SEASONAL VARIATIONS IN MEAN LEVEL OF ARGENTINE SEA

by Marciano A. BALAY, Technical Adviser,
Argentine Navy Hydrographic Office

The present article is solely intended as a contribution to knowledge of the seasonal variations in the mean level of the Argentine Sea and of related factors.

Owing to its physical and economic significance, this is a subject of world-wide interest and it has been included in the scientific research programme of the International Geophysical Year.

INTRODUCTION

Among the various oscillatory rhythms of mean sea level, seasonal variations are remarkable for their size and physical and economic consequences. They are generated by the sun as it apparently moves along the ecliptic during 365.24 mean solar days.

Their effect on mean sea level occurs in the form of very long-period tide waves, such as semi-annual and annual waves, the sun-spot cycle waves and their higher and lower harmonics, etc.

Variations in water temperature, coinciding with annual seasonal changes, likewise give rise to changes in mean sea level presumably due to changes in the volume of the mass of water and the consequent displacement of oceanic masses.

It is moreover known that any atmospheric disturbance or change results in surface oscillations of largely different periods, varying from a few seconds or minutes (waves, tsunamis, or seiches), to two or three days or even several years (storm surges, sun-spot cycle waves and harmonics thereof, etc.).

It is also known that an increase in air temperature is normally accompanied by a decrease in atmospheric pressure and greater precipitation; these factors will consequently increase mean sea level.

Similarly, a decrease in air temperature is usually accompanied by an increase in atmospheric pressure and lower precipitation, which lowers the mean sea level.

It has furthermore been discovered that the particular oscillatory rhythms determined by variations in weather factors, and especially the sun-spot cycle, have a definite influence on mean level.

Thus, if tidal observations are to be used to determine « normal mean sea level » for geodetic purposes, the series of observations should be extended to include a minimum eleven-year cycle, in order to eliminate oscillations produced by water disturbances when integrating the tide-curve for the period (1).

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(1) M. A. BALAY : Determination of mean level of Argentine Sea. See *International Hydrographic Review*, Vol. XXXIII, No. 2, November 1956. Special Publication of Argentine Navy Hydrographic Office (1955). *Revista Cartografica* (PAIGH) No. 5 (1957).

As stated above, it is assumed that a part of the observed seasonal variations can be attributed to a change in the volume of the column of water, which is subject to heating during the summer months.

This process, described as a « volumetric change in sea level », appears to account tor only a minute portion of variation, as we shall sea later on.

Similarly, seasonal variations in water density (specific gravity) are reflected in the distribution of the dynamic topography of the sea surface, which changes in slope and circulation, thus giving rise to an inflow or outflow of large ocean masses across the equator.

According to observations carried out in either hemisphere, the existence was discovered in the southern hemisphere of an increase in mean level during summer which coincided with a decrease in the northern hemisphere during the same period, and vice versa during winter (fig. 1).

In the Argentine Sea, a mean seasonal difference was determined between 1945 and 1955 ranging from 8 cm in summer (February) to — 11 cm in winter (September) with reference to « normal mean sea level ».

In the following discussion, an attempt will be made to show that a component part of this difference corresponds to each of the disturbance factors described above, i.e. tidal, oceanographical, and meteorological factors.

Tidal factors

The tide waves produced by lunisolar attraction in the large ocean basins surrounding the Argentine Sea are propagated towards the continent in the shape of deflected waves subjected to a series of transformations due to the gradual rise of the sea bottom and to meteorological disturbances. These, combined with the effect of the earth's rotation on the moving masses of water, cause the amplitudes of the oscillations to increase to such an extent that upon arrival on the coast considerable values are attained.

Tides in the Argentine Sea accordingly assume widely different forms and amplitudes, depending on whether the tide waves are progressive, stationary, amphidromic, associated with tidal currents having corresponding characteristics, i.e. of an alternating or rotary type.

These various types and amplitudes are affected by the topographic pattern of the area (extent of continental shelf, depth, nature of bottom, etc.), and range from the mixed type (2 feet opposite Mar del Plata) to the semi-diurnal type (40 feet off the section of the Patagonian coast adjacent to Puerto Gallegos).

All oscillations in sea level are faithfully recorded by the system of tide stations installed for this purpose and continuously operated by the Hydrographic Office.

For the sake of brevity, discussion will here be limited to records obtained at the following stations:

Buenos Aires
Mar del Plata
Quequén
Belgrano
Madryn
Comodoro Rivadavia

Extensive series of observations are available for these stations.

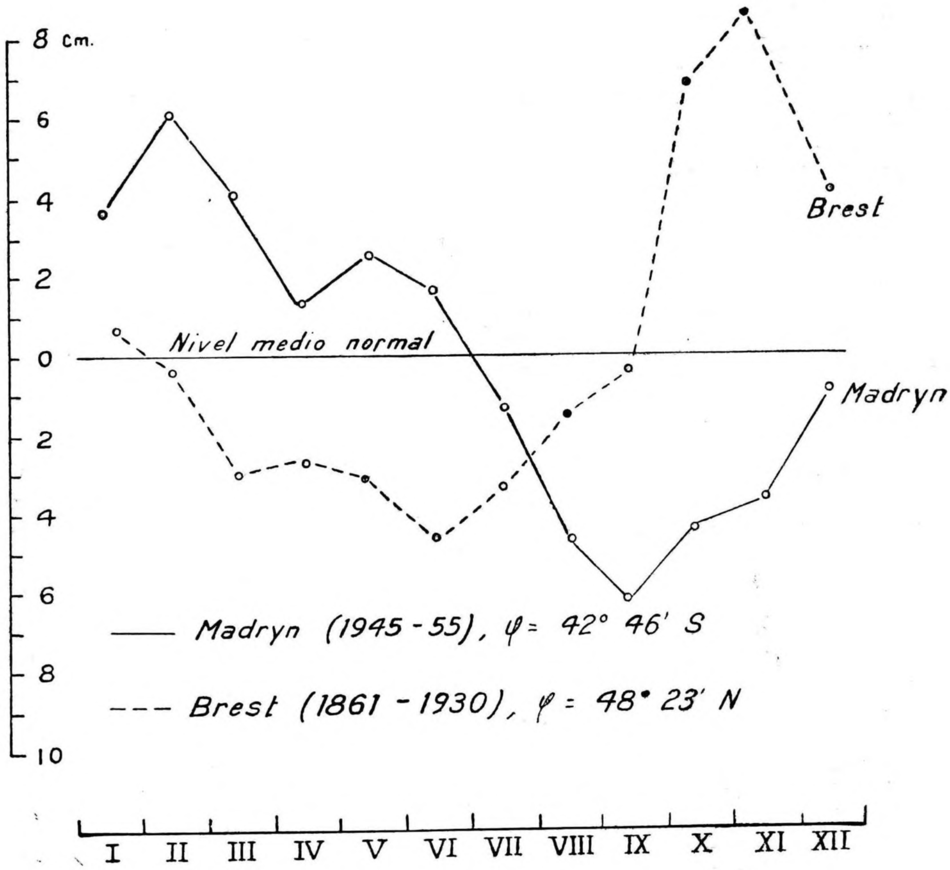

Fig. 1.
Mean curves of seasonal M.S.L. variation in Argentine Sea (Madryn) and at Brest (France).

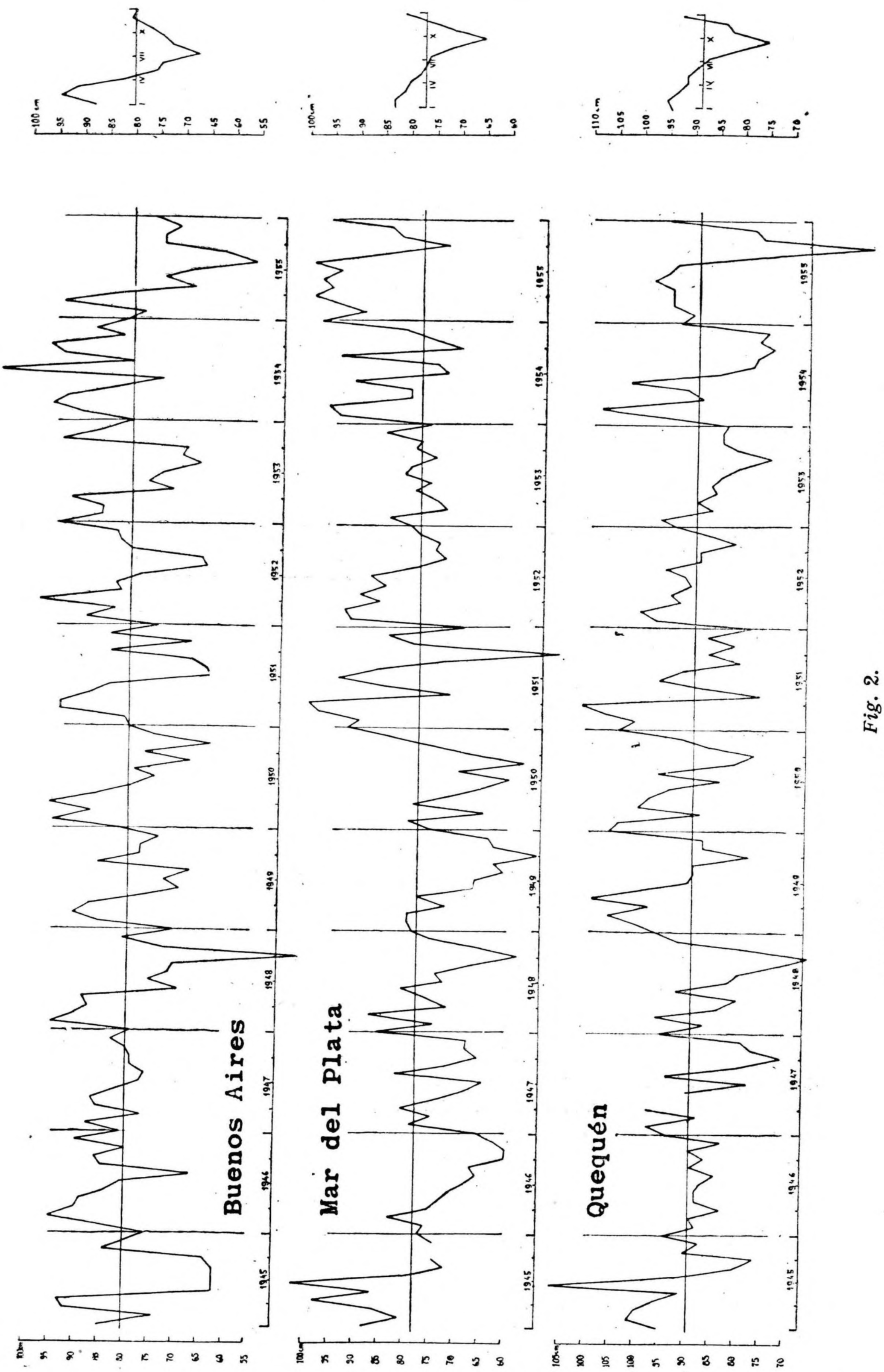

Fig. 2.
Monthly M.S.L. variations in Argentine Sea (1945-1955).

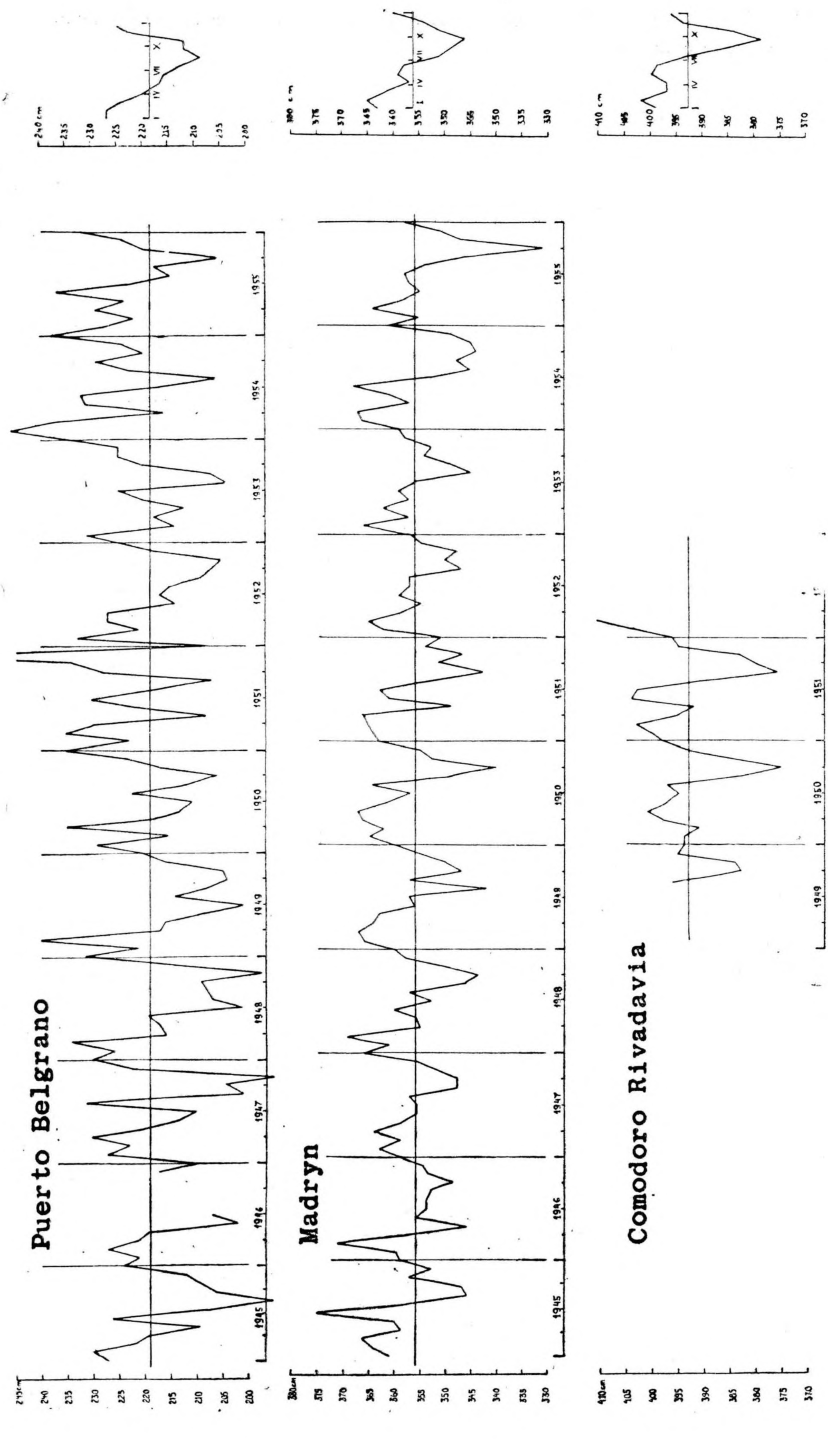

Fig. 2 bis.

In order to complete the foregoing observations and as a check, the following stations were also considered:

Palermo
San Clemente
Rosales
Delgada
San Antonio
Deseado
Ushuaia
Antarctic Group.

Statistics examined included an observation cycle extending over 11 years and recorded at each station to within an accuracy of 5 mm for each hourly height. The values of mean monthly levels were determined for the period 1945-1955 by taking the mean of hourly heights (see tables attached).

With the values of the monthly mean levels referred to tide-gauge datum, diagrams were plotted showing the monthly variation at each place, and the corresponding mean annual curve for the period 1945-1955 (fig. 2).

A simple analysis of these diagrams suffices to show the sequence of the tidal phenomenon and the systematic and regular occurrence of periods of minimum and maximum variation of mean sea level according to season.

The extreme values (maximum and minimum) respectively correspond to the summer and winther months, and the others fluctuate around the « normal mean level » for the period.

The average annual curves of the period for each place show significant similarities, since their variations are not only parallel in time, but of approximately equivalent amplitude (19 cm).

This pattern was found to exist over the whole coast, including Rio de la Plata. It may thus be asserted that the mean level of the Argentine Sea and of Rio de la Plata is subject to a mean annual oscillation of approximately constant phase and amplitude throughout, which is evidenced by a tide wave reaching absolute maximum in February and minimum in September.

The average annual variation diagram (fig. 3) for the Argentine Sea, obtained with the diagrams corresponding to the stations mentioned above, shows perfect regularity and minimum discrepancies with the component diagrams. This at least suggests that the preponderant disturbance factor is simultaneously active over the whole Argentine Sea with the same periodicity and intensity.

The necessity now arises of distinguishing the action of each factor involved and of attempting to evaluate its influence.

After correcting the values of the mean curve of annual variation for the Argentine Sea for the effect of atmospheric pressure (mean monthly values), and after subjecting them to harmonic analysis, we shall determine the phases and amplitudes of the constituent waves Sa (solar annual) and Ssa (solar semi-annual). The former results from the annual variation in the sun's distance (from the summer solstice to the winter solstice, parallax); the latter results from declinational variation (from the vernal equinox to the autumnal equinox).

Figure 4 shows these constituent waves and their theorical resultant.

ARGENTINE MEAN SEA LEVEL
PORT OF BUENOS AIRES
Values in cm

Months .... Years	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Means in mm
1944	99	89	99	80	70	71	58	62	64	77	72	85	772
1945	85	74	92	93	62	62	62	62	64	84	80	76	747
1946	85	95	90	89	84	81	67	85	86	80	90	81	844
1947	88	77	86	87	82	77	76	79	79	80	83	79	811
1948	95	91	88	89	70	76	72	71	46	73	81	71	769
1949	86	91	88	78	70	73	68	86	78	78	74	82	793
1950	95	88	96	87	80	75	79	68	77	64	75	80	803
1951	81	94	94	88	84	64	65	68	84	68	84	75	791
1952	89	80	98	82	83	78	65	66	80	82	83	94	817
1953	86	86	92	72	77	74	67	70	69	94	86	80	794
1954	90	96	93	83	74	106	80	94	93	82	88	81	883
1955	78	94	84	68	74	68	56	62	74	74	71	76	733
Means in mm	881	879	917	830	758	754	679	728	745	780	806	800	796

ARGENTINE MEAN SEA LEVEL
PORT OF MAR DEL PLATA
Values in cm

Months .... Years	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Means in mm
1944	—	—	—	—	—	—	—	—	70	78	76	84	770
1945	88	81	86	98	87	102	80	72	74	—	75	77	836
1946	76	83	75	73	71	68	66	68	60	60	62	66	690
1947	79	75	81	74	68	65	82	73	66	68	68	86	738
1948	75	87	72	76	81	73	74	67	57	65	75	79	734
1949	80	80	72	78	67	65	61	63	54	63	64	76	686
1950	80	65	79	72	65	60	70	57	68	75	84	92	723
1951	90	98	100	72	85	94	86	73	50	79	87	69	819
1952	92	93	86	90	85	88	79	73	75	74	78	80	828
1953	84	73	75	79	76	81	78	75	79	78	85	76	783
1954	94	96	80	80	91	73	75	94	70	75	87	98	839
1955	89	94	99	96	98	94	99	85	73	82	84	96	908
Means in mm	843	841	823	807	795	785	773	727	663	725	766	816	779

ARGENTINE MEAN SEA LEVEL
PUERTO QUEQUEN
Values in cm

Months .... Years	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Means in mm
1944	85	92	95	97	86	95	78	83	80	84	82	92	874
1945	95	101	100	96	91	117	92	80	76	90	87	94	933
1946	88	89	83	92	92	87	84	89	86	89	83	94	880
1947	98	88	98	—	90	78	94	80	71	77	79	95	862
1948	87	96	84	80	92	82	80	71	66	78	92	96	837
1949	100	106	98	109	99	90	89	89	78	87	87	106	948
1950	104	88	100	98	94	84	96	81	77	86	93	104	921
1951	101	107	111	76	87	96	91	80	86	81	86	78	900
1952	97	100	92	94	90	91	95	88	88	81	86	93	913
1953	96	86	89	85	86	84	80	74	81	84	84	83	843
1954	96	108	87	91	102	85	78	77	74	77	75	93	869
1955	90	94	94	94	98	94	93	74	54	76	78	94	861
Means in mm	948	963	943	920	923	903	875	805	764	825	843	935	887

ARGENTINE MEAN SEA LEVEL
PUERTO BELGRANO
Values in cm

Months .... Years	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Means in mm
1944	219	218	223	223	211	218	202	207	209	209	218	218	2146
1945	227	230	222	219	209	226	208	195	206	209	212	224	2156
1946	221	227	221	219	202	207	—	—	212	—	217	210	2151
1947	227	223	230	220	213	210	231	201	204	195	222	230	2172
1948	226	234	216	217	219	201	207	208	209	197	214	231	2149
1949	221	240	217	216	209	201	214	208	204	205	216	220	2143
1950	229	215	235	218	213	211	222	212	206	217	223	235	2197
1951	223	235	230	208	222	230	218	207	228	234	261	208	2253
1952	233	221	227	227	214	217	215	209	207	205	218	225	2182
1953	231	214	218	212	220	225	204	207	220	225	225	235	2197
1954	244	237	216	231	232	217	206	223	229	220	224	238	2264
1955	228	222	229	224	237	223	215	218	206	220	224	232	2232
Means in mm	2274	2263	2237	2195	2168	2155	2129	2086	2117	2124	2228	2255	2187

ARGENTINE MEAN SEA LEVEL
PUERTO MADRYN
Values in mm

Months .... Years	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Means in mm
1945	3614	3642	3659	3593	3602	3746	3575	3457	3473	3565	3527	3587	3587
1946	3597	3706	3581	3462	3563	3537	3543	3534	3485	3541	3545	3592	3557
1947	3629	3591	3641	3589	3555	3564	3565	3475	3476	3516	3564	3659	3569
1948	3608	3688	3551	3558	3602	3532	3566	3464	3442	3514	3575	3604	3559
1949	3661	3667	3638	3633	3555	3573	3417	3567	3467	3495	3550	3601	3569
1950	3654	3624	3655	3668	3607	3567	3637	3494	3397	3530	3554	3630	3585
1951	3635	3645	3660	3493	3606	3627	3547	3428	3514	3465	3543	3506	3556
1952	3624	3652	3594	3548	3590	3565	3566	3470	3496	3483	3551	3573	3559
1953	3661	3572	3617	3569	3586	3559	3448	3486	3536	3533	3578	3589	3561
1954	3658	3672	3566	3614	3683	3530	3444	3481	3443	3453	3491	3612	3554
1955	3551	3643	3580	3567	3566	3584	3535	3455	3312	3456	3503	3573	3527
Means in mm	3627	3646	3613	3572	3592	3580	3531	3483	3458	3505	3543	3593	3562

ARGENTINE MEAN SEA LEVEL
PUERTO COMODORO RIVADAVIA
Values in cm

Months .... / Years	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Means in mm
1949	—	—	—	—	—	—	—	396	383	384	395	394	3904
1950	394	391	398	401	397	395	397	383	375	385	393	398	3923
1951	400	403	395	392	404	403	391	376	380	383	395	396	3932
1952	404	411	—	—	—	—	—	—	—	—	—	—	4075
Means in mm	3993	4017	3965	3965	4005	3990	3940	3850	3793	3840	3943	3960	3933

ARGENTINE MEAN SEA LEVEL

Monthly Means for 1945-1955 period

Values in mm

Months	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Means (1945-55)
Mar del Plata	843	841	823	807	795	785	773	727	663	725	766	816	780
Pto. Quequén	948	963	943	920	923	903	875	805	764	825	843	935	887
Pto. Belgrano	2274	2263	2237	2195	2168	2155	2129	2086	2117	2124	2228	2255	2186
Pto. Madryn	3627	3646	3613	3572	3592	3580	3531	3483	3458	3505	3543	3593	3562
C. Rivadavia	3993	4017	3965	3965	4005	3990	3940	3850	3793	3840	3943	3960	3938

The relative importance and mutual relationship of the two constituents may be observed. The solar annual wave Sa has greater physical significance, its mean amplitude being H = 10.5 cm. The Ssa wave, whose amplitude is 4.0 cm, perturbs the former wave, so that the resultant wave takes the characterictic shape of ordinary tide waves, with strong diurnal inequality.

The amplitudes determined for Sa and Ssa are particularly large, since they are greater than the amplitudes for the other diurnal and semi-diurnal constituents off the coast of Buenos Aires Province and Rio de la Plata. Although basically astronomical, the Sa and Ssa waves are largely influenced by meteorological and oceanographic factors, which in these areas are dominant and of marked regularity.

The resultant curve (Sa + Ssa) closely resembles the curve obtained through observations, especially with regard to time, since its maxima and minima likewise occur in February and September respectively.

The residual curve (fig. 4) has the characteristics of a shallow-water wave. It is symmetrical with respect to normal mean level and has a periodicity of about four months.

We know that the tide waves originate in the large ocean basins, and that they are then propagated towards the mainland over the continental shelves into estuaries, gulfs and bays of relatively shallow depth. The structure then changes in such a way that the period of rise is shorter than that of fall, and results in the appearance of residual waves known as shallow water waves.

In the diagram showing the annual variation of mean level in the Argentine Sea (fig. 4), the residual wave obtained may tentatively be regarded as a shallow water wave owing to the presence of the continental shelf. The sea bottom is thus raised considerably above the Argentine Atlantic trench, and resistance is offered to the free propagation of very-long-period tide waves such as the Sa (solar annual) wave.

Here the (Sa + Ssa) wave may be assimilated for analysis purposes to the diurnal wave, so that the shallow water waves it could generate would be of varying period, i.e. semi-diurnal, third-diurnal or less.

The type met with here has a period of about 4 months, and may thus be regarded as a third-annual wave, designated as $(S\frac{1}{3}a)$.

Analysis of this curve results in a mean range of 1.6 cm, a relatively important value as compared with other factors affecting seasonal variations in mean sea level.

It should be added that this residual wave $(S\frac{1}{3}a)$ had not previously been determined for the Argentine Sea.

Separate discussion of the characteristics of sea level variations at individual points along the Argentine coast will enable their properties and possible connection with other geographical factors to be determined.

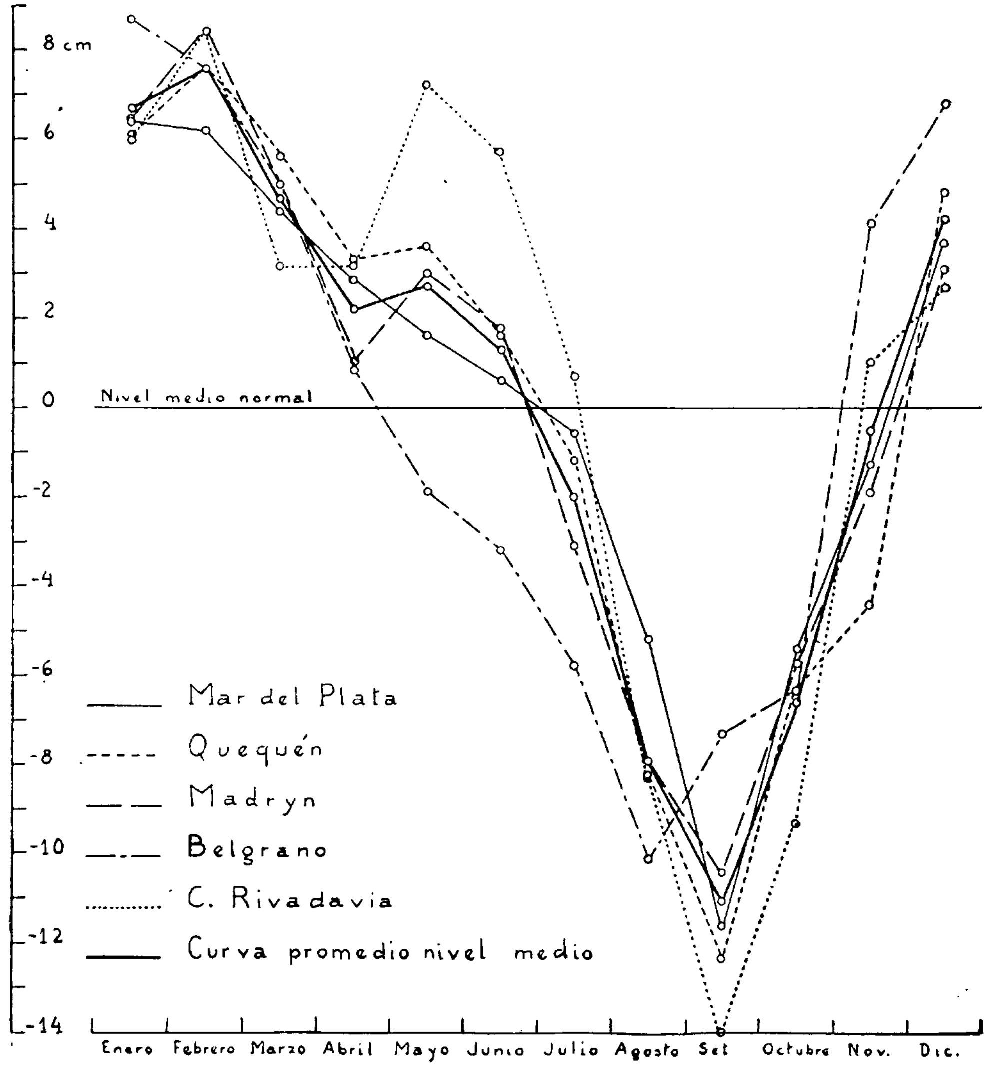

Fig. 3.
Mean curve of annual M.S.L. variation in Argentine Sea.

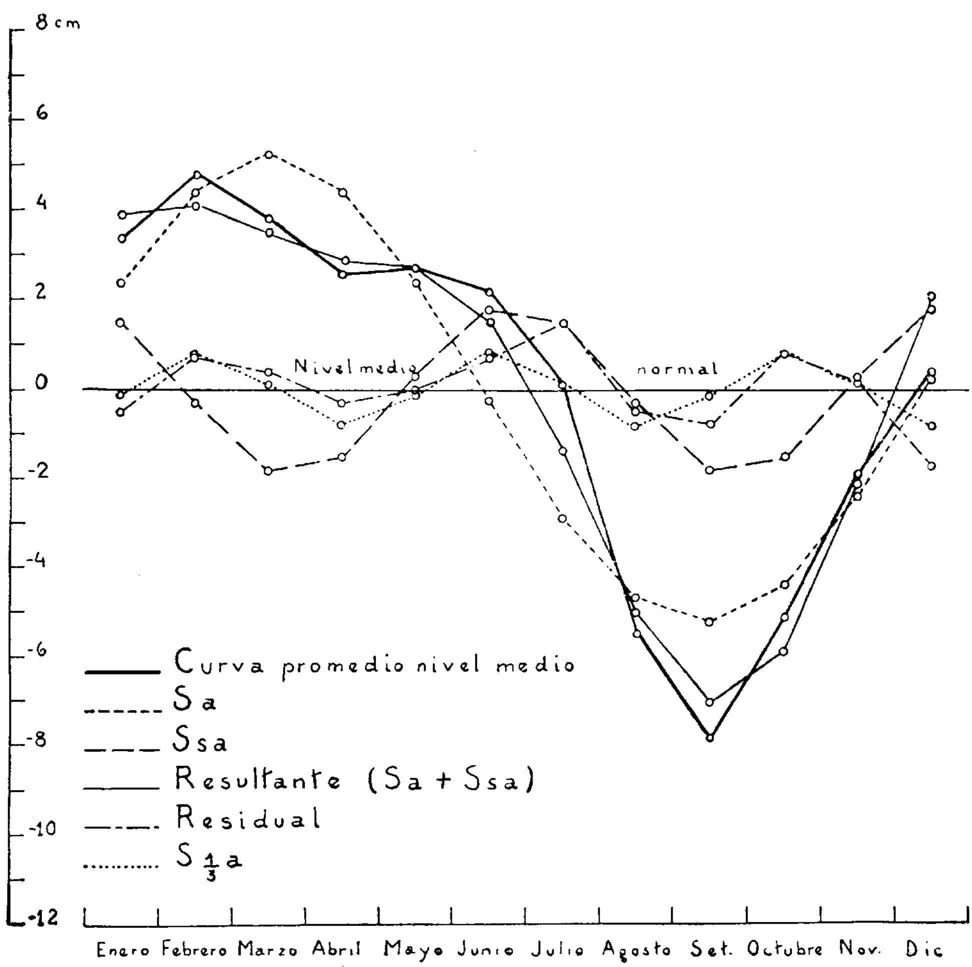

Fig. 4.
Mean curve of annual M.S.L. variation in Argentine Sea.

OCEANOGRAPHIC FACTORS

The oceans are known to be huge sources of the heat produced by solar radiation, not only because water covers the major part of the earth, but also because of all liquids and solids, with the exception of ammonia, water possesses the highest specific heat (i.e. the greatest capacity of heat absorption), which means that in order to increase its temperature by one degree, more heat is needed than for other substances.

If we compare temperature variations at sea with those on land, we shall see that the former are the smaller in range, both as regards daily and seasonal values.

The temperature of water in the oceans may vary betwen 2° and 3° C below the freezing point of fresh water, and up to 30° C above it, whereas air temperatures on land may range from 30° C below zero to more than 50° C above.

At a particular place, the temperature of the sea surface may vary by 10° C according to season; but no more than 1° C as between day and night. Daily maximum temperatures are recorded around 1400 hours, and minimums at about 0500 hours.

Latitude generally constitutes the dominant factor in variations of sea temperature, in conjunction with depth and the seasons.

No seasonal variations are recorded in deep water (more than 200 m), where the temperature is virtually constant (- 3° C to - 1.5° C). Differences with respect to the surface along a particular vertical may thus be as large as those existing between two remote points on the surface.

Temperature variations according to latitude are evidenced by a decrease from 27° C at the equator to -3° C in the Arctic or Antarctic. Ocean currents, drift ice and storm waves also affect these values, however, and produce significant temperature variations in longitude.

Ocean currents are generally due to variations in the physical state of water, rather than to external forces.

Among the internal forces, those which deserve special attention are caused by pressure differences between adjacent maritime areas. These are due either to temperature differences between zones or to salinity changes resulting from rainfall, the increased flow of rivers in flood, or melting icebergs.

The water masses find the level corresponding to their density by vertically dividing into layers respectively designated by oceanographers as surface water, upper water, intermediate, deep, and bottom water.

The water of highest density, either because of its low temperature or high salinity, or for both reasons, will sink under the lower-density water, which will rise to take the other's place. These shifts produce vertical currents known as convection currents (transference of heat), whose effects are principally felt in higher latitudes through the accumulation of dense water near the bottom, as in the Arctic and Antarctic.

The tide-generating force also influences variations in the strength of ocean currents, in combination with seasonal variations in mean sea level.

Moreover, tide waves, which are characterized by more or less elliptical motion and by water particles of varying size (according to region) are a permanent cause of change in the thermohaline state of the seas.

Among the principal external forces should be mentioned the action of weather, which affects the sea surface to a considerable extent and causes the water masses to shift in order that the disturbed equilibrium may be restored.

The foregoing outline should give some idea of the complex relationship between the various physical states of the sea, and the resulting shifts and movements of the water masses.

In the Argentine Sea, the thermal year occurs in the form of two periods or seasons. The first takes place from December to May, with surface temperatures from 16° to 23° opposite Mar del Plata, 14° to 18° at the latitude of Madryn, and 7° to 9° at the Tierra del Fuego level. The second period extends from June to November, with surface temperatures from 15° to 11°, 13° to 10°, and 6° to 5° respectively for the same locations (the temperatures given are coastal temperatures).

Generally speaking, the minimum temperature period, i.e., the season at sea corresponding to the June-November period, is the more consistent, and this stability increases with latitude.

In the remotest (coastal) areas of the Argentine Sea, the mean annual variation is respectively 13° and 3°.

Prior to the uneven annual variation in temperature, which exceeds the normal variation for latitude, the possibility here occurs of a considerable transport of warm water from the north in the summer and autumn, with strong regression of masses towards the south, corresponding with the elevation of mean sea level at this period.

In winter and spring the reverse pattern occurs.

At Mar del Plata station, it was discovered that sudden variations in water temperature occurred in coincidence with abnormal variations in sea level caused by storm waves. It is known that the latter are produced by meteorological factors : they arrive at Mar del Plata either from the south, when the sea level is increased by transport of cold water, or from the north, when the level decreases due to the shifting of the warmer masses.

These disturbances are of a random character. It cannot be denied, however, that they occur with greater frequency when the storm waves come from the south. This interferes with results and conclusions, since increases in sea level will be recorded with decreases in temperature and vice versa.

Such problems, including the strong temperature variation according to longitude observed at the latitude of Mar del Plata and its influence on variations in mean sea level, will be solved during investigations scheduled from 1 July 1957 as part of the International Geophysical Year programme.

METEOROLOGICAL FACTORS

Atmospheric pressure

Normal distribution of pressure over the Argentine Sea is characterized by:

(a) an anti-cyclone of large extent over the Atlantic covering lower latitude areas and extending over Uruguay and Brazil ;

(b) a low pressure area (perhaps the lowest in the world) located almost permanently in the upper latitudes and shifting around the Antarctic continent and adjacent areas.

As a result, a decrease in the annual mean value of atmospheric pressure is observed ranging from 1016 mb at Mar del Plata to 997 mb at Tierra del Fuego, which undoubtedly affects the mean level of the Argentine Sea. This decrease is in accordance with latitude up to about 45°; from this point to Tierra del Fuego the decrease becomes more marked, and the velocity of the west wind in these latitudes increases.

Minimum pressures are observed during the summer months over the entire Argentine Sea, whereas maximum pressures are recorded in winter.

The masses of cold (polar) air enter through Patagonia and spread northeastwards over the Argentine Sea. They displace the warmer air covering this region and cause the formation of an extensive cold front. Such fronts are mainly characterized by changes in wind direction from the north to the south sector. As the cold air mass enters the north part of the country, the current loses strength, the air gains stability as it grows warmer, and returns southwards until another polar air mass causes it to shift once again towards the north. The sea level is consequently affected by these fluctuations and rises or falls according to wind direction. This fact may be checked by comparing daily the recorded tide with the predicted tide.

Cold fronts occur about 90 times a year. Their average length is 3 or 4 days, between extremes of 1 up to 15 days.

When the front comes from the south, the winds arrive from the southeast; when the front is from the west, the wind direction is from the southwest. Large masses of water are displaced, causing the mean sea level to rise up to 150 cm over its normal mean value.

Maximum mean monthly values of atmospheric pressure occur in September for Mar del Plata (1015.7 mb) and Punta Delgada (1009.1 mb); and in June and September for Tierra del Fuego (1003.7 mb). Minimum values have been recorded in December and January for Mar del Plata (1008.3 mb) and Punta Delgada (1001.1 mb); and in February for Tierra del Fuego (996.6 mb).

The sequence of variations in mean monthly values of atmospheric pressure in the Argentine Sea shows the following characteristics:

Atmospheric Pressure in Millibars

Month	Mean monthly values for the period 1945-55 Mar del Plata	Pta. Delgada	C. Rivadavia	Tierra del Fuego
January	1008.7	1002.1	999.9	997.1
February	1009.7	1002.3	999.8	996.6
March	1011.4	1003.6	1001.3	1000.8
April	1013.5	1005.1	1002.6	1000.2
May	1013.1	1004.0	1001.4	998.6
June	1014.3	1004.6	1002.6	1003.9
July	1014.8	1006.6	1003.7	999.3
August	1015.4	1008.2	1003.3	998.3
September	1015.7	1009.1	1005.4	1003.7
October	1014.1	1006.5	1003.2	995.9
November	1011.1	1003.3	1000.8	997.6
December	1008.3	1001.0	999.2	999.2
Means	1012.5	1004.7	1001.9	999.3

These mean values have been shown in diagrammatic form on the « average annual curve for the period » of mean sea level, on a convenient scale, for Mar del Plata, Madryn and C. Rivadavia. The purpose is to establish the relationship between variations in the two curves, bearing in mind that sea level decreases with increased pressure, and vice versa (fig. 5).

An interesting aspect is the coincidence in time and amplitude of the maximum mean sea level variations with the minimum atmospheric pressure values. Both curves show symmetrical inflections.

The influence of atmospheric pressure is considerable, whether on daily sea level variations, or on monthly and seasonal variations; it must be considered in research involving knowledge and determination of the laws governing mean sea level variations, regardless of the cycle involved.

The largest absolute variations in atmospheric pressure occur in August and September, and minimum variations in January.

Differences in absolute maximum and minimum values (1945-1955)

	Maximum		Minimum	
Place	mb	Period	mb	Period
Mar del Plata	37.5	IX-1948	11.7	I-1948
Punta Delgada	37.4	VIII-IX-1950	15.5	I-1950
Tierra del Fuego.....	54.5	VIII-1946	19.7	I-1948

Winds

The prevailing winds on the Argentine coast up to approximately 45° S latitude originate from the NW, N and NE sectors. As the latitude increases, winds mainly originate from the west sector throughout the year.

The frequency diagrams for Mar del Plata, Punta Delgada and C. Rivadavia show the lines of greater frequency and those immediately following, indicating the wind pattern.

Mar del Plata: The most frequent winds are from the N and NE sectors in spring, summer and autumn, and from the NW sector in winter.

Secondary frequency shows a prevalence of winds from the S sector in autumn and spring, from the SW and W in winter, and NW in summer.

Punta Delgada: The most frequent winds are from the N sector throughout the year.

The secondary frequency sharply defines the seasons, as the prevailing winds are from the south in spring and summer, and from WNW in autumn and winter.

C. Rivadavia: The most frequent winds definitely originate from the W sector throughout the year.

The secondary frequency shows winds from the NE and SW in spring and summer, and from the NW in autumn and winter.

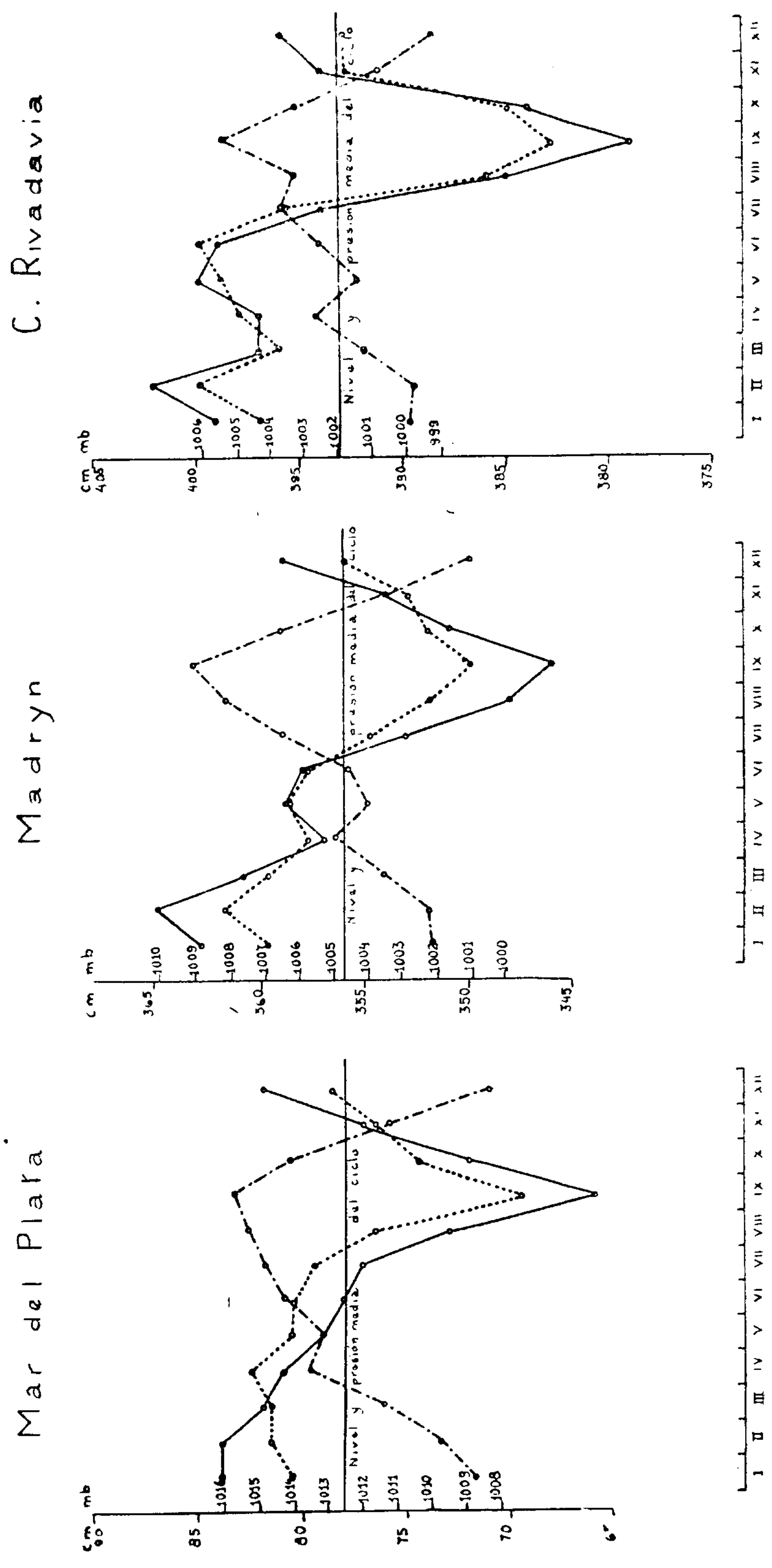

Fig. 5.
Argentine Sea. Comparison between curves of annual M.S.L. and atmospheric pressure variations.

—— Mean Sea Level (monthly means).
— · — · — Atmospheric pressure (monthly means).
.... Mean Sea Level reduced for the local atmospheric pressure.

Mar del Plata. Frequency (n) of wind direction.

Direction.... Month	N	NE	E	SE	S	SW	W	NW	C
January	14.5	16.0	9.0	10.1	13.9	8.9	3.4	14.4	9.8
February	15.7	19.7	9.8	8.1	12.6	6.8	6.3	12.6	8.3
March	14.2	14.3	7.5	8.5	13.0	9.1	6.2	16.1	11.0
April	19.5	8.9	4.5	6.5	13.0	9.2	10.6	16.5	11.4
May	15.9	5.8	3.8	4.9	8.1	8.4	17.0	24.6	11.6
June	15.9	4.9	3.0	4.6	7.2	9.0	18.3	20.9	16.3
July	16.2	5.1	2.7	4.1	8.8	13.5	17.2	18.9	13.3
August	13.6	10.3	5.7	4.7	11.9	12.3	13.4	15.9	12.3
September ...	14.0	14.8	7.1	9.9	13.6	11.2	7.8	9.9	11.7
October	12.8	18.1	7.6	5.8	12.4	13.0	6.7	14.9	8.8
November ...	18.3	17.1	7.4	7.2	15.4	8.8	5.1	13.8	6.7
December ...	10.2	17.3	8.0	8.8	14.8	12.9	5.1	17.1	5.8

———— Maximum frequency — N and NE in spring, summer and autumn ; NW in winter.

- - - - - Secondary frequency — NW in summer and autumn ; W in winter ; S in spring.

Punta Delgada. Frequency (n) of wind direction.

Direction.... Month	N	NE	E	SE	S	SW	W	NW	C
January	28.4	9.1	6.0	5.1	26.9	10.9	8.1	5.1	0.5
February	24.2	12.2	5.1	4.6	19.1	13.9	9.8	11.2	—
March	24.9	10.1	2.6	4.1	18.7	15.1	11.1	12.4	0.9
April	29.6	8.6	3.5	1.7	12.4	11.9	14.9	16.2	1.1
May	34.7	3.8	3.4	2.2	12.1	11.5	18.5	13.7	—
June	33.8	3.2	1.6	2.9	7.8	11.6	18.4	20.7	—
July	27.5	4.3	3.2	1.3	11.6	15.9	18.9	16.9	0.2
August	24.9	6.5	1.1	2.8	12.9	17.4	16.1	18.3	—
September ...	32.1	9.4	3.1	4.2	16.5	12.9	9.1	12.0	0.7
October	31.4	8.2	2.4	2.4	17.9	18.5	10.8	7.8	0.6
November ...	25.6	6.2	8.0	4.4	22.7	12.9	10.7	9.6	—
December ...	22.7	11.9	4.3	3.5	22.7	15.8	12.3	6.9	—

———— Maximum frequency — N throughout the year.

- - - - - Secondary frequency — S and SW in spring and summer ; W and NW in autumn and winter.

Comodoro Rivadavia. Frequency (*n*) of wind direction.

Direction.... Month	N	NE	E	SE	S	SW	W	NW	C
January	6.0	11.6	9.9	3.7	5.2	12.4	42.9	6.6	1.7
February ...	5.8	8.6	7.9	4.5	6.2	11.6	47.9	5.6	1.9
March	6.5	6.2	7.3	3.5	6.4	13.3	40.8	8.7	7.3
April	5.1	3.0	5.5	3.3	5.3	13.2	46.3	11.8	6.5
May	6.3	2.7	2.6	1.6	3.8	12.0	48.5	15.8	6.7
June	5.0	3.3	2.3	2.6	4.4	12.8	48.0	14.5	7.1
July	6.0	4.4	3.1	2.1	4.9	13.0	46.6	15.3	4.6
August	5.7	3.8	3.4	3.9	5.9	12.1	48.5	12.1	4.6
September..	6.2	6.1	6.0	4.6	5.1	7.9	47.2	12.6	4.3
October ...	5.3	5.7	5.3	2.7	5.4	6.4	54.1	11.8	3.3
November..	6.6	9.3	7.8	6.4	5.3	6.6	48.0	6.8	3.2
December..	4.5	11.3	9.4	5.2	7.7	9.0	46.1	4.1	2.7

———— Maximum frequency — W throughout the year.

- - - - - Secondary frequency — SW in summer ; NW in autumn and winter ; NE in spring.

Evaluation of variation factors

In order to evaluate the action of each of the above-mentioned factors on the mean level of the Argentine Sea, their effect and relative importance have been analysed at various places.

For purposes of simplification, only the tidal stations at Mar del Plata, Madryn and Comodoro Rivadavia have been considered, for which better and more complete information is available.

Consideration was first given to the meteorological factor whose action is mainly evidenced by variations in atmospheric pressure.

Monthly mean values of mean sea level were thus corrected according to the ratio between the density of mercury and sea-water respectively (13 mm variation in the height of sea level per 1 mm variation in atmospheric pressure). Although not strictly accurate, since no allowance is made for the important effect of pressure gradients, especially in shallow coastal areas, this system may nevertheless be retained when dealing with monthly mean values.

The influence of wind on the Argentine Sea generally results in a lowering of the mean level, although in some cases winds acting jointly with cold fronts from these considerably raise this level.

Diagrams of frequency values enable the direction of wind to be evaluated for each month of the year, and its influence to be estimated.

After correction of the monthly values for atmospheric pressure (fig. 4), harmonic analysis was used to determine components Sa and Ssa, which, as previously stated, represent the annual and semi-annual effect of the sun (variations of parallax and declination respectively).

The values obtained for the amplitudes of waves Sa and Ssa not only include direct action of the sun as an attractive force (mass), but its action as a source of heat evidenced by seasonal variations in the temperature of sea water.

Following computation of the values for each place, shown below, a graph was made based on the same system of coordinates used for the mean level curve; this procedure was also followed in the case of the resultant wave, i.e. (Sa + Ssa) (fig. 6).

Place	Sa		Ssa	
	— β	Amplitude mm	— β	Amplitude mm
Mar del Plata	76° 42	90.3	331° 80	33.3
Madryn	60° 83	96.8	358° 75	27.6
C. Rivadavia	75° 03	135.8	307° 30	80.9

Mean values for the period 1945-55.

A comparison between the resultant curve (Sa + Ssa) and the mean level curve (corrected for atmospheric pressure) shows perfect correlation. It may therefore be assumed that monthly variations in mean sea level are principally due to solar action.

The difference between them reveals the presence of a residual wave of four-month periodicity (one-third year) occurring along the Argentine coast, since it may be observed at Mar del Plata as well as at Madryn and Comodoro Rivadavia.

This residual wave ($S\frac{1}{3}a$) may be generated by wave (Sa + Ssa) as it passes over the continental shelf.

Following the analysis of the ($S\frac{1}{3}a$) residuals, their parameters were determined for each place, with the following results:

Place	1/3 annual solar wave	
	— β	Amplitude mm
Mar del Plata	171° 33	20.4
Madryn	85° 37	25.4
C. Rivadavia	121° 07	31.2

The residual curve ($S\frac{1}{3}a$) obviously indicates the necessity of allowing for the action of continental shelves in the determination of mean sea level; it is therefore believed that ideal conditions for this type of research would consist in the observation of oscillations in open and deep water, such as off islands in the ocean with a small insular shelf.

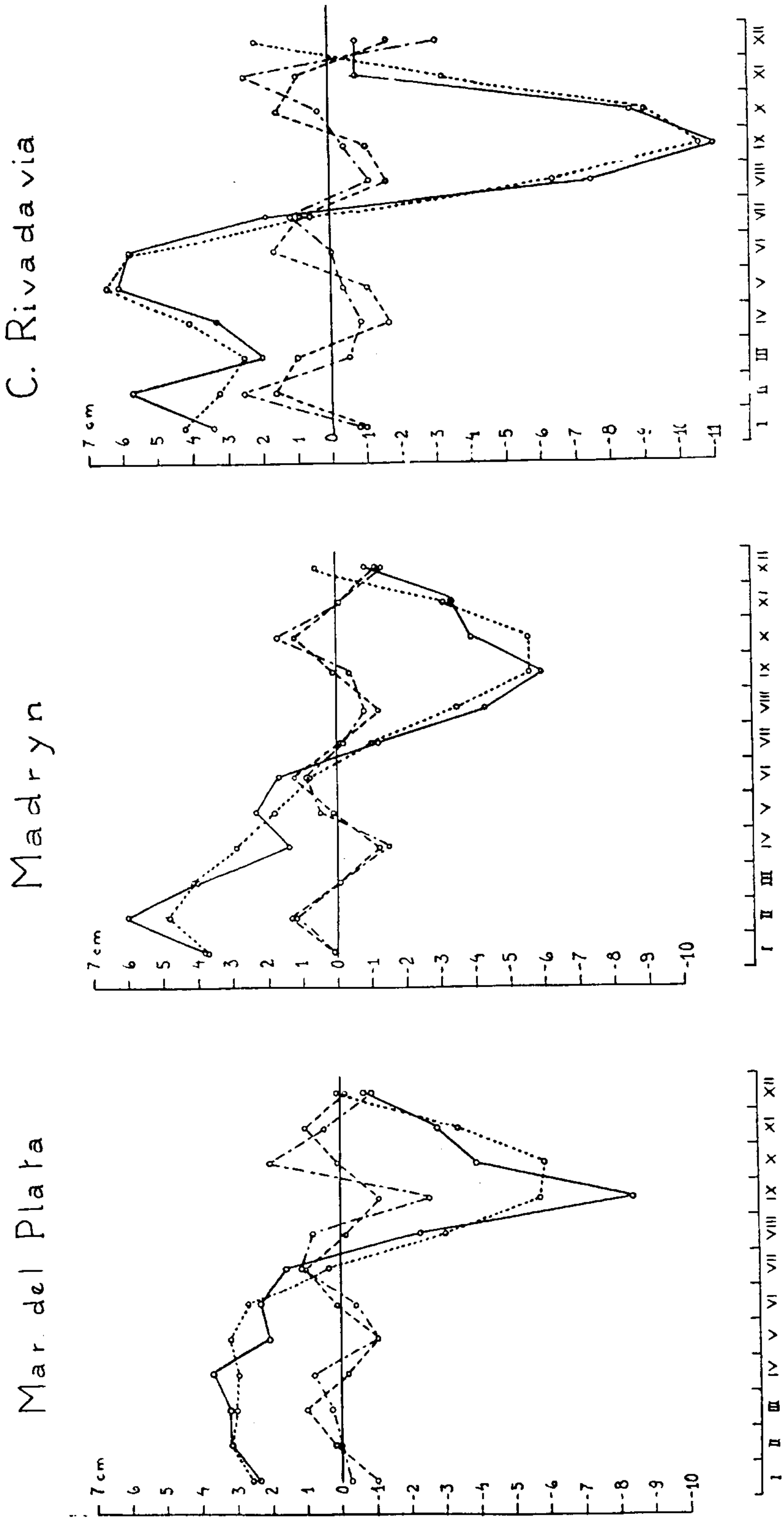

Fig. 6.
Mean Sea Level in Argentine Sea.
Seasonal variation diagrams.

....	Compound Tide Sa + Ssa.
————	M.S.L. corrected for pressure.
– · – · –	Residual Tide.
— — —	S 1/3 a.

ANALYSIS OF SEASONAL VARIATION FACTORS

Mar del Plata:

The mean sea level variation curve shows the following characteristics:

(a) From January to July inclusive, values are above normal mean level for the period, and from August to December, below this level;

(b) Dispersion with respect to the normal mean is greater in the case of negative values than for positive values;

(c) The summer and autumn period is more regular than the winter and spring period. Negative dispersion is greatest in September, with —11.7 cm, whereas the largest amount of positive dispersion occurs in January, with +6.3 cm;

(d) The greatest amount of disturbance on the ($S \frac{1}{3} a$) residual curve is observed in spring, and seems to be due to the irregular action of wind.

Geographical factors. The thermal year in the Argentine Sea opposite Mar del Plata consists of two seasons: a « temperate » season including summer and autumm, and a « cold » season including winter and spring.

The maximum variation in surface temperature between these two seasons is around 13° C.

Variations in atmospheric pressure likewise are marked by two periods with respect to the annual mean: a « low-pressure » period extending from November to March (summer and autumn), and a « high-pressure » period from April to October (winter and spring). Maximum annual dispersion between mean monthly values reaches 7.4 mb (+3.2 in September and —4.2 in December).

A certain regularity is moreover evident in the frequency of wind. The prevailing winds are from the north sector in summer and autumn and from the west sector in winter. In spring, the regime is more irregular, with winds arriving with equal frequency from the south and west.

The mean sea level variation curve systematically shows the action of each of these factors.

Madryn:

The mean sea level variation curve shows the following characteristics:

(a) From January to June inclusive, values are above normal mean sea level for the period, and from July to December, below this level;

(b) Dispersion with respect to the normal mean is approximately equivalent for both positive and negative values;

(c) The period of positive values (summer and autumn) shows a significant amount of discontinuity between April and June. The maximum positive value occurs in February (+8.4 cm), and the maximum negative value in September (—10.4 cm)

(d) The residual curve is perfectly adapted to the ($S \frac{1}{3} a$) wave, proving the regular and compensating action of the disturbing factors.

Geographical factors. The thermal year in the Argentine Sea at the level of Madryn consists of two seasons: a « temperate » season from December to May, and a « cold » season from June to November. Temperature variations offshore between the two seasons amount to as much as 8°.

Variations in atmospheric pressure also fall within two different periods in relation to the annual mean: a « low-pressure » period from November to May, and a « high-pressure » period from July to October. Maximum annual dispersion between mean monthly values is 7.0 mb (+4.4 in September and —2.6 in January)

Prevailing winds are from the north sector ; but in spring and summer winds are prevalent to a certain extent from the south, and in autumn and winter from the west.

The action of all these factors on the mean sea level at Madryn is distributed with considerable regularity.

Comodoro Rivadavia :

The mean sea level variation curve shows the following characteristics :

(a) From January to July inclusive, values are above normal mean sea level for the period, and from August to December below this level ;

(b) Dispersion with respect to the normal mean is greater for negative values than for positive values ;

(c) The period of positive values (summer and autumn) shows a significant lack of continuity between March and June. Maximum positive values occur in February (+7.8 cm) and May (+6.6 cm), and maximum negative values in September (—14.6 cm);

(d) The residual curve regularly follows the $(S\frac{1}{3}a)$ wave, but shows a few differences which give rise to an additional wave with a three-month period.

The lack of continuity observed between March and June appears to indicate the inflow and outflow of respectively cold and temperate water masses.

Geographical factors. The thermal year in the Argentine Sea at the Comodoro Rivadavia level consists of two seasons: « temperate » from December to May, and « cold » from June to November. The temperature between seasons varies by as much as 6°.

Atmospheric pressure variations fall within two different periods in relation to the annual mean: a « low-pressure » period from November to May, and a « high-pressure » one from July to October. Maximum annual dispersion between mean monthly values reaches 6.2 mb (+3.5 in September and — 2.7 in December).

The most frequent winds are from the west sector throughout the year, although there are also prevailing winds from the NW in autumn and winter, from the SW in summer, and from the NE in spring.

As this area is in the middle latitudes, it is affected by the inflow and outflow of subtropical and antarctic water masses, which appear on the diagrams as sudden breaks.

CONCLUSIONS

There is a considerable amount of correlation between monthly variations in mean sea level and contributory factors at various places off the Argentine seaboard.

Maximum positive dispersion of mean level with respect to the normal mean for the period analysed (1944-55) occurs in January as regards Buenos Aires Province (+6 cm), and in February with reference to the remaining Patagonian littoral (+7 cm). Maximum negative dispersion is recorded in September throughout the Argentine Sea (—12 cm).

Negative dispersion values are much higher than positive values along the entire coast, Madryn alone excepted, where positive dispersion exceeds negative dispersion by 2 cm.

We may consider the amplitude of the annual oscillation of mean level in the Argentine Sea to be constant, since it remains in the vicinity of 20 cm.

Maximum positive mean monthly values of atmospheric pressure occur in September ; maximum negative values are recorded in December and January. Amplitudes oscillate around 7.4 mb at Mar del Plata; 8.1 mb at Punta Delgada; 6.2 mb at Comodoro Rivadavia ; and 7.1 mb at Rio Grande.

Variations in surface water temperatures between seasons (temperate and cold) fluctuate around 13°C off Mar del Plata, and 4°C off the NE coast of Tierra del Fuego.

The four-month residual wave ($S \frac{1}{3} a$) occurs with marked regularity over the entire Argentine Sea, with a mean amplitude of 2.5 cm, in evident confirmation of the disturbing influence of the continental shelf on the (Sa + Ssa) wave. The leading factor affecting seasonal variations of mean sea level is undoubtedly the annual solar wave, represented by the sum of Sa and Ssa.

As stated previously, the annual solar wave includes, in addition to the effects of meteorological action, the effects of the sun's attractive force and of its thermal action as a source of heat on the sea.

The effect of the sun as a mass (attractive force) varies with declination and parallax. Its influence increases with latitude, with the result that the (Sa + Ssa) wave values are relatively larger than in the lower latitudes.

The action of the sun as a source of heat is dependent on latitude. As the Argentine Sea is largely oriented latitude-wise, thermal influences vary considerably, and decrease as the latitude increases.

An additional factor, which principally occurs in the middle latitudes, is the shifting of large water masses in their search for thermohaline balance and the volumetric changes due to the heating of sea water during the summer months.

Such shifts in the water masses are moreover subject to the Coriolis effect, evidenced by a shifting of the water particles to the left with respect to the direction of flow in the southern hemisphere, and to the right in the northern hemisphere.

The foregoing processes give rise to an uneven distribution in latitude of the values corresponding to the factors involved, apparently explaining the remarkable constancy of mean level seasonal variations off the Argentine seaboard. As already stated, this amplitude fluctuates in the neighbourhood of 20 cm throughout the year.

The task of differentiating and evaluating the factors which contribute to mean level seasonal variations in different zones of the Argentine Sea is consequently a heavy one, as all such factors act simultaneously and with varying intensity for each time and place. This is true for the factors affecting the (Sa + Ssa) solar wave, those resulting from atmospheric pressure and wind, volumetric changes and the shifting of water masses, and those involved in the recently determined $(S\frac{1}{3}a)$ residual wave.

This problem of universal nature and interest is one of the scientific projects on the agenda of the International Geophysical Year. Working groups have been created for this purpose, principally in maritime countries, and the tidal stations required in all seas have been selected, to be supplemented by appropriate meteorological and oceanographic observations.

After information simultaneously covering all seas has been collected, the laws governing seasonal variations of mean sea level can be established with certainty, and the influence of all the disturbance factors analysed above can be computed with accuracy.

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