associated therewith, which is maximum if they occur over shallow maritime areas. As the depth increases, there is a significant decrease in dynamic action, until it practically reaches the static values.

The influence of meteorological factors in the Argentine Sea is considerable, principally on the Buenos Aires Province coast. It decreases towards the South, with the result that the coastal region between the Valdes peninsula and Cabo Blanco is least affected. The amount of this influence on mean sea-level is subject to the random or systematic nature of the atmospheric disturbances, even though these be of slight intensity.

In the following section, an attempt will be made to establish the limits of this influence on the mean level of the Argentine Sea by analysing a series of observations recorded at Madryn Station extending over a mean Metonic cycle or 117 synodical months, in which no hourly heights are lacking and which have been obtained to within 0.5 cm.

COMPUTATION OF MEAN SEA LEVEL

For the sake of convenience, computation of mean sea-level is begun by taking the arithmetical mean of the hourly heights corresponding to the basic cycle or « mean solar day ».

The series of mean values thus obtained bring out, by means of the differences between them, the effects of factors unrelated to the tide, and emphasize the necessity of considering an extensive series of observations until other cycles of major tidal significance are covered.

The lunar synodical month (29.53 mean solar days) in thus first arrived at as the most appropriate expression of the series required for determination of the desired level, inasmuch as the mean of the hourly heights of the tide will eliminate the effects of the diurnal and semi-diurnal constituent waves, as well as the effects of the fortnightly constituents Mf and Msf, the monthly lunar constituent and a major part of meteorological action of a random nature Consideration of a series of such new approximate values for mean sea-level spread over one or more years of observation will likewise involve a relative disparity, even though their determination will have automatically eliminated much of the disturbing effects of a periodic and random nature.

A simple analysis of these will show the irregularity of their distribution with respect to their mean value, as well as the various degrees of dispersal over the entire series considered.

Seasonal influences, characterized by the solar waves Sa and Ssa, which are respectively annual and semi-annual, will likewise appear in this series.

By continuing computations over a complete period of revolution of the lunar perigee (8.85 years = 109 synodical lunations), a very good determination will be obtained of mean sea-level, which will show a slight discrepancy as compared with a similar consecutive period.

But by completing the cycle of revolution of the moon's ascending node, which covers 18.6 years (230 synodical months), or preferably the Metonic cycle of 19.0 years (235 lunations), a « first-order » determination of mean sea-level will be obtained. It will then be possible to ascertain with adequate accuracy that (within the limits of present tidal techniques) the determined value meets the concept of a « no-tide surface », although not with absolute preciseness.

Computation of mean sea-level will therepon be developed by a series of observations recorded at Madryn Tidal Station, extending over a mean Metonic cycle or 117 continuous lunations. For the sake of brevity, the mean monthly lunar (synodical) values are given directly, referred to tide-gauge datum.

Estación Mareográfica Madryn

4 Agosto 1944 - 18 Enero 1954

Valores medios - 117 lunaciones
en mm.

Mes lunar	Valor medio	Mes lunar	Valor medio	Mes lunar	Valor medio	Mes lunar	Valor medio	Mes lunar	Valor medio	Mes lunar	Valor medio
1	3539	21	3601	41	3545	61	3550	80	3620	99	3555
2	3484	22	3477	42	3642	62	3563	81	3622	100	3484
3	3523	23	3530	43	3622	63	3536	82	3675	101	3481
4	3513	24	3512	44	3704	64	3462	83	3531	102	3486
5	3599	25	3572	45	3532	65	3487	84	3605	103	3545
6	3624	26	3473	46	3587	66	3559	85	3622	104	3571
7	3633	27	3539	47	3570	67	3600	86	3572	105	3637
8	3668	28	3533	48	3598	68	3638	87	3472	106	3598
9	3602	29	3546	49	3526	69	3615	88	3517	107	3629
10	3562	30	3604	50	3531	70	3669	89	3425	108	3550
11	3811	31	3626	51	3416	71	3667	90	3532	109	3602
12	3563	32	3625	52	3468	72	3569	91	3507	110	3537
13	3493	33	3625	53	3549	73	3571	92	3544	111	3479
14	3453	34	3580	54	3559	74	3620	93	3645	112	3484
15	3520	35	3552	55	3648	75	3530	94	3606	113	3523
16	3558	36	3564	56	3690	76	3415	95	3554	114	3519
17	3564	37	3549	57	3623	77	3509	96	3536	115	3590
18	3585	38	3499	58	3607	78	3533	97	3591	116	3592
19	3693	39	3472	59	3637	79	3651	98	3556	117	3618
20	3583	40	3512	60	3577						

A parallel determination was also made of the mean values corresponding to the calendar months covering the same observation period, in order to establish differences as between both computation methods. The differences obtained are small as regards Madryn Station, but it appears advisable to adopt cycles of astronomical significance. Similarly, the final mean value showed a slight discrepancy.

Figure 17 is a graph showing the mean values obtained by each method, in which the influence of factors unrelated to the tide may moreover be evaluated.

Computations will be effected with the values given, i.e. with those corresponding to lunar months.

It is of interest to establish the manner in which such values are distributed according to a frequency diagram (Fig. 18).

In order to plot the diagram, the values in the series involved should first be arranged in a certain statistical order, and then classified according to an interval governed by the following considerations:

(a) For an equivalent number of observations the diagram tends to become regular as the classification interval increases, but its distribution varies with respect to the arithmetical mean.

(b) The diagram tends to become regular more rapidly when the interval is increased than when the number of observations is increased.

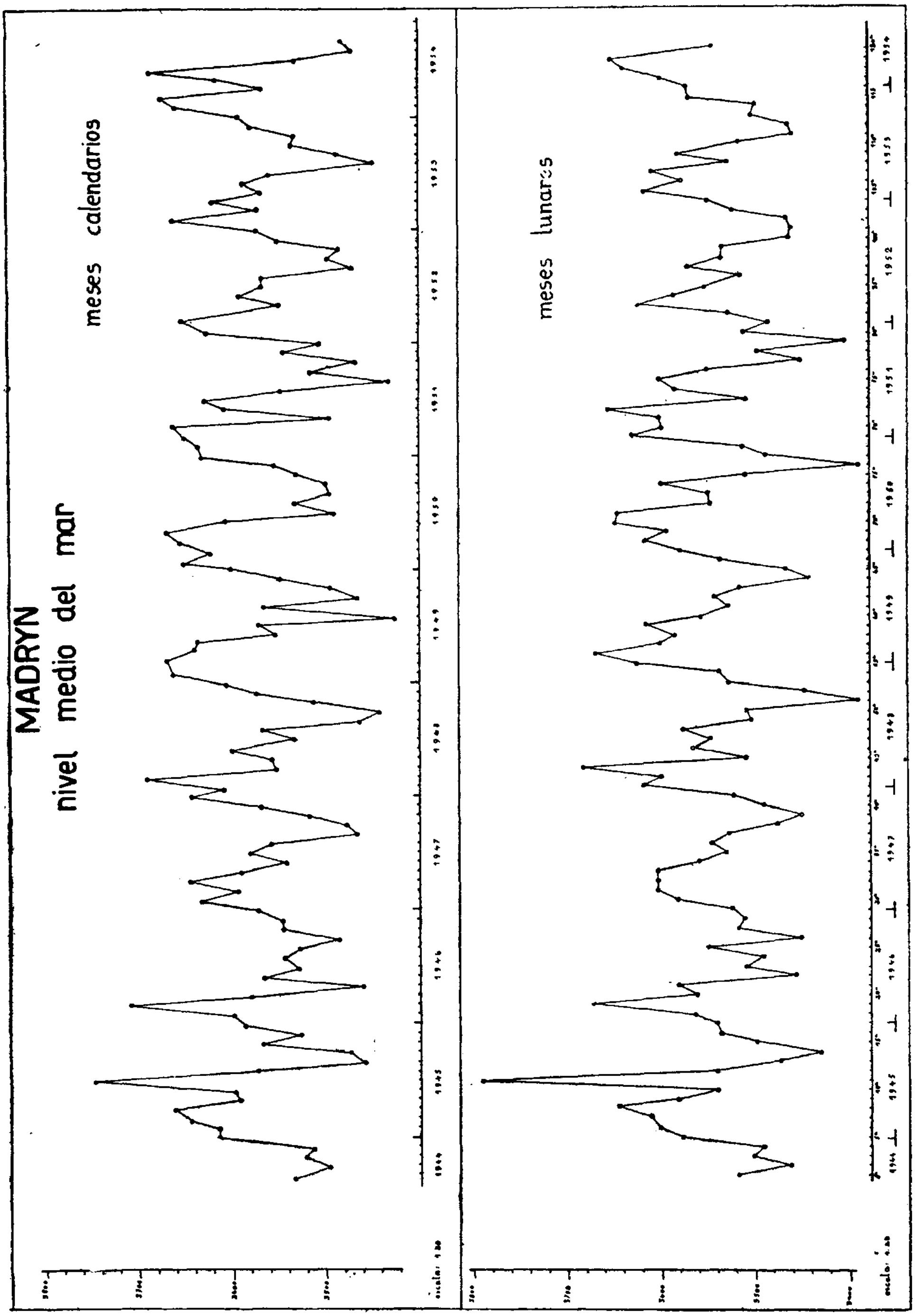

MADRYN
nivel medio del mar
meses calendarios
meses lunares

Fig. 17.

(c) As the classification interval decreases and the number of observations is indefinitely increased, the diagram tends follow the normal frequency curve.

Computation of arithmetical mean (M_x) of the mean square deviation (σ) mm.

a : 50 mm.	x	y	δ	δ ²	δ y	δy²	xy
3400-3449	3425	3	— 4	16	— 12	48	10.275
3450-3499	3475	16	— 3	9	— 48	144	55.600
3500-3549	3525	30	— 2	4	— 60	120	105.750
3550-3599	3575	31	— 1	1	— 31	31	110.825
3600-3649	3625	28	0	0	0	0	101.500
3650-3699	3675	7	1	1	7	7	25.725
3700-3749	3725	1	2	4	2	4	3.725
3750-3799	3775	0	3	9	0	0	0
3800-3849	3825	1	4	16	4	16	3.825
		117			— 130	370	417.225

$$M_x = \frac{\Sigma\, x\, y}{\Sigma\, y} = 3666 \text{ mm.} \quad \sigma = a\sqrt{\frac{\Sigma\, d^2\, y}{\Sigma\, y} - \left(\frac{\Sigma\, d\, y}{\Sigma\, y}\right)^2} = \delta \pm 67 \text{ mm.}$$

Taking the frequencies (y_0) as ordinates, a diagram of observed mean frequencies can be constructed which will either follow or not follow the law of the normal probability curve (Fig. 18).

DIAGRAM OF MEAN FREQUENCIES OBSERVED

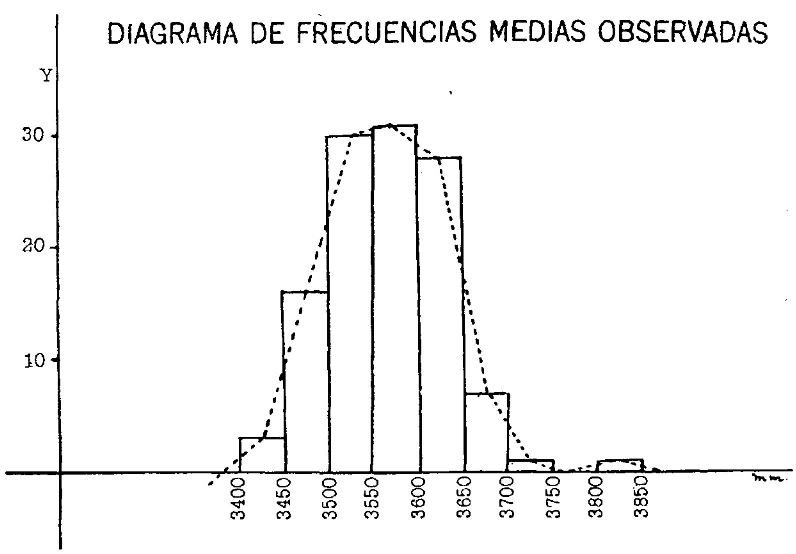


Fig. 18.

The distribution of values with respect to their mean value fixes the degrees of dispersion of the analyzed series and determines the significance of the arithmetical mean, which in this case represents mean sea-level.

The value of the mean square deviation, as a frequency curve which obeys the law of simple probability, will determine on each side of the mean ordinate the points of inflection, which upon indicating a change in the frequency pattern, will establish the normal upper and lower limits of the arithmetical mean in the represented series.

In this case, the mean square deviation is of considerable value ($\sigma = \pm 67$ mm.), considering the extent of the series examined and the quality of the observations used in the computations.

Before analysing the possible causes of the observed degrees of dispersion, it will be appropriate to establish beforehand whether the distribution of the observed frequencies follows the normal curve law.

For the adaptation of a simple probability curve to the diagram of observed mean frequencies, the deviations should first be expressed in fractions of σ, and then the ordinates calculated by mean of a table of areas of the normal curve in terms of its abscissae.

NORMAL FREQUENCY CURVE ADAPTED TO DIAGRAM OF OBSERVED FREQUENCIES

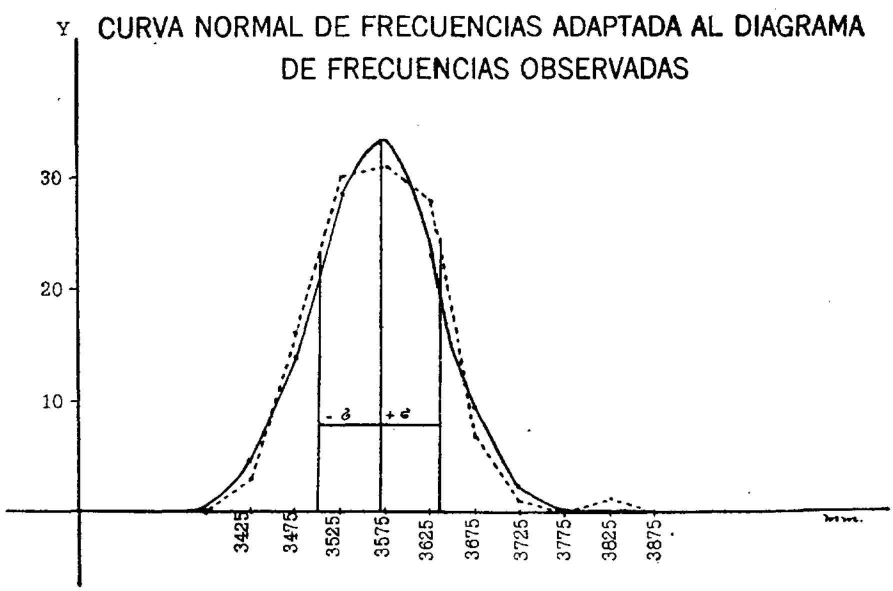


Fig. 19.

Computation of frequencies of normal curve adapted to distribution of observed frequencies

(1)

Mean levels. Classific. intervals	x mm.	x'	$x_1 = \frac{x' - M_x}{\sigma}$	(v) $\delta = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x_1} e^{-\frac{1}{2}x^2} d_x$	$\frac{y'}{N}$	y'
					0.0066	0.77
		3400	— 2.48	0.0066		
3400-3449	3425				0.0352	4.12
		3450	— 1.73	0.0418		
3450-3499	3475				0.1193	13.96
		3500	— 0.99	0.1611		
3500-3549	3525				0.2441	28.56
		3550	— 0.24	0.4052		
3550-3599	3575				0.2898	33.91
		3600	0.51	0.6950		
3600-3649	3625				0.1994	23.33
		3650	1.25	0.8944		
3650-3699	3675				0.0829	9.70
		3700	2.00	0.9773		
3700-3749	3725				0.0197	2.30
		3750	2.75	0.9970		
3800-3849	3775				0.0028	0.33
		3800	3.49	0.9998		
3800-3825	3825				0.0002	0.02
		3850	4.24	1.0000	following	
					0.0000	0.00
					Σ	117

Analysis of quality of adaptation.

The major differences between the theoretical and observed frequencies are as follows:

Mean point mm.	Observed frequency y	Theoretical frequency y'	y — y'	σ
3625	28	23,33	4,67	4.32
3575	31	33,91	— 2,91	

(1) Tables of probability integrals. - Table A of « Laboratory Manual and Problems for Elements of Statistical Method », Albert E. Waugh. 2nd edition, 1944.

The mean square error of a frequency distribution is given by:

$$\sigma = \pm \frac{y' (N - y')}{N}$$

where:

y' = theoretical frequencies at a point
N = total number of frequencies

Calculating σ for the first case, we get:

$$\sigma = \pm 4.32$$

With respect to this value, the adaptation may be considered as correct.

The values in the middle group of the diagram thus determined represent the common or ordinary values and the rest the extraordinary values.

A greater frequency in higher values than in lower values is observed with respect to the middle group, which is logical in view of the greater action of maritime winds.

The mean sea-level value of this series of 117 synodical lunations (mean Metonic cycle) thus determined will be equivalent to:

3566 mm. ± 67 mm. above the Madryn tide-gauge datum.

Compulation with annual values.

Compulation will then be made by considering the annual values of mean level, determined by the arithmetical mean of the 365 days in each year, approximately the same period being covered.

Compulation or arithmetical mean of the mean square deviation.

Years	x mm.	$\delta = x - M_x$	δ^2
1945	3587	21	441
1946	3557	— 9	81
1947	3569	3	9
1948	3559	— 7	49
1949	3569	3	9
1950	3585	19	361
1951	3556	— 10	100
1952	3559	— 7	49
1953	3561	— 5	25
1954	3554	— 12	144
Σ	35656		1268

$$M_x = \frac{\Sigma x}{n} = 3566 \text{ mm.} \qquad \sigma = \sqrt{\frac{\Sigma \delta^2}{n}} = 11.26 \text{ mm.}$$

Mean sea-level at Madryn for the period 1945-1954 will therefore be given by:

3566 mm ± 11.3 mm above the Madryn tide-gauge datum.

INFLUENCES OF OSCILLATIONS OF THE SEA NOT CAUSED BY THE TIDE

From the statistical analysis of the series considered (lunar months) there arises a dispersion of values, with respect to the mean, of great significance.

Although such values, resulting from a minor cycle (lunar month) only represent an approximate determination of mean level, their divergence with respect to the mean is in excess of the remainder of astronomical origin, which has not been totally eliminated owing to the short extent of the period (29 days).

It may easily be surmised, and such is corroborated by calculation, that the dispersions are the result of factors unrelated to the tide. Meteorological factors appear to primarily responsible, owing to their strength and frequency of occurrence, and instances thereof have already been given.

When considering daily values of mean level, wide discrepancies are observed, mainly due to weather action.

Mean monthly values are more regular, (Fig. 17), although it may be seen how a storm wave can change such values (March 1950).

The important fact is, however, to establish whether such factors are random or systematic, since in the first case they will cancel out if a long series of observations is considered, and in the second case they will largely be reduced whatever the series considered, and the resulting surface will be different from the one sought.

If the frequency diagram is asymmetric with reference to its mean ordinate, the existence of a systematic influence may be inferred which affects the mean level.

The mean square dispersion gives an indication enabling the quality of the values forming the analysed series to be evaluated.

In the case of Madryn, the result is a dispersion of $\pm$ 67 mm. for the « lunar month » series, and of $\pm$ 11 mm. for the « annual values » series, over an identical time period. From this may be deduced the existence of a considerable disturbance of seasonal character.

Nevertheless, the final value of the mean level obtained by both methods remains constant, as it was hoped.

The « annual values » series also shows various changes indicating the existence of factors unrelated to the tide and of a systematic nature in view of the uneven distribution over the period analysed.

The diagram of annual mean level variations (Fig. 20) brings out two major changes, corresponding to the years 1945 and 1950 and having a systematic character, since they are in the same direction. Distribution over the other years is fairly regular and of a random nature, since it occurs alternately above and below the mean value.

If both these values, i.e. those relating to 1945 and 1950, are left aside for a moment, the resultant mean value will be 3560 mm., with a mean square distribution of $\pm$ 5.3 mm.

The action of atmospheric pressure on the mean level at Madryn may be observed from the diagrams in Figure 21, representing the annual variation of the

ESTACION MADRYN

DIAGRAMA DE LA VARIACION ANUAL DEL NIVEL MEDIO DEL MAR

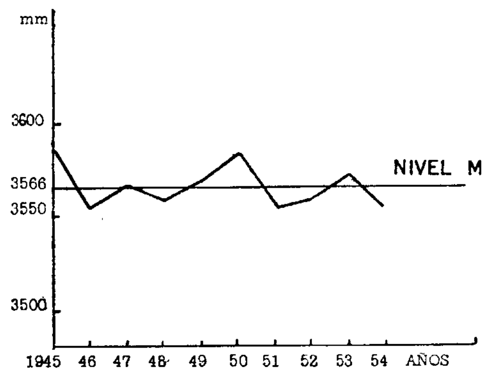


FIGURA 20

DIAGRAMA DE LA VARIACION DEL NIVEL MEDIO Y DE LA PRESION AFMOSFERICA

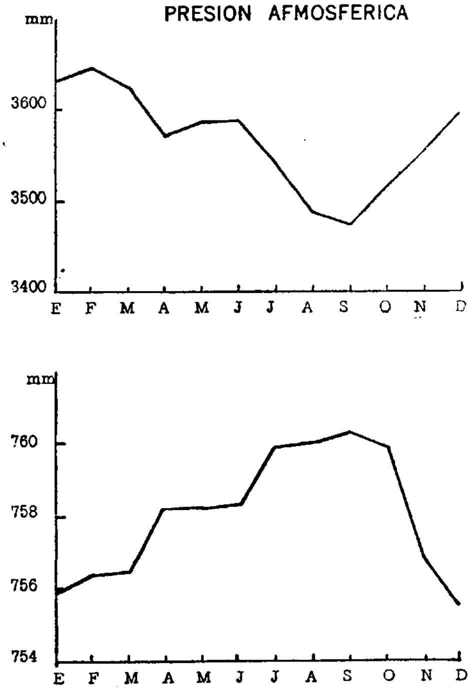


FIGURA 21

mean level during the period 1945-1953 in relation to variations in the annual atmospheric pressure (monthly means).

This means that the phenomenon of disturbances unrelated to the tide should be clearly established in order that true significance may be evaluated with scientific accuracy, and their effects eliminated from determinations of the mean sea-level.

It will be seen that the variations in the mean monthly values of mean sea-level correspond to variations in the opposite direction of the mean monthly values of atmospheric pressure, as the larger the pressure the smaller the height, and vice versa.

The wind frequency in the zone is given in the diagram of Figure 22, and its action on mean level in that of Figure 23.

From these it may be deduced that the winds of the west-southwest sector, which occur with the greatest frequency, have a minimum effect on mean level, whereas the winds of the northern and southern sectors, which are those of prevailing influence over the sea, are less frequent, and thus lead to the assumption of systematic action.

The very-long-period variations of mean sea-level also follow seasonal changes in water temperature, combined with variations in density and salinity, which suggests a possible variation in the volume of water rather than a change in overall quantity.

It has been observed, however, that in the Argentine Sea the lowest mean level values occur in spring (September), while the highest occur in the fall (March), such dispersion attaining with respect to the normal level a mean value of 10 cm.

From the information presently available, it is not possible to determine whether this phenomenon is related to a shifting of water masses, as it has not been established whether the currents generated by the changing physical state of the water occur from the surface to the bottom.

The necessity therefore arises for a study of meteorological action in the entire zone of influence, whether over the sea or land, with reference to the tide-station network.

The tide-station system will record all disturbances produced by the forces unrelated to the tide, which will facilitate delimitation of the zone affected. This will enable its actual range to be established, by intercomparison of the marigrams and comparison with the corresponding computed astronomical tide. The records subjected to disturbances can thus be brought out, and can then be correlated with the atmospheric disturbances producing them.

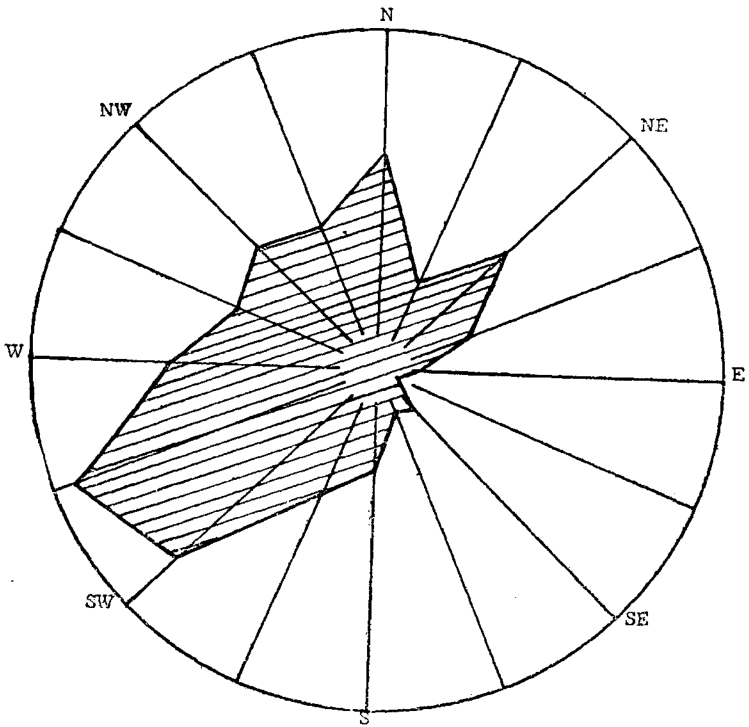
From a systematic study of the records obtained from a vast, continuously-operating tide-station system, the stations which appear to be the least disturbed will emerge as being located in areas where the influences unrelated to the tide are minimum and can be compensated over a long series of observations.

Once the tide-station subjected to least disturbance is ascertained, its records can be considered as best suited for determining the mean sea-level.

The records used in this work are those obtained at Madryn Station, which show a certain amount of disturbances unrelated to the tide occurring in irregular

ESTACIÓN MADRYN 1945

FRECUENCIA DE VIENTOS POR DIRECCION

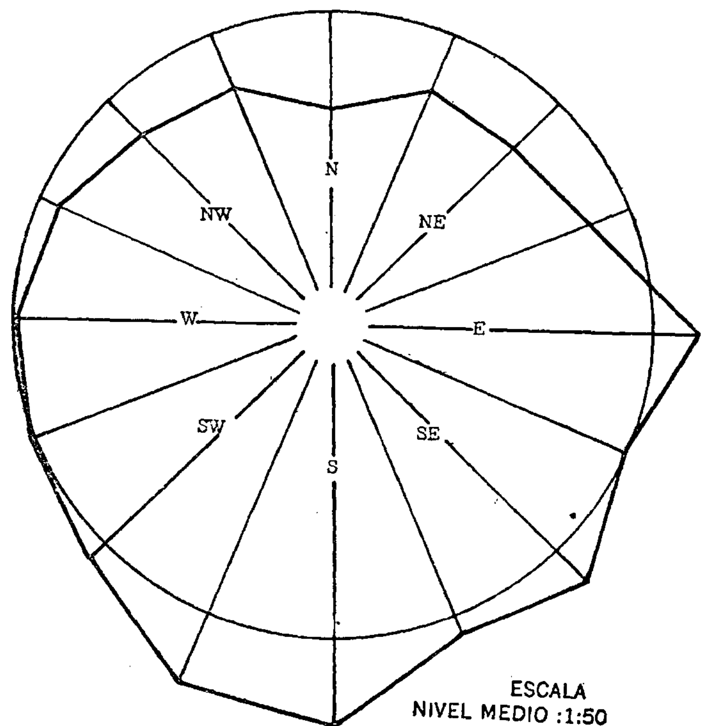


FRECUENCIA EN %

FIGURA 22

Wind directional frequency.

VARIACION DEL NIVEL MEDIO POR LA ACCION DEL VIENTO



ESCALA
NIVEL MEDIO :1:50
3566 mm
DIFERENCIAS: 1:10

FIGURA 23

Mean level variation under action of wind.

form, and which supply a mean sea-level value, at the end of a Metonic half-cycle, subject to an uncertainty of $\pm$ 11 mm.

This value of the mean oscillation, within whose limits the ideal surface sought may be assumed to lie, suggests the necessity of clarifying the records used for its determination by ascertaining the effect of factors not related to the tide.

The study and evaluation of such influences are extremely thorough, as it is believed that they should be carried out separately and simultaneously with direct computation, i.e. that the mean values of the factors unrelated to the tide should be established throughout the analysed series and mathematically applied to the result of the integration of the tide-curve.

This can be done either by mechanical means, in which the short-and very-long-period oscillations are recorded separately from the tide or by computational procedures, by correlating the diagrams with the dynamic aspect of the atmosphere.

The Tidal Division of the Argentine Hydrographic Office is at present carrying out such investigations of records obtained from its tidal network, and hopes to complete a Metonic cycle of continuous observations enabling the determination with scientific accuracy of the mean sea-level, thus supplying the country with a reference plane for heights.

ACKNOWLEDGEMENTS. I wish to express my appreciation to Professor Yolanda Mazzantini de Garcia and to Professor Alicia Lohner, both tidal experts detached to the Hydrographic Office, for their efficient collaboration in carrying out this work.

All the documents used in the work are the property of the Departments of Oceanography and Maritime Meteorology of the Hydrographic Office.

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