On the causes of « high water » in the Northern Adriatic Sea, with special reference to the Venice Lagoon

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Summary. — It is a widespread belief of experts that the reasons of the increased frequency of "high waters" in the Lagoon of Venice are limited to the gradual sinking of the area (in connection with disorderly underground extractions of water) and to bradiseism of the West coast of the High Adriatic Sea.

Actually, the High Adriatic is envolved in a process of slow filling caused by the enormous amount of erosion products dragged into it by tens of rivers flowing into it. This material reaches exceptional proportions in flood periods, especially of the Po River. The resulting raise of the sea bottom exceeds on the whole the effect of eustatism and bradiseism. Thus, the hydrodynamic balance of the Gulf of Venice is subjected to continuous changes, which means that by continuous, very slow thinning out of the water thickness the water is bound (the other conditions remaining unvaried) to increase slowly the amplitude of its free, forced or progressive movements and to increase slowly, but progressively the period of its free oscillations. This latter aspect is particularly intriguing if one considers that the free oscillations of about 11.7 hours and 23 hours tend, extremely slowly though, to coincide with the rhythm of the half-daily and daily tides and thus accentuate the resonance effect in the course of time.

It was found that beginning with 1940 the earth's mean air temperature, which was slightly rising since 1880, inverted its tendency. In spite of reducing the eustatic effects, the temperature reduction gave rise to a progressive increase of precipitations which led to an accentuation of the efficiency of natural causes governing the high waters. Last but not least of the latter is the "lightening" of the sea due to reduced salinity, accompanied by a decrease of density, of molecular viscosity and of surface tension. It is responsible of isostatic effects, of easing and strengthening of sea motions due to resonance phenomena.

In any case, there is evidence that the chief reason of high waters in the Gulf of Venice must be sought in the passage of low pressure zones from

the open sea toward the shore. The consequent swelling of the sea proceeds along the sloped sea bottom, reaches the resonance point (which may often happen in the High Adriatic) where it is considerably intensified, sometimes by several units over the static effect, and this increase amplitude leads up to the coast. The efficiency of this mechanism is the stronger the less inclined is the sea bottom. Therefore, as a consequence of the sinking of the Western part of the Gulf of Venice, to a particular extent in the delta area, the influence of this phenomenon on the high waters has been gradually increasing since 1951.

It is proved that the High Adriatic (or parts of it) may become extremely sensitive to stresses causes by pressure variations passing over the area, and that resonance phenomena may be produced by periodical confluences as well as by kinetic coincidences. In any event, the pressure variations must by far be considered the most efficient cause of high waters in the Venetian lagoons.

Contrary to a widespread belief, the wind has no determining weight in the formation of high waters; its intervention always constitutes a secondary cause.

The search of remedies to save Venice is, of course, not within the scope of this writing. It is merely emphasized that the aggravation of the situation is linked, as above recalled, to further possible sinkings of the underground layers. In a previous work I mentioned the similarly alarming situation of Wilmington (Long Beach) where the local base of the US Navy — as a consequence of oil extractions from the nearby field of Long Beach — had subsided to such an extent that in 1959 the wharfs had almost sunk below sea level. The intervention provided by the introduction of large amounts of water into the subsoil of the entire area that had been affected, was not only able to arrest the alarming phenomena, but succeeded even in raising again the external surface to its original level referred to the sea. An acurately prepared action of underground pressurization of the Lagoon area should not fail to achieve equally appreciable results for Venice.

1. – "HIGH WATER" IN A BASIN OF CONSTANT CONFIGURATION.

Let us suppose that the morphological features of the Northern Adriatic Sea have remained unchanged during the past century. In this assumption — and apart from the astronomical tide considered equally unchanged as it has taken place during the period in question — which are the causes responsible for the high water observed in the Venetian lagoons? Obviously, the causes are to be seeked in the interactions occurring between the atmosphere and the hydrosphere. From time to time my attention has been repeatedly attracted by those phenomena. I have summed up their fundamental aspects in a study written in 1963 to which the reader is referred (¹).

Here I wish to underline that water movements of exceptional size have always been linked to resonance phenomena, arising during the propagation of more or less vast perturbations of the atmospheric pressure above the underlying water basin. The principal reasons of resonance are two: the propagation velocity of the atmospheric perturbation which tends toward the velocity of free waves of the sea over which it passes, and the bearing period of the pressure variation tending to coincide with the period proper to a free oscillation of the underlying basin.

The first reason explains, for instance, the variation of the water level in the Gulf of Trieste, and hence, the free transversal oscillation of the High Adriatic Sea. I have dealt with this subject repeatedly, so that it will be sufficient to recall the formula which summarizes the course of the phenomenon. When considering a canal which is closed at the extreme $x = 0$ and extends indefinitely in the direction of positive x's, the vertical movement is found to be subject to the relation

$$\zeta = \frac{1}{1 - v^2/c^2} \left\{ F\,(t - x/v) - \frac{v}{c}\, F\,(t - x/c) \right\},$$

where v indicates the perturbation velocity, c the velocity of the free sea waves and F any function of its arguments. In the case of the Gulf of Trieste the free oscillation takes place provided that the perturbing cause propagates from West to East, normal to the bottom of the Gulf (²).

Concerning the second condition of resonance, it may be verified in many instances. Reduced to its simplest expression, the theory may be summarized in the following formula:

$$\eta = \frac{k\,M}{\varrho c^2\,(m^2 - 1)} \left[\cos k\,(x - vt) - \frac{m}{\sin 2\,klm} \left\{ \sin k\,(l + vt). \right.\right.$$

$$\left.\left. \cos km\,(x - l) + \sin k\,(l - vt) \cos km\,(x + l) \right\} \right],$$

where η represents the vertical movement, c the propagation velocity of a long wave, ϱ the density, v the velocity of the perturbing action represented by

$$M_o = M \cos k(x - vt),$$

where M is a generally small figure. The conditions at the limits are represented by an horizontal movement equal to zero for $x = \pm l$ with the length of the closed basin being $2l$. With slight variations the relation is valid for the open basin, too. Besides, h is the mean depth of the basin, and $m = v/c$.

In a first approximation we may consider

$$c = \sqrt{gh}\,, \qquad T_i = \frac{4\,l}{i\sqrt{gh}} \quad \text{for } i = 1, 2, \ldots$$

Contrary to what might appear, in this case η does not tend toward the infinite for $v = c$, whereas the resonance exists when $\sin 2klm \to 0$. If s is an entire, and provided $2\,klm = s\pi$, one has $\dfrac{T_i}{T_s} = \dfrac{s}{i}$, where T_s is the period of the perturbing force (*).

This elementary theory allowed me to explain the genesis of the internal waves of the Lake of Bracciano (3) and of the Lake of Garda (4), the formation of the free oscillations (uninodal, binodal...) in the Lake of Caldonazzo (5), as well as the sea storms in the Harbour of Civitavecchia (78).

There is no doubt that we have here one of the perturbing reasons bringing about the high water levels of the Venetian lagoons, every time the interaction between air and water is able to excite the free oscillations of the High Adriatic or of the entire Adriatic Sea.

How may be explained, then, the alarmingly increasing frequency of high water in the Venetian lagoons and particularly at Venice? Supposing that morphologically nothing has changed in the Adriatic, neither the bottom nor the water level, a change in the weather conditions must be presumed to which the said phenomena are connected. Although this hypothesis does not appear venturous — as will be seen — it is not my task to prove whether it is valid or not; who has more information available than I, has possibly something to say with regard to this.

(*) For gulfs, bays, open seas $\eta = \dfrac{h\ M}{\varrho\ c^2\ (m^2 - 1)} \Big| \cos k(x - vt) -$

$$- \frac{m \sin k(l - vt)}{\sin 2\,klm} \left\{ \cos km(x + l) - \cos km\,(x - l) \right\} \Big|$$

where $\eta = 0$ for $x = 0$ (mouth of open basin, of length l). Besides,

$$\frac{T_i}{T_s} = \frac{s}{2\,i - 1}\,.$$

But has the High Adriatic remained morphologically the same during the last decades?

2. – Morphological changes of the High Adriatic Sea.

Strictly speaking, no water basin, however large it may be, maintains its form unchanged: variations of level, advancements of shores due to progressive sand deposits, withdrawals of shores due to erosions, changes of the bottom due to river deposits etc. are factors capable of modifying continuously the form of a basin and the water volume.

The changes of this kind are negligible even over longer time periods, as far as the Oceans are concerned, but not in cases of inland seas. They may even take place rather rapidly with small, closed basins.

Among the inland seas the Adriatic, and particularly the High Adriatic, is certainly among the most subjected to changes of this kind.

There is no doubt that still in the first centuries a.C. the Adriatic reached much farther than presently into the Po Valley and occupied all the line between Ravenna and Aquileia, and that several centuries before Christ it extended to large parts of the territories including presently the area around Ferrara, the lower plains near Padova, the lowlands around the Po Estuary and other Venetian regions. Ravenna with its outstanding harbour in the Roman period, as well as Adria, the town which gave its name to the entire sea bordering it, are today situated a long way inland.

At the same time a progressive subsidence of the underground took place, partly due to a solidification of the soft and muddy surface layer, and partly to a slow flexion of the bottom of the Po-Adriatic ditch. This explains how such towns as Spina, Eraclea, Altino and others were gradually swallowed up and covered by mud and reedy marshes.

The piling up of debris and earth by the rivers and the subsidence of the underground were the chief reasons of so many radical changes in the Venetian – Po estuary region in the course of centuries (⁶).

Generally, even today it is the earth which defeats the sea: the slow work of the same forces which gradually built up the Po Valley continues indefatigably. The sand and clay, the mud carried by the rivers to their mouths and pushed on into the sea eventually pile up on the bottom, fill in the deeper parts and contribute to the formation of a layer gently falling off toward the open sea and slowly raising the sea bottom.

Even if one leaves apart the variations of the shore, which are strongest in the area of the Po Delta, the bottom of the High Adriatic Sea is thus subjected to continuous changes due to the turbidity of the rivers. The latter reach the order of 370,000000 tons per year in the case of the Adige River, at Boara Pisani near its mouth, as deducted from the mean annual turbiometrical data for the 1957-1963 period (7). If one considers the numerous rivers flowing into the High Adriatic, the largest of which, but by far not all, are the Isonzo, the Tagliamento, the Livenza, the Piave, the Brenta, the Adige, the Po, the Reno... one is readily aware of the enormous amount of material which is continuously unloaded into this stretch of sea. The afflux takes sometimes gigantic proportions during floods and overflows of rivers near their mouths, and chiefly of the Po.

The dumping of turbid material by means of rivers concerns without doubt, as far as the finer components are considered, the entire High Adriatic Sea. Obviously, an exact appraisal of the changes taking place on the bottom of the High Adriatic in the course of time is not an easy matter. It would require dependable bathymetrical charts obtained through frequent and thorough measuring campaigns. Unfortunately, this requirement is met only to a very limited extent.

Anyway, the order of magnitude of major variations may be obtained from comparisons of bathymetrical charts executed after measurements made in different periods. To this effect, figure 7 is referred to comparisons between developments of the sea bottom in three different directions, as expressed by bathymetrical charts of the period 1867-1873 (8) and of the year 1896 (1928) (9). It will be noted that in all three cases examined the bottom showed decidedly a raising tendency. This applies as well to comparisons in other directions which would be too lengthy to report here (*). Of course, the results are only of an indicative nature and roughly approximative, but they are sufficient to give evidence of a progressive, low rise of the High Adriatic sea bottom as a consequence of the huge amount

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(*) No comparisons with more recent bathymetrics have been made since these were entered in charts of rather reduced scales, and since the results are gathered in isobath lines rather than being registered point after point as in earlier times. The bathymetrical explorations recently made for C.N.R. in the High Adriatic (10) will be valuable for future comparisons.

of material of erosion carried forward from the Alps and the Appennine by the rivers flowing into it.

We shall revert to this subject.

It will be helpful to cover now some hydrodinamical aspects.

3. – ON FREE AND FORCED OSCILLATIONS OF A BASIN SUBJECT TO TIDE.

3.1. *General.*

It is known that a water basin, either closed or open, may present two types of oscillations proper (or free) ones and forced ones. The period of proper oscillations depends on the configuration of the basin; the period of the forced oscillations coincides with that of the perturbing force and is therefore independent from the basin's geometrical features.

If T is the kinetic energy of a mechanical system, made up by a certain amount of material points, with a finite number n of degrees of freedom, whose situation may be defined by n parametres $q_1, q_2 \ldots q_n$, if $q'_r = \frac{dq_r}{dt}$ and if U represents the potential energy due to the internal forces, the equations of Lagrange, concerning the motion of the system, will be:

$$\frac{d}{dt}\frac{dT}{dq'_r} - \frac{dT}{dq_r} + \frac{dU}{dq_r} = Q_r \qquad (r = 1, 2, \ldots n) \qquad [1]$$

where Q_r represent the external forces.

The extention to the problems of the tides is obtained by replacing the finite sums by integrals.

Equations [1] are valid only for absolute motions. Considering the rotation of the Earth, a relative motion of the seas follows. If q_o (*) indicates the actual orientation of the system in the absolute space $\left(\frac{dT}{dq_o} = \frac{dU}{dq_o} = 0\right)$, by the lack of external couples tending

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(*) If one supposes three mobile axes invariably bound the solid earth and three fixed axes, and coinciding the axes z in the two systems, q_o will represent the angle of mobile axes with fixed axes; and the other coordinates q_r indicate the relative position of the system referred to the mobile axes.

to vary the Earth's rotation ($Q_o = 0$), the equation of Lagrange for the parameter q_o is reduced to $\frac{d}{dt}\frac{dT}{dq_o'} = 0$, and hence $\frac{dT}{dq_o} = p_o$, where p_o is a constant. Made

$$H = T - U - p_o\, q_o'$$

one finds the equations of Lagrange becoming (11)

$$\frac{d}{dt}\frac{dH}{dq_r'} - \frac{dH}{dq_r} = Q_r \qquad (r = 1, 2, \dots n) \tag{2}$$

The equations of Lagrange maintain, therefore, the same form when one considers the balance on the relative motion.

3.2. *Study of the free oscillations.*

When the external forces are zero ($Q_r = 0$), the equation of Lagrange for the parameter q_k becomes

$$\frac{d}{dt}\frac{dH}{dq_k'} - \frac{dH}{dq_k} = 0 \tag{3}$$

Here we have n linear equations with constant coefficients.

We express the various elements of H depending on the mechanical properties of the system. We have

$$T = \sum \frac{m}{2}(x'^2 + y'^2 + z'^2) + q_o' \sum m\,(xy' - yx') + q_o'^2 \sum \frac{m}{2}(x^2 + y^2),$$

where m represents the mass of a material point of coordinates x, y, z referred to the free axes, and the apexes stand for derivatives against time. If T' expresses the half kinetic energy of the system in its relative motion, M the angular momentum and J the relative moment of inertia, we may write

$$T = T' + q_o' M + q_o'^2 \frac{J}{2}.$$

Furthermore

$$p_o = \frac{dT}{dq_o'} = M + q_o' J$$

so that

$$H = T' - U - \frac{1}{2J}(p_o - M)^2.$$

Considering the smallness of coordinates and of velocities, so that all the terms above the 2nd degree may be neglected, plotting against q', we have

$$H_2 = T' - \frac{M^2}{2J} : \quad H_1 = \frac{p_o M}{J} ; \quad H_o = -U - \frac{p_o^2}{2J}$$

Therefore, by emphasizing the various parts of H, equations [3] become

$$\frac{d}{dt}\frac{dH_2}{dq_k'} + \frac{d}{dt}\frac{dH_1}{dq_k'} - \frac{dH_1}{dq_k} - \frac{dH_o}{dq_k} = 0 \qquad [4]$$

Since H_2 is a polynomial of the 2nd degree in q', $\frac{dH_2}{dq_k'}$ will assume the form $\frac{dH_2}{dq_k'} = \sum a_{rk}'' q_r'$, from which $a_{rk}'' = \frac{d^2 H_2}{dq_r' \, dq_k'}$ where a_{rk} are constants.

It is proved (Poincaré, l.c., p. 12) that, since H_1 is a polynomial of the 1st degree in q and in q', after

$$a_{rk}' = \frac{d^2 H_1}{dq_r \, dq_k'} - \frac{d^2 H_1}{dq_r' \, dq_k}$$

it follows:

$$\frac{d}{dt}\frac{dH_1}{dq_k'} - \frac{dH_1}{dq_k} = \sum a_{rk}' q_r'.$$

While, being H_o a polynomial of the 2nd degree in q, after

$$a_{rk} = -\frac{d^2 H_2}{dq_r \, dq_k}$$

then

$$-\frac{dH_o}{dq} = \sum a_{rk} q_r.$$

Therefore, the equations of Legrange [4] take the form

$$\sum (a_{rk}'' q_r'' + a_{rk}' q_r' + a_{rk} q_r) = 0.$$

We have n linear equations with constant coefficients, whose system may be integrated by putting

$$q_r = \alpha_r e^{\lambda t}$$

where λ and α_r are determined so that the equations are satisfied. By substitution the latter become then

$$\sum \alpha_r (a_{rk}'' \lambda^2 + a_{rk}' \lambda + a_{rk}) = 0$$

or, after

$$C_{rk} = a_{rk}'' \lambda^2 + a_{rk}' \lambda + a_{rk},$$

$$\sum \alpha_r C_{rk} = 0 \qquad [5]$$

We have n homogeneous linear equations in $n + 1$ unknown values, $\alpha_1, \alpha_2 \ldots \alpha_n, \lambda$. The problem is possible if the determinant of the said equations is zero:

$$\Delta(\lambda) = 0. \qquad [6]$$

On the other hand, it is proved that $\Delta(\lambda) = \Delta(-\lambda)$. Therefore, equation [6] has equal roots two by two, of opposite sign.

In the case of stable equilibrium, of interest to us, these roots (Poincaré, l.c., p. 14) are purely imaginary:

$$\lambda = i\mu,$$

being μ real. Therefore, there are $2n$ particular solutions which sutisfy the equations of Lagrange and correspond to the $2n$ roots of equation [6]. They constitute the *harmonic solutions its own* of the system, periodical functions of time, proportional to an imaginary exponential.

If

$$\alpha_r = \varrho_r e^{i\omega_r}$$

each of the system's complex harmonic natural oscillations will be given by the n values

$$q_r = \varrho_r \, e^{i(\mu t + \omega_r)}$$

of parameteres q.

Since the differential equations are linear and have real coefficients, the real part and the imaginary part of the complex solutions will satisfy the problem separately. Thus, to each complex solution correspond two real solutions

$$q_r = \varrho_r \cos (\mu t + \omega_r)$$

$$q_r = \varrho_r \sin (\mu t + \omega_r).$$

These are *the natural-free-harmonic real oscillations of the system.* By combining the $2n$ particular solutions of the differential equations we obtain the problem's general solution.

The period of a free oscillation, corresponding to the value of μ, is given by $\dfrac{2\,\pi}{\mu} = \dfrac{2\,\pi}{\lambda}\, i$. The equation in λ defines, therefore, the periods of the free oscillations.

We are determining now ϱ_r and ω_r, viz. a_r.

If we indicate by D_{rk} the minors of the determinant $\Delta(\lambda)$, we have

$$\Delta = \sum C_{rk} \, D_{rk}.$$

From the theory of homogeneous linear equations follows

$$\frac{a_1}{D_{1k}} = \frac{a_2}{D_{2k}} = \ .\ .\ .\ .\ = \frac{a_n}{D_{nk}} \ .$$

The minors are complex quantities completely determined, once λ is known. This allows to determine a_r.

3.3. *Study of the forced oscillations.*

With the action of non zero external forces, the term Q_r of the Lagrange equation, concerning the parameter q_r, takes the form

$$Q_r = \sum K_{rh} \, e^{\lambda_h t}$$

where the exponential factors are harmonic functions of time.

We are now considering the complex components of the perturbing force. *Each of them will bring about an isochronal forced oscillation with* *the same period*; and when all components at the same time will act *the resulting oscillation will be the sum of the oscillations caused by each of them, due to the principle of overlapping of the small movements.*

So we examine only one of them. We put

$$Q_r = K_r\, e^{\lambda t}.$$

To this perturbing force corresponds a forced oscillation

$$q_r = \varepsilon_r\, e^{\lambda t}. \qquad [7]$$

In that case the Lagrange equations become

$$\frac{d}{dt}\,\frac{d\Pi}{dq_k'} - \frac{d\Pi}{dq_k} = K_k\, e^{\lambda t} \qquad (k = 1, 2, \ldots n) \qquad [8]$$

By distinguishing the three parts of Π already considered in the previous paragraph, equations [8] become

$$\sum \left(a_{rk}''\, q_r'' + a_{rk}'\, q_r' + a_{rk}\, q_r\right) = K_k\, e^{\lambda t},$$

with k and r varying from 1 to n.

For equation [7], and by recalling [5] we have the set of equations

$$\sum \varepsilon_r\, C_{rk} = K_k$$

Since λ is given, the C_{rk} are known constants.

Each of these equations includes the n unknown values ε_r; n is the number of the equations. Like eqs. [5], they are of the first degree, no more homogeneous but with a second member. They will be solved, therefore, by the Kramer method. In each solution at denominator shall appear the determinant with C_{rk} coefficients of unknown terms formed, whilst at numerator shall be the same determinant where C_{r1}, $C_{r2} \ldots$ C_{rn} are replaced by K_1, $K_2, \ldots$ K_n, respectively [that is $\sum K_h\, D_{rh}(\lambda)$].

A particular solution of the problem of forced oscillations is given, therefore, by the n values

$$\varepsilon_r = \frac{\sum K_h\, D_{rh}(\lambda)}{\Delta(\lambda)}\,.$$

3.4. *Comparison between forced and free oscillations.*

The quantity ε_r is a rational function which can be divided into simple elements.

If we indicate by λ_j one of the $2n$ roots of equation $\Delta(\lambda) = 0$, we have seen that the corresponding proper oscillation is given by the values of parametres

$$q_{rj} = a_{rj}\, e^{\lambda_j t}$$

where j varies from 1 to $2n$ and r from 1 to n.

These q-values are solutions of the homogeneous differential equations where $q_r = \varepsilon_r\, e^{\lambda t}$ is a particular solution of the same equations with a second member.

The problem of the forced oscillations will therefore be solved by adding to the particular solution any solution of the homogeneous equations, in other words an its own solution. The roots of the denominator, $\lambda = \lambda_j$, are the ones which define the periods of free oscillations of the system; to each of such roots corresponds a term $\dfrac{\sum K_h\, D_{rh}\,(\lambda_j)}{(\lambda - \lambda_j)\, \Delta'(\lambda_j)}$ $(h = 1, 2, \ldots n)$. By summing with respect to j $(j = 1, 2 \ldots 2n)$ we get

$$\varepsilon_r = \sum \frac{\sum K_h\, D_{rh}\,(\lambda_j)}{(\lambda - \lambda_j)\, \Delta'(\lambda_j)}\,.$$

As the conjugated imaginary solutions are $s_{rj} = \beta_{rj}\, e^{-\lambda_j t}$, it is proved that (Poincaré, *l.c.* pages 15-16-20) the ratio $\dfrac{D_{rh}\,(\lambda_j)}{a_{rj}\,\beta_{hj}}$ is independent from r and h, so that we may write

$$\frac{D_{rh}\,(\lambda_j)}{a_{rj}\,\beta_{hj}} = \mu_j\, \Delta'(\lambda_j)$$

which leads to

$$\varepsilon_r = \sum \sum \frac{K_h\, \mu_j\, a_{rj}\, \beta_{hj}}{\lambda - \lambda_j},$$

from which the expressions of q_r parametres follow. By writing $q_r{}^{\circ}$ to indicate that this solution is a *particular* one of the nonhomogeneous equations, we get

$$q_r{}^{\circ} = \sum_{j=1}^{i=2n} \left(\frac{a_{rj}\, e^{\lambda t}}{\lambda - \lambda_j} \sum_{1}^{n}{}_h\, K_h\, \mu_j\, \beta_{hj} \right). \qquad [9]$$

λ and K_h are given constants, since referred to the known perturbing force; λ_j, μ_j, a_{rj} and β_{hj} are as well constants referred to the free oscillation, the period of which is defined by the root λ_j of equation [6].

It is proved (Poincaré, *l.c.*, p. 26) that $2\,\mu_k = -\lambda_k$, so that, after

$$T_o = \sum K_h\,\beta_{hj},$$

equation [9] may be written

$$q_r{}^o = -\frac{1}{2}\sum T_o\,a_{rj}\,\frac{\lambda_j}{\lambda-\lambda_j}\,e^{\lambda t}. \qquad [10]$$

Except one coefficient which does not depend on j, the general term of $q_r{}^o$ will be $a_{rj}\,e^{\lambda t}$. Every term corresponds to a harmonic forced oscillation. By comparing this oscillation with the corresponding free oscillation, we see that a_{rj} is the same for both oscillations, being the exponential coefficient $e^{\lambda t}$ for the former and $e^{\lambda_j t}$ for the latter.

Each forced oscillation has thus, in its various points, the same phase difference as the corresponding harmonic natural oscillation and a proportional amplitude, but its period is different from it, namely that of the perturbing force.

A very interesting fact is to be underlined. Let us suppose that λ is very near one of the values λ_j pertaining to the free oscillations. *The corresponding term in the expression of q_r becomes then predominant, and the observed forced oscillation differs very little with regard to the period, the ratio of amplitudes and the phase difference in various points of one of the system's harmonic free oscillations: and this tendency to coincide is accompanied by a magnification of the resulting motion. This is the case of resonance which takes place in certain sea basins with strong tide action*, such as in the Fundy Bay and other areas, *approaching to a proper harmonic oscillation of the basins.*

To which extent does this phenomenon apply to the High Adriatic Sea? And, should it occur even in limited proportions, which is its present tendency? Do the morphological variations contribute to accentuate its effects?

4. – ON FREE OSCILLATIONS OF THE ADRIATIC SEA AND OF PARTS OF IT.

It is several centuries that the tides of the Adriatic have been observed and studied. Giuseppe Toaldo deals with subject at large in a publication of 1781 (12), and particularly in article VIII: "Essay on the tide of the Adriatic Gulf" in which he distinguishes the diurnal tide, the "mestrual" (the monthly) tide and the annual tide. But more accurate research was done toward the end of the last century and in the beginning of the present (13-19).

It is the merit of von Kesslitz to have proved for the first time the existence of a natural oscillation of the Adriatic Sea whose period he estimated to be about 23 hours. He considered this oscillation the uninodal of the entire Adriatic, the uninode being situated where the Adriatic is linked to the Mediterranean (which was effectively proved by von Sterneck). Also Defant (20) accepted von Kesslitz's conclusions and calculated for the period of the Adriatic, considered as a gulf of the Mediterranean, a value of 22.4 hours, near which reached by von Kesslitz from his observations.

Von Kesslitz had also observed a stationary wave of a period of about 12 hours. This oscillation, very near the semidiurnal tide, was initially interpreted in a different way. Defant considered it as a fundamental oscillation for the Adriatic which he conceived like a lake, and hence with two troughs at the extreme North and South (Channel of Otranto). Others attributed it only to the oscillation of the open Northern Adriatic basin, for which von Sterneck indicated a period of 12 hours, Oddone one of 11.5 hours (21).

How do the free oscillations of the Adriatic originate?

The influence of atmospheric pressure variations on closed basins is not limited — as could be already seen, by the way — to static action; very often it induces dynamic phenomena and gives rise to sometimes considerable level differences. The wind, too, has an influence on the sea level. In the Adriatic, as is known, the Scirocco wind pushes the water toward the Northern coasts and causes rises. The Bora, which blows from ENE, brings about the opposite effect.

Francesco Vercelli, who on different occasions had to look into the effect of the weather perturbations on the sea level, pointed out in a study dated 1922 (22), in a diagram of a year's recordings of the Trieste tide gauge, the existence of periodical waves having a period of about 11 hours and others with a period of about 22 hours, similarly to what von Kesslitz had previously ascertained for the ports of Pola (18) and Ragusa (19). By applying to the recorded curve his method of period analysis, Vercelli found — as he writes in the said study — periods of approximately 22.2 hours and 11 hours for the two above mentioned waves. Von Kesslitz's approximate values were thus corrected by Vercelli of about one hour (less).

Concerning the uninodals, an attempt made by Oddone with a small model of the Adriatic, led to values which are probably excessive (21).

By applying Vercelli's cymoanalysis, Polli examined four sections of tide gauge curves recorded in Trieste on January 29, February 2, 1948, June 3-6, 1948, October 18-22, 1949 and April 15-17, 1950, respectively (23). In the examined cases Polli found values of 21.4 (± 0.7), 21.2, 21.5 and 21.0 hours for the uninodal of the entire sea, and 12.2 hours for the semidiurnal wave, thus returning to von Kesslitz's value. A remark should be made, however, about the uninodal. In reality, the values given are mean values. In figure 1 of Polli's work (l.c., page 70) the first complete wave shows a period of 20.5 hours, the second one of 23.7 hours, the third one of 21.0 hours, the fifth one of 21.9 hours, etc. From fig. 2 (l.c., page 71) it is hard to deduct trustworthy values. There are clearly time-independent oscillations, having a pseudo-period of about 28 hours, another with one of 21.4 hours. Fig. 3 (l.c., page 74) shows as well that the first oscillation with a period of 23.9 hours is separated from the next which has a small amplitude. The average of 21.5 hours, taken from Polli's work, should be viewed, therefore, only as indicative. I shall revert to it later.

The value of 21 hours, calculated by C. Bajc (24), cannot be considered very exact, as the author admits himself, for having been deducted from too daring schemes, which cannot take into account the elementary consequences of the basin form on the period of its free oscillations.

Only a differential method which gives due consideration to the continuous variations of the basin's form is able to lead to acceptable approximations. This is obvious to anybody who has collected experience in the study of the water-surface oscillations. Therefore, in my opinion the most trustworthy values for the natural periods of the Adriatic Sea are those collected by Kasumovic (25). He extended Chrystal's method to some fourty cross sections which led him to a normal curve, similar to the one I found in due time for the Lake of Levico, and then to the same system of operative formulas (26). The fundamental oscillation of the Adriatic Sea as a gulf open toward the Mediterranean thus proves to have the value of 22.11 hours (method of Chrystal) and 23.16 hours (method of Goldberg) which approaches the value of 23.34 hours as calculated by Defant. The average of observations led Kasumovic to the value of 22.7 ± 0.8 hours, which fairly agrees with the calculated values.

With the Chrystal method applied to the stretch of sea between the Venetian coasts and the line running from Mt. Gargano to the Islands of Pelagosa, Lagosta, Curzola, considered as a lake, Kasumovic obtains for the natural oscillation of about 12 hours the value of 11.34 hours, while the average of observations leads him to 11.76 ± 0.3 hours. The author's hypothesis is supported by the tide gauge recordings showing opposite troughs at Venice and at Vieste, with a nodal line running from Ancona to the Island of Pago. Kasumovic reaches this conclusion after having shown that Defant's hypothesis is erroneous which made the oscillation of about 12 hours the uninodal of the entire Adriatic oscillating like a lake.

But let us revert for an instance to the uninodal natural oscillation of the Adriatic. As I said above, in my opinion *its period* is the one calculated by Kasumovic, that is *at least 22 hours*. If it is, as could be proved, the fundamental of the Adriatic as a gulf open toward the central Mediterranean, the laws of hydrodynamics warrant the possibility of being realized since its nodal line comes out over a basin with natural oscillations of a longer period. That this is its origin is also proved, besides, by the recordings where the waves appear with their own character, sometimes intervalled by roughly equal wave lengths (Vercelli, l.c., table IV), sometimes partially overlapped (Polli, l.c., page 70), sometimes separated by more or less long intervals (Polli, l.c., page 71) or even isolated (Polli, l.c., page 74). And this explains itself by taking into account that these waves are oscillations of a basin which is open above another, much larger basin. In that way, when the perturbing cause is acting, the oscillation returning from the gulf base, proceeds beyond the node as a progressive wave and runs out then in one period. The rise of a new oscillation presupposes the continuity of the originating cause or its reappearance which may be in advance or after an entire period (27-31). Any method of period analysis requires the continuity of the investigated wave train. If it is lacking, the data will have to be averaged with inevitable "lengthenings" and "shortenings", so that the results are frequently far from reality. For these reasons I think that Kasumovic's mean value of observations (22.7 ± 0.8 hours) gathered with other methods, deserves more trust.

Owing to the way in which it happens, also the wave of about 12 hours is subject to quick attenuations as soon as the perturbing cause fails to appear, although to a lesser degree than the wave of about 22 hours.

Even more limitated parts of the Adriatic are capable of sizeable natural oscillations (figs. 1-6). Thus, when a weather perturbation moves from West to East and crosses the High Adriatic, the Gulf of Trieste becomes subject to a free oscillation at a rhythm of about 3.5 hours, as I could prove in 1937. When the energy of the perturbing force is sufficient, the level variation of the Gulf of Trieste changes into a natural oscillation of the Gulf of Venice as a cross oscillation of the High Adriatic (²). It always takes part in the big weather events. As the first maximum is reached at Trieste, some 3.5-4 hours later the Venice tide is overlapped by an increase varying between 15 and 40 cms. Here one gets aware of a possibility of forecasting, and be it only partially, the high water in Venice (figs. 1, 4-6).

5. – EFFECTS OF DEPTH ON THE AMPLITUDE OF FREE OR FORCED OSCILLATIONS OF A BASIN.

After having examined the periods of the chief free oscillations of the Adriatic, we are now trying to fix the behaviour of the latter in the Gulf of Venice, that is in the part in which we are interested. To this end we have to remember some aspects of hydrodynamics.

According to the theory and to the observation of the natural oscillations of a water basin — provided the other conditions are equal — the amplitude of oscillations is always largest in the spots of lesser depth, and the diversity grows with the increase of the depth difference at the two extremes (in the case of closed basins). This explains why, for instance, the uninodal of the Lake of Caldonazzo has an amplitude twice as large in the extreme North (San Cristoforo) than in the South (Lido of Caldonazzo) (³⁰·⁵), why the uninodal of the Lake of Levico is four times as large in the North than in the South (²⁶·³⁰) and why the amplitude in the Lake of Albano is about five times as large in the East than in the extreme West where the depth is considerable (³¹). This effect becomes most spectacular with artificial basins created by damming the Alpine valleys. Therefore the fundamental free oscillations next to the dam have always considerably lower amplitudes than the ones observed at the end more upstream of the dam.

Let us consider the case of the Adriatic. This sea may be roughly considered as having been built up by two consecutive concavities, one of limited depth in the North (except the meso-adriatic ditch of little extension) and one of over 1,000 m depth in the South (fig. 8-9). The boundary-line between the two basins may be seen roughly the jointing-line Vieste-Ragusa, as around this line the sea depth falls almost abruptly from 200 to 1,200 metres (fig. 8).

That being stated, we are now considering the *free oscillations* of a basin made up by two such concavities. In order to block out the problem we imagine a channel limited by two vertical walls $x = -b$, $x = +b'$ and with a step-shaped in $x = 0$. The depths in the two sections are indicated by h and h' (fig. 10); they are considered rather small in comparison to the wavelengths.

We have to find a function φ of x, y which satisfies the condition (Poincaré, l.c., page 90)

$$\frac{d^2\varphi}{dt^2} = gh\,\Delta_2\,\varphi$$

where Δ_2 is the Laplacian of φ.

Since φ is always proportional to $e^{\lambda t}$, where λ expresses the wave-pulsation, we may write for the free oscillations

$$\lambda^2\,\varphi = gh\,\Delta_2\,\varphi. \qquad [11]$$

Referring to the basin's deep part, we put

$$\varphi = Ae^{\lambda t}\cos i\lambda a\,(x + b)$$

and will get

$$\frac{d\varphi}{dx} = -\,i\lambda a\;Ae^{\lambda t}\,\sin i\lambda a\,(x + b);\;\frac{d^2\varphi}{dx^2} = \lambda^2 a^2\varphi;\;\frac{d\varphi}{dy} = 0;\;\frac{d^2\varphi}{dy^2} = 0.$$

The condition $\frac{d\varphi}{dx} = 0$ for $x = -\,b$ is satisfied. Besides, $\Delta_2\,\varphi = \lambda^2 a^2\varphi$.

From equation [11] we get therefore

$$a = \frac{1}{\sqrt{gh}}\,. \qquad [12]$$

For the less deep part, provided

$$\varphi = A' \, e^{\lambda t} \cos i \, \lambda \, a' \, (x - b'),$$

after the boundary-conditions have been fulfilled, we get also

$$a' = \frac{1}{\sqrt{gh'}} \, . \qquad [13]$$

φ as a continuous function takes equal values at the one side of $x = 0$ and the other, from which follows

$$A \cos i\lambda ab = A' \cos i\lambda a'b'. \qquad [14]$$

Being $x = 0$, also $h \frac{d\varphi}{dx}$ must be continuous $\left(h \frac{d\varphi}{dx}\right)_{x=0} = \left(h' \frac{d\varphi}{dx}\right)_{x=0}$

It follows $haA \sin i\lambda ab = - h'a'A' \sin i\lambda a'b'$. [15]

Dividing equations [14], [15] by members one obtains

$$ah \operatorname{tang} i\lambda ab = - a'h' \operatorname{tang} i\lambda a'b'.$$

Therefore, for $h' < h$ is $a' \neq a$; and since for [12] and [13]

$$\frac{a'h'}{ah} = \sqrt{\frac{h'}{h}} \, ,$$

it follows

$$a'h' < ah.$$

In absolute value, we have therefore

$$| \operatorname{tang} \, i\lambda ab \, | < | \operatorname{tang} \, i\lambda a'b' \, |.$$

Since λ is imaginary (page 86), the arguments $i\lambda ab$ and $i\lambda a'b'$ are real; therefore, since the cosines decrease as the tangents increase, we have in absolute value

$$| \cos \, i\lambda ab \, | > | \cos \, i\lambda a'b' \, |$$

from which follows for eq. [14]

$$A' > A,$$

which means that the amplitude of the free wave results higher in the less deep part of the basin.

We are now examining the propagation of a *forced wave* along the above mentioned channel. As previously, we assume a depth h for $x < 0$ and one h' for $x > 0$, so that for $x = 0$ the depth turns abruptly from h to h' (fig. 10). In order to approach the problem of tides, the said depths are considered infinitely small in comparison to the wave length.

In the section $x < 0$ we are considering a wave propagating toward the positive x's. Hitting against the step-shaped $x = 0$, this wave suffers a partial reflection. In the first section the movement depends therefore on a function

$$\varphi = F(t - ax) + F_1(t + ax).$$

Since the equation of the motion is

$$\frac{d^2\varphi}{dt^2} = gh \frac{d^2\varphi}{dx^2}$$

we'll have in φ

$$a = \frac{1}{\sqrt{gh}}. \qquad [16]$$

In the section beyond the $x = 0$ step-shaped, we have the propagation of the residual wave

$$\varphi = F_2(t - a'x),$$

with

$$a' = \frac{1}{\sqrt{gh'}}. \qquad [17]$$

Through the continuity, in $x = 0$ it must be

$$F + F_1 = F_2. \qquad [18]$$

Besides, it is proved that for $x = 0$, also $h \frac{d\varphi}{dx}$ must be continuous, so that we'll have on both sides of the step-shaped

$$ah\,[F'(t) - F_1'(t)] = a\,h'F_2'(t),$$

where F' represents the derivative of F with respect to x. By integrating one obtains

$$ah\,(F - F_1) = a'h'F_2. \qquad [19]$$

Combined with equation [18], this relation allows to determine F_1 and F_2, once F has been assigned. On the other hand, from equations [16] and [17], it is deducted

$$\frac{a'h'}{a\,h} = \sqrt{\frac{h'}{h}}\,.$$

Therefore, for $h' < h$, from equation [19] follows $F - F_1 < F_2$, and therefore, for equation [18]

$$F_2 > F.$$

Thus, the movement takes place with an higher amplitude in the less deep part of the channel.

At last we are considering a *progressive wave* propagating along the same channel. For [11], the equation of wave propagation may be written

$$gh\,\frac{d^2\varphi}{dx^2} = \lambda^2\varphi \qquad [20]$$

where, in the deeper section (depth $= h$),

$$\varphi = B\,e^{i\mu x + \lambda t} + B'\,e^{-i\mu x + \lambda t}, \qquad [21]$$

while beyond the $x = 0$ step-shaped leading to the second section, on the prolongation to the first section (in our case represented by the Adriatic ditch which extends into the High Adriatic)

$$\varphi = B''\,e^{i\mu' x\,+\,\lambda t}. \qquad [22]$$

Moreover, from [21] one has

$$\frac{d\varphi}{dx} = i\mu\,(B\,e^{i\mu x} - B'\,e^{-i\mu x})\,e^{\lambda t};\ \ \frac{d^2\varphi}{dx^2} = -\,\mu^2\varphi. \qquad [23]$$

from [20] one gets then

$$-\frac{\mu^2}{\lambda^2} = \frac{1}{gh}\,.$$

From [22] results

$$\frac{d\varphi}{dx} = i\mu' B'' e^{i\mu' x + \lambda t} \quad ; \quad \frac{d^2\varphi}{dx^2} = -\mu'^2 B'' e^{i\mu' x + \lambda t} \qquad [24]$$

and therefore, for [20]

$$-\frac{\mu'^2}{\lambda^2} = \frac{1}{gh'}$$

so that

$$\frac{\mu}{\mu'} = \sqrt{\frac{h'}{h}}\,. \qquad [25]$$

The first continuity-condition requires that [21] and [22] become equal for $x = 0$; from which

$$B + B' = B''. \qquad [26]$$

The second continuity-condition, in correspondence to the step-shaped $(x = 0)$ leads to the equality

$$h\,\frac{d\varphi}{dx} = h'\,\frac{d\varphi}{dx}\;;$$

from [23] and [24] it therefore results

$$\frac{\mu}{\mu'}\,h\,(B - B') = h'\,B'',$$

whence for [25] and [26]

$$2\,B = B''\left(1 + \sqrt{\frac{h'}{h}}\right)$$

and, at last,

$$B'' = \frac{2\,B}{1 + \sqrt{\frac{h'}{h}}}\,.$$

Therefore, for $h' < h$ is $B'' > B$.

Consequentely *the wave propagating in the section of lesser depth has an higher amplitude than the one acting in the deeper section.*

In conclusion: A system of long waves, in whichever way it propagates toward the high Adriatic, reaches the Venetian coasts with a larger amplitude than that with which it had run through the Southern Adriatic.

6. – ON THE RESONANCE EFFECT IN A « HIGH WATER ».

We are now considering another cause of dynamic changes of the sea level, in connection with a variation of atmospheric pressure.

The Japanese H. Yamada, Y. Okabe and M. Kumazawa proved (32) that when a liquid intumescence — after a weather perturbation of invariable intensity advancing at constant velocity on the water surface — rises along an inclined bed and approaches the shore, *the high of the wave is all the higher the smaller is the slope of the bottom:* the sudden increase takes place when the pressure variation passes over the resonance point, which had been defined with respect to the water depth.

If $P = P(X)$, where $X = x - Vt$, expresses the intensity of the atmospheric pressure perturbation acting on the water surface on which it propagates at V-velocity (x defining, with $y = 0$, the mean position of the liquid surface), one has

$$h\,(x) = h_o \left(1 - \lambda \,\text{tangh}\, \frac{x}{L_2} \right),$$

where h_o indicates the depth in the point $x = 0$, λ is a constant, and L_2 the length of the area sloping down.

It is proved that the wave-resonance originated by the passage of the perturbation sets in exactly at the h_o depth, so that we get

$$\sqrt{gh_o} = V.$$

As the extension $2L_1$ of the perturbation ($-L_1 < X < L_1$) increases, we have obviously a growth of the area hit by the heavy-sea; and the more L_2 increases, the less inclined is the bottom slope between two fixed depths h_1 and h_2 (h_1 offshore, h_2 near the coast).

The surface and the bottom of the water are represented respectively by

$$y = \eta\,(x, t) \text{ and } y = -\,h\,(x).$$

If u is the horizontal component of the liquid velocity, the following differential equations have to be satisfied (33):

$$\frac{\partial u}{\partial t} + u\,\frac{\partial u}{\partial x} = -\,g\,\frac{\partial}{\partial x}\,(\eta + P)$$

$$\frac{\partial \eta}{\partial t} = -\,\frac{\partial}{\partial x}\left[\,u\,(h + \eta)\right]$$

After fixing the P — variation field

$$P = -\,P_o \left\{ 1 + \cos\left(\pi\,\frac{x - Vt}{L_1}\right)\right\} \text{ for } \frac{x - Vt}{L_1} \leqslant 1, \text{ (otherwise } P = 0)$$

the authors effect a series of calculations with the following starting data

$$P_o = 0.10 \text{ m},\ L_1 = 10 \text{ km},\ V = 15.3362 \text{ m/sec}$$

$$h_o = 24 \text{ m},\ h_1 = h_o\,(1 + \lambda) = 40 \text{ m},\ h_2 = h_o\,(1 - \lambda) = 8 \text{ m} \qquad [27]$$

where $\lambda = 2/3$. Since $g = 9.80$ m/sec^2, one has

$$\frac{V^2}{gh_o} = 1.00,\ \frac{V^2}{gh_1} = 0.60,\ \frac{V^2}{gh_2} = 3.00.$$

The results are summarized in two tables and two figures. We are interested here to present the figure which gives the variation of η, that is of the surface lifting, in L_1 as h varies (fig. 11). One notes the considerable effect on the amplitude of the wavy motion

$$m = V/(gh_1)^{1/2} = (h_o/h_1)^{1/2}$$

$m \rightarrow 1$ for both falling and rising values: the high water accompanying the low pressure increases as $m \rightarrow 1$, and, after passing over $m = 1$, constitutes the free wave behind the low pressure: it tends to swell as it moves up the sloped bottom, and it increases all the more the ampler is the original wave. The resonance effect becomes more accentuated when the conditions next to the state of maximum amplification reach their maximum extension before and after the resonance point, and therefore when the transfer from the subcritical to the supercritical point is reached over a wide bottom having as slight a slope as possible. Fig. 12 shows the results of calculations made with a computer of the University of Kyoto with the starting data [27]. The values of P, u and η at the time of $t = 0$ are reconstructed in (A), (B) and (C), respectively on time point zero (S.0). The thick lines in (B) and (C) show u (velocity of current) and η (elevation of surface) for appropriate time points. It is shown that *the maximum of high-water and the maximum current velocity occur when the perturbation approaches the upper end of the sloped bottom.*

The resulting from the action of the sloped bottom and of the resonance depth, is to be considered the only effect as the meaning of the slope and of the resonance depth one is not separable.

It is to be underlined, however, that *the more the slope of the bottom grades the more the amplitude of the elevation of the sea level increases.* Thus, the phenomenon of resonance does not take place in one single point. It is rather to be understood as a complex effect over a more or less large area. In part II (^{34}) of their work the above named authors show that the viscosity effect is negligible as far as resonance phenomena are concerned, and that furthermore the high water originating from a clearly larger dimensioned depression viewed with respect to the linear scale of the sloped bottom, does not provoke sizeable changes (v. p. es. fig. 5). At last they prove that the effects of the meteorological agents can only be expressed in terms of a gradient of atmospheric pressure. Thus, the influence of the wind [estimated, for instance, for the Adriatic by F. Stravisi (^{35})] may as well be included in the same calculation scheme. In other words, the same kind of approximate solution is valid for a meteorological perturbation taken as a whole.

We will see that the considered effect concerns very closely the Gulf of Venice.

7. – EUSTATISM AND OTHER CAUSES ACTING ON THE SEA LEVEL.

After the theoretical references of the previous numbers, we are now dealing again with the situation between earth and sea in the area of Venice. This situation depends on the motions of one or the other or — as usually — of both of them, so that the gradual increase or decrease of the level difference between reference-points on land and the mean sea level (*l m m*) is the result of the water and earth relative motions.

Generally speaking, the *l m m* is presently increasing on our planet. The reason is seen in the progressive increase of air temperature in the last century (at least until 1940) and in the consequently more intense ice-melting. This inherent increase, for which the term of "eustatism" is also used, has been estimated with a mean value of 1.1-1.2 mm/year for the last thirty years.

Such estimates are extremely delicate. They are chiefly based on tide gauge data: the tide gauge sites are, of course, under the influence of local perturbations which may disguise — as they really do — the course of the phenomenon under a worldly aspect. This gives rise to inevitable perplexities and downright contradictions.

In this regard it may be useful to call the attention on the results of a study by William L. Donn and David M. Shaw of the Lamont Geological Observatory (36) after which the sea level of the last century is connected to the behavior of air temperature. On the basis of studies by Willett (37) and carried on by Mitchell (38), a yearly whole temperature growth of 0.8°F (0.4°C) was in course between 1880 and 1940, with a worldly temperature growth in Winter of 1.2°F (0.6°C) in the same period (fig. 13, upper part). The lower part of fig. 13 shows an even larger annual temperature increase of 1.6°F (0.9°C) and one of 2.4°F (1.3°C) for Winter periods for the latitudes between 40° and 70° N.

Since the beginning of 1940 a new fact is observed: an inversion of thermic development. The moderate cooling off which took place after that year compensated by about 30% the temperature increase of the period 1880-1940.

Another climatic parameter became subject to a similar effect: the rain. A decrease of precipitations during the first 40 years of this century was ascertained, followed by an increase of raininess after 1940. This temperature behavior was reflected also on the sea levels. Donn and Shaw elaborated the observations of nine tide gauges stations on the U.S. Atlantic seabord. They divided them into two series, one from the beginning of observations in 1939 and the other from 1940 to 1960. They also calculated with the least squares method the rectilinear behaviour of each series for each station (fig. 14). All stations except Portland showed a trend to increase up to about 1940. After that year all the stations except Portland, Charleston and Galveston show a tendency toward a clear decrease of the rise of the sea level, although the rise went on in all nine stations. Portland is undoubtedly abnormal, Charleston furnishes incomplete data before 1942, while other stations are under the action of natural and occasionally artificial local factors. With the exception of Portland and Charleston, the mean rise of sea level with the other seven stations before 1940 amounted to 0.7 ft (21 cm) for a fifty year period. Between 1940 and 1960 the increase of sea level averaged 0.4 ft (12 cm) for a fifty year period, which represents a 40% decrease of the rising tendency. The thermic expansion of the surface layers of the Ocean (with a thickness of some 400 m) may account for about one cm only of the observed changes. The level increase is attributed *almost* entirely to the ice-melting in the higher latitudes, so that the temperature decrease beginning with 1940 resulted in a reduction of ice-melting which seems to give a reasonable explanation to the lessened degree of growth of the sea level.

As suggested by the above authors, it must be underlined, however, that the here reported values of the trend to rise *are not typical of the world's sea level and therefore cannot be attributed entirely to ice melting.* In fact, the elaboration of the tide gauge data from the U.S. Pacific coasts show a rise of sea level which is *about half of that observed along the Atlantic coasts.*

Therefore, a maximum of caution is required when forecasts on the behavior of eustatism are to be made, especially with regard to the present phenomenon of inversion of the wordly average temperature. The latter aspect appears to have been completely neglected in the elaborations of the experts engaged in finding solutions for the problem of Venice.

But these are not yet all the causes apt to contribute to the variations of the sea level. It was observed that the sea level of each hemisphere is high during its autumn and low during its spring ([39, 40]); according to a first conclusion, the principal change of the mean level is to be attributed to the variations of density in the Ocean (v. 9.3).

The atmospheric pressure has a tangible effect, too, which is stronger in high latitudes than in the low ones. Thus, in the Pacific as well as in the North Atlantic the effect on the variations of the level, temperature, salinity of the water is much less important than that of atmospheric pressure (41). This is shown, for instance, by fig. 15 which gives a comparison between sea level and behavior of atmospheric pressure along the Southern coast of Iceland.

Quite a different aspect is taken by the same phenomena at lower altitudes. A study on the variations of sea level at the Bermuda Islands showed (41) that the wave of maximum temperature in the Ocean progresses downward by some 40 m per month and reaches its deepest penetration at about 200 m in January and February. In the warmer months an upper thermocline of a mean depth of about 80 m gradually flattens as the thermic wave moves downward. A detailed work of calculations on data of temperature, salinity, density and dynamic anomaly (understood as correction by cms of the conversion of depths measured in real depths) has shown that fundamental isostatic variations take place only in the upper 2,000 ms.

A further complex inquiry (41) on the tide gauge observations made at the Bermudas from June 1954 to May 1962 led to the results summarized in fig. 16, which shows that for the Bermuda area the predominant effect is the so-called "steric effect", that is the change of level brought about by the deviations from the depths of normal pressures as a result of volume expansions.

Therefore, the results of research on the sea level near the Bermudas and near Iceland confirm previous conclusions gained from studies of the Pacific Ocean: the variations of sea level are attributable to a very large degree to the "steric effects" in low latitudes (connected to dynamic anomalies associated to the thermic wave) and to barometric effects in high latitudes. These conclusions are based on the contrast between the yearly zonal thermic condition in the oceans and the yearly pressure variations in the atmosphere.

This is not yet all. Other complications arise from the fact that even the Oceans are animated by free oscillations. The North Atlantic, for instance, shows considerable free oscillations of which recently the features of the first three gravitational modes with periods of 21, 14 and 11 hours respectively, and structures of one, two and three amphidromic systems have been studied.

It is true that the above described facts are attenuated in their effects if estimates cover more years. The remaining values are not easy to estimate. Besides, although these phenomena were ascertained for the Oceans, this does not necessarily mean they do not apply, to a more or less limited extent, to the inland seas, especially if they show features like the oceans, such as the Mediterranean (*).

It must be concluded, therefore, that the exact valuation, based on selection, of the sea level variations are anything but easy. Presently, every forecast is made more problematic by the inversion of the world's temperature as mentioned above.

Let us look again at the Adriatic.

On the basis of data reported by Mosetti [44] (Table I, page 246) I wished to determine the behavior of the *lmm* in the course of the last decades for some ports of the Dalmatian and Istrian coast (**). Figures 17,18 show in graphs the values of the *lmm* for Ragusa, Spalato and Buccari on the Dalmatian coast and for Pola and Rovigno on the Istrian coast. The straight dots-and-dashes lines were calculated after the least squares method. It is observed that the available data were too few and had too heavy deviations to allow secure approximations. The results are thus to be considered merely indicative.

For *Ragusa* a *lmm* mean annual increase of 0.74 mms could be found. For *Spalato* the mean annual increase was of 2.2 mms in the examined 14 year period (the strong analogy of the *lmm* behavior of Ragusa and Spalato between 1958 and 1967 is striking). For *Buccari* (in the Gulf of Quarnaro) the increase from 1950 to 1967 was 1.35 mms/year. For *Rovigno d'Istria* there were 2.3 mms of annual increase from 1955 to 1967. At *Pola* the observation period of tide gauges was longest, lasting from 1897 to 1921 (and resumed in 1962). Until 1921 the mean annual increase observed was only 4/10 mms.

(*) S. Polli [43], for instance, values simultaneous annual oscillations of the mean level of the Mediterranean Sea of an amplitude of about 11 cms, with maxima in November and minima in January.

(**) S. Polli determined the value of the century-old variation of sea levels for 11 Italian ports. The mean value of the variation for the Italian seas corresponds to an increase of the sea level of 16 cms/century against the 11 cms/century of all the seas of the world.

Evidently, the result of the calculations cannot afford sure conclusions, as without any doubt there are influences of local phenomena whose effects cannot be easily caught. On an average, however, it appears possible to state that the mean level suffered a major mean annual increase from 1954 to 1967 from Ragusa to Rovigno. To which extent are these results influenced by the "apparent" increase of the mean level to the strong dynamic variations of the sea level due by transient depressions caused, especially in the High Adriatic?

8. – SUBSIDENCE OF GROUND, BRADYSEISM.

8.1. After summarizing some of the reasons responsible for the increase of the sea level in the world, we come to the phenomenon of ground subsidence which is intimately connected to the apparent increase of the sea level at Venice.

A general phenomenon of subsidence appears to be attached to the Adriatic arc, at least from the Tagliamento river mouth to Ravenna; this subsidence is certainly active in the area of the Po delta, where it has reached exceptional proportions. Concerning the delta, the chief, if not unique, reason of the ground flexion was well detected at its time: the disorderly extraction of methane containing waters. I covered this argument exhaustingly in previous papers and would not repeat myself here ([46, 47]). We have to limit ourselves to the problem of our interest: Venice.

A trustworthy comparison of levelling measurements carried out in a defined area would require levelling lines expressly set up there, in possibly remote times and remeasured at regular intervals with the same methods and the same exactness. Such conditions did actually not prevail in the Venice area before 1970 ([48]).

The Italian Military Geographical Institute (I.G.M.) carried out some precision levellings in the last 100 years, the first begun in the last decades of the past century and finished in 1908, the second in 1925, a high precision line Genoa-Venice in 1942, a new fundamental altimetric network in 1952 and a high precision levelling in 1968, to which must be added the levellings carried out by private firms in 1961 and 1964, for the account of the "Magistrato alle Acque".

Thus the picture is one of heterogeneous surveys (as to precision and methods used) made in sundry times with *a scanty number* of common levelling-marks. Anyway, it is not my business to criticize the results.

I am limiting myself to report the comparison between the various levellings made at the levelling-mark of Punta della Dogana (Santa Maria della Salute). This may be summarized in the following results: between the 1942 and the 1961 levellings the mean annual subsidence (in a time interval of 19 years) was 3.3 mms; between 1961 and 1968 (7 years interval) the mean annual subsidence was 2.0 mms. The mean annual flexion between 1942 and 1968 were 2.9 mms. All measurements taken at levelling-mark Punta della Dogana are lying within an uncertainty band of over ± 1 cm.

The tide gauge measurements showed a mean annual increase of the *lmm* in the order of 1.2 mms, attributable to eustatism.

Concerning the comparison between the tide gauge data of Santa Maria della Salute and Trieste a difference of level was observed, with a clear and progressive increase for Venice, beginning around 1926.

The subsidence shows no signs of continuity or linearity: there was evidence of overlappings of obvious ondulations. It must be emphasized, however, that the Lagoon tide gauges have no sufficiently long observation series to enable them to deduct the possible periodicity of the overlapped waves and their fundamental characteristics (49). Thus, the comparison with the altimetrical results is only one of first and rough approximation.

Anyway, on the base of altimetric and tide gauge observations, it appears possible to conclude that the subsidence in the last 40 years (1929-1967) for the area of the Centre of Venice-Marghera is in the order of 2.7-3 mms per annum. The subsidence movement appears to have set in between 1925 and 1930 and is still in course.

Owing to the above mentioned reasons, these results should be accepted with mental reserve.

These reserves concern, of course, all conclusions and illaticns drawn by starting from the above data, and among them the consideration of a total subsidence of the Venetian ground of some 20 cms since 1900. By accepting this date one was induced to believe that the effective high water, attributable to mere astronomical and meteorological reasons, would not become subject to appreciable increases in the last decades, which would lead to the conclusion that the increased frequency of the high water should be attributable to the progressive increase of the relative sea level, as the sum of the progressive inherent increase of the sea level and of the contemporaneous subsidence of the ground of Venice (50). Such a conclusion is doubtful, of course: a sum of uncertainties cannot bring forth a sure date (*). It is my conviction, supported by what I have to say further on, that the causes of the more frequent rises of high water cannot be limited to the two just discussed.

8.2. The results summarized in the previous paragraph, about which their very authors did not spare reserves, have met with ample opposition. According to some it is not trustworthy, due to the fact that three recent levelings attribute to the main point of the summit of the water gauge in the Calle Loredan (townhall of Venice) a subsidence represented by three different values:

Magistrato alle Acque	9.94 cms
Public Works Ministry	18.60 cms
Military Geographic Institute (IGM)	25.00 cms.

"The said discrepancies of over double and triple the first bradoseismic quantity are incompatible and thus indicate errors in the various levelings" (52). The author of this statement indulges in a detailed criticism of the main points chosen for the various levelings and of their more or less marked unsuitability as well as of the strident contradictions of their results (**).

To my belief, the most interesting part of O. Spagnuolo's work (52)

(*) G. Supino (51) makes some remarks on the method followed by Mosetti about the estimates of high water; among other things, he reproaches him to have taken into consideration the mean annual level of the year examined rather than — as would have been more correct — the "theoretical" sea level as resulting from the subsidence of the ground and from the rise of the sea. But even if Mosetti's determinations should be valid, according to Supino one cannot infer that the frequency of the effective high water did not grow during the past decades; such rise appears proved if one looks at the fact "that from 1914 to 1943 (that is in thirty years) there have been four high waters, whereas from 1944 to 1969 (that is in 26 years) there have been eleven".

(**) Certainly, I cannot interfere with these criticisms. I am only observing that as far as the bridge over the Crevada River is concerned (in the neighbourhood of Conegliano), the abutment on which the main point is mounted appeared restored at the end of November 1972. Besides, I note that the datum point of the I.G.M. leveling is at about 500 ms distance from the Crevada, at 0.50 ms from the Northeast corner of the building "Ristorante Nazioni Unite". I also underline the fact that this main point is on the immediate margin of National Highway Nr. 13 and therefore subjected to very heavy traffic movements, largely by heavy vehicles.

is where he refers the subsidence to elements of construction certainly connected with the mean level of sea water "such as the bridges linking the numerous islands of Venice to each other, the drinking water wells, the fortifications (...) and any other work, having a project date, or a date of actual building operations, which bears connection to the sea level and which should be retraceable with the State Archive or in the Venetian libraries" (l.c., page 34). The research done by the author led him to retrace drawings and building projects in archives and libraries which show, for instance, that the Ponte della Paglia bridge, built in 1360, was at the summit of the arch at a distance of "pie 8½" (l.c., page 35), that is about 2,96 ms from the "Comun dell'acqua" (mean sea level of that period). This value differs only little from the present one (*).

Very small differences are resulting for the Rialto bridge, the Ponte delle Guglie bridge and for other bridges, and the same conclusion is valid for the other century-old works such as the Forte di Sant'Andrea, the navigation basins (**), the Villa della Malcontenta, the rain water collecting basins as those of Campo San Trovaso, of Pellestrina etc. (***).

Notwithstanding, I think that a clearance of 10-15 cms may well be presumed between the old and the present sea level, although a part of the sinking of the construction items must certainly be attributed to the inevitable subsidence of buildings of several centuries of age such as bridges, forts, columns and other works bound to sink more or less into the supporting ground.

(*) Spagnuolo translates 8,5 Venetian feet into 2,80 ms, which suggests that he considered the Venetian foot inferior to the size of 0.348 ms which is commonly used.

(**) Concerning the old navigation basins between lagoon basins and ship canals on land, Spagnuolo points out that they functioned regularly. "After four hundred years of existence those impressing hydraulic works are still in perfect working conditions" (l.c., page 49).

(***) A particular upon which the author of the above work calls the reader's attention regards the two large columns rising on the Piazzetta di San Marco, at the basin's margin. These columns were erected in 1172 and "always remained at the same level of their erection as can be proved by examining the old prints showing the Basin of St. Marc" (l.c., page 57). If I am right, some experts tried to explain the unchanged altimetric value maintained by the columns for eight centuries from the "backflow of the ground under the bulk of the buildings of the Library of the Doge Palace" (l.c., page 57). I hope this is only a controversial sally.

Without denying the subsidence in course, other scholars contest its officially admitted value, partly on the grounds that some local subsidences caused by digging deep canals (such as the collapse of part of the Fort of Sant'Andrea) or by erosion or other casual causes "are often presented as saggings of the whole lagoon basin" (Pisenti and Rosa Salva (53), page 10). Without excluding subsidence phenomena, the mentioned authors affirm that they are present to a much lesser extent; if the suggested values were true, many several centuries old bridges would be unserviceable since long.

In any event, even if the subsidence of the lagoon ground cannot be denied (with its actual amount probably inferior to the one suggested by some experts), one fact should be, according to me, strongly underlined: the said subsidence tends to increase toward Chioggia, reaching exceptional values at Porto Corsini. In 1967, in the preface to my work on the phenomena of abnormal subsidence around the Po Delta I wrote: "It should not be forgotten that within the area subject to a subsidence reaching at some spots 3½ ms in less than a decade, there are towns like Venice and Ravenna, where in the course of recent years the underground is suffering flexions which may be defined abnormal" (46) l.c., page 332). And since the subsidence of the Delta Region was attributed as early as 1958 to the disorderly extraction of methane containing waters out of underground layers, I added (l.c., page 398): "The effect of the extraction which is more than obvious in the area where the drills were brought down may easily extend to a certain distance from the extraction sites. In this regard it should not be forgotten that the flexions brought about in Long Beach after oil had been extracted reached out considerably to some bordering areas and made themselves felt also in the -Los Angeles area, at about 40 kms distance (...). At about 16 kms distance from the area of maximum flexion (Ca Vendramin), the subsidence observed between 1951 and 1963 was about 35 cms, having reached the value of as much as 20 cms from 1958 to 1963 in only five years, three of which *after* the 'milkings' had been stopped. It should be borne in mind that 15 kms North lies Chioggia, and Venice at about 35 kms from Porto Caleri...". I concluded that, should those correlations be considered daring, I would be glad if my error could be proved. I repeated the same conceptions in 1970 (47).

Regarding the growing subsidence from Venice to Chioggia and to Porto Caleri, a few years after having published the above considerations an expert wrote [(44), page 253]: "The fact that Chioggia subsided more than Marghera and Venice and that Porto Corsini presents still stronger motions, would suggest that at least one of the hypocentres of the subsidence is situated in the area of the Po Delta. Besides, the subsidence of the Delta has already been proved by precision levellings, apart from tide gauge data".

This confirms my repeated previous declarations, which had fallen on general indifference or denial (47).

To conclude these short notes, it may be observed that the opinions concerning the stability of the underground of Venice and its lagoon are most divergent, ranging from those which deny flatly any, even the slightest bending to those which consider subsidences of such proportions as to suggest the submergence of Venice under the sea level within a few years (*).

9. – GROWING FREQUENCY OF "HIGH WATERS" AND ITS INTERPRETATION.

9.1. There is no doubt that the subsidence is happening; maybe it is exaggerated in one direction and in the other, so far as the extent is concerned.

As a matter of fact, unfortunately, the "high water" days in Venice are alarmingly increasing. Speaking only of the last decades, the tides of over 110 cms pass from the 2 high waters of the 1916-1926 period to 8 between 1927 and 1936, to 3 from 1937 to 1946, to 10 in the decade 1947-1956 and to 29 in the decade 1957-1966, with a trend to further increase in the following years. If one takes into account the levels over 70 cms, one passes from the 164 cases between 1964 and 1966 to 197 from 1966 to 1968 and reaches the maximum frequency of the unprecedent 295 cases between 1968 and 1970 (Pisenti, Rosa Salva, l.c., pages 9 and 10).

I am now calling your attention on a detail to which I attribute much importance. Generally, the graphs of sea levels are redistributed on continuous curves. I think that in this order of examinations such a procedure tend to disguise the abrupt variations in the behavior of the inquired phenomenon. In their above said work the Americans

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(*) P. ex. according to some the sinking (for geological reasons) was about 1 mm/year in the last 1 800 000 years, followed by 5-7 mm/year of the last lustrums after the water-fold reduction; if one adds the rise of the sea level by eustatism, Venice should now be floating with in anybody knowing it.

Donn and Shaw (36) prefer to average along straight lines with the least squares method. Such a procedure, if applied for instance to the diagram of mean levels recorded at Punta della Salute (fig. 19) with respect to 1935-1950 and 1951-1969 respectively would reveal a solution of continuity in the tendency of the phenomenon of high waters around the year 1950.

Moreover, this solution of continuity in the behavior of the *l m m* around the year 1950 may also be observed in other ports of the West coast of the Gulf of Venice. We consider, for instance, the behavior of the annual *lmm* of Porto Corsini South of the Delta, as resulting from the observation data for the 1934-1967 period [(44), page 246], reported in fig. 20. One notes clearly the abrupt leap of the tendency to rise, around the year 1950.

But a discontinuity around that period becomes evident also from other studies. In particular, Ing. Paolo Pirazzoli (54) based his research on the yearly *l m m* elaborated by the Hydrographic Office of the "Magistrato alle Acque" of Venice on the basis of the tide gauge recordings of the period 1871-1968, that is from 1871 to 1906 of the data recorded by the tide gauge of Campo Santo Stefano, and from 1906 onward of the data of station of Punta della Salute. The data appear rather scattered, but on the whole they show a tendency to increase (fig. 21). In order to eliminate overlappings attributable to particular meteorological conditions, errors or other casual reasons, Pirazzoli chose a certain filtering operation by replacing every annual value of *lmm* by "the average of a certain number of consecutive values of which the given value is the central element". The results are summarized in the first two figures of the mentioned work. The author notes that "on the whole it may be observed that the curves of mean currents present the following common features: a period with small oscillations around a rather constant value (until about 1890), a period of growth almost linear between 1890 and 1910 approximately; a period with important oscillations around a tendentially growing value between 1910 and about 1950, another almost linear growth period beginning from 1950 forward" (l.c., page 3). The obtained curves were then replaced by a line made up by sections of straight or parabolic lines, after which the parameters of the various sections were calculated with the least squares method after the points of discontinuity had been chosen.

It will be noted that in all cases the year 1950 constitutes a point of discontinuity. The superimposed oscillation, too (fig. 21), shows a strong regain of the sea level toward 1926, attributed by Pirazzoli to the industrial comeback of Porto Marghera, but the true discontinuity clearly marked is that around 1950.

We remember that, beginning with that date, there were the abnormal ground subsidence phenomena brought about in the Po Delta region by the disorderly extraction of methane containing waters and that in November 1951 there was one of the strongest floods of the Po in the last centuries.

We have to stop for a certain while on these events as they are intimately connected with the alarming frequency of high waters in the Venetian lagoons (*).

9.2. *Epeirogenesis and sand-filling in the High Adriatic. The West coast subsidence and its consequences.*

As was recalled above, after a long flood period, the Po River broke its banks in autumn 1951 in the neighbourhood of Occhiobello and flooded into a large area of the Delta. It reached the sea over a large front. In the long period of high waters and floods, which was the common feature of all rivers flowing into the Adriatic, an very large amount of turbid and eroded material was dragged into the sea, the equivalent of which is normally conveyed only in *tens of years.*

This has certainly contributed to accentuate the difference between the mean depths of the Low and the High Adriatic and to increase abruptly the natural tendency toward a conversion of the periods

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(*) Periodical analyses of the series of sea levels of some Italian ports have been attempted. S. Polli applied the cymanalysis to a fifty year series of Trieste (1890-1942) and to a seventy year series of Venice (1872-1941) [55]; he obtained components of 22; 11.3; 8; 5.5; 4; 3; 2 years. The wave of 22 years, which is common to almost all climatic analyses previously made by others, corresponds to twice the cyclus of sunspots and is considered by many authors as a fundamental cycle. It would be followed by harmonic cycles of 11; 7.5; 5.6 years.

A spectral analysis of the data pertaining to the *l m m* of Porto Corsini, Venice, Genoa and Trieste was successively carried out, after the Fourier method, by Caputo and others [56]. The annual periods found for all tide gauges were 20.0; 12.5; 8.3; 6.7; 4.0; 3.4.

of the forced and of the free waves to common values, which resulted in an increase of amplitudes of the "high waters", provided the meteorological perturbations remain unchanged.

But, going further back in time, we find another clear coincidence between large floods and following "high water" increase. 1926, 1927 and 1928 (as well as 1951) were years of large floods of several North Italian rivers [(57) Table I]; particularly, the major floods of the Po in the present century were, besides the above said of 1951, those of May and November 1926 [(57), page 163]. Beginning with 1927 the frequency of high waters increased rapidly and caused the simultaneous apparent increase of the mean level. In Venice [(59), page 7] the tides of equal or higher level than 1.10 ms over the *lmm*, which between 1884 and 1926 had been only three, rose abruptly to 10 in the 12 following years between 1926 and 1938. To impute local changes to industrial settlements in the Marghera area would be rather off the point, firstly because the beginning of those settlements was modest as it continued to be for many years (*), and because high waters accentuated at the same time also elsewhere, between Venice and Porto Corsini. It is my conviction that the principal cause is to be sought in the sudden unbalance between eustatism and tectonic bending (the latter to a much slighter extent) on one side and the action of slow sand filling due to abnormal affluxes of turbid and eroded materials on the other, with a clear advantage of the latter, and in the simultaneous growth of the interaction between atmosphere and hydrosphere (partly due to the lightening of the water as its salinity decreases), the meteorological perturbations being equal. The disappearance of high waters in the 1938-1947 decade (and the simultaneous apparent standing of the *l m m*) indicates that the above mentioned unbalance was decreasing with the return of normal turbid matter components, with the return of salinity and the persistent eustatism.

But the natural equilibrium was again broken in 1951 with the tre-

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(*) "Marghera was created and built on a limited scale. Later, in contrast with Volpi's sensibleness, the area was opened to new initiatives [(59), p. 98]". The expansion work began in 1919 and ended in 1935. It is to be noted that in 1922 there were 16 mills, while in 1955, when Giuseppe Volpi long since had been dead, the number had reached 180!

mendous November flood and the following sudden increase of sand filling in the high Adriatic.

And here I deem it suitable to revert on the struggle between earth and water in the Po Valley, a subject already covered in Nr. 2.

It is known that between one glacial period and another the Po depression passed repeatedly from the continental to the sea-condition.

However, it is to be observed — as writes P. Leonardi — "that with each return into the Po depression *the sea shallowed more and more and reduced its extent*, for despite of the progressive subsidence due to the sedimentary material compaction and to the still acting positive bradiseism in the coastal areas, the wandering swelled river of the Po Valley deposited, in the emersion periods, such an amount of alluvium that the Po Gulf was gradually filled up" (60).

This filling process of the High Adriatic gradually accentuated during the latest centuries in the course of regulation and damming of the rivers. Thus, the Po Delta advanced by some 25 ms a year (61) between the XIIIth and XVIIth centuries. Between 1600 and 1804 the growth was about 73 ms per year. "The difference is explained by artificial damming through which the major part of the suspended material which was first abundantly lost along the river beds was now carried along and kept in the current." (62). With further reference to the Po, Marinelli (63) calculated that the mean growth of the Delta in the seventy year period 1823-1893 was in the order of 0.762 square kms per year.

An estimate of suspended solid material, carried by the Po toward the sea and in various ways distributed on the sea bottom by the currents, was made as well. The amount varies, of course, with the climate and the seasons. Thus, in the period of ten years — from 1914 to 1922 not very rainy — the quantity of material suspended in the Po and carried off by it resulted to be about 17½ million cubic metres per year (64), whereas in the above said seventy year period Marinelli estimates that the mean annual deposit was in the order of 29 million cubic metres. To the suspended material carried off must be added, however, the dragged part, that is another 10% of solid suspended material.

Anyhow, assuming that every year the Po conveys about 30 million cubic metres of fine solid material toward the sea, a brief calculation shows that this is sufficient to cover an area of around 3,000 square kms (measuring about 50 × 60 kms) with a *1 cm* thick layer. The distribution would of course not be uniform, especially due to the currents.

But the Po is not the only river which flows into the High Adriatic, although the largest. Particularly the Venetian rivers from the Adige to the Isonzo carry their aggregate contribution of turbid material into the Gulf of Venice. According to the data published by the Hydrographic Office of the Magistrato alle Acque, the Adige, for instance, carried in 1933 suspended solid material, as ascertained from accurate turbid material measurements at Boara Pisani, in the amount of 1,096800 tons [65]. In other words, in one year the Adige carries, as a gross estimate, an amount of dissolved material into the sea which covers an area of about 100 square kms with a 1 cm layer.

This is not all. During the flood periods the afflux of material is enormously higher. For instance, when it is swollen, the Loira River carries a water amount of 312 times as much as normal. This relation decreases sizeably if a river flows through forest areas: the ratio is only 70:1 in the case of the Rhine River downstream the Lake of Constance (De Marchi, l.c., p. 247). At any rate it is always on the very high side. During a flood period a river is able to convey an amount of unbound material into the sea, which under normal conditions he conveys in tens of years.

In this way, the lifting up of the bottom of the High Adriatic by unloading of fine solid materials through the rivers flowing into it exceeds strongly the level variations caused by eustasism. Remaining the perturbing causes unvaried, the amplitude of the oscillations in the High Adriatic slowly tends to increase. This increase turns abruptly stronger with sudden flood waves (1879-1882, 1926-1928, since 1951). But the raise of the sea bottom brings about a still more insidious variation: the increase of the proper period of the stretch of sea subject to free oscillations, especially those of the High Adriatic. As it is known, remaining the other conditions unchanged, this period is approximately inversely proportional to the square of depth and grows as the latter diminishes. Since, for instance, the free wave of 11.8 hours is next to the half-day tide, even a very light increase of its period — being in the resonance zone — is apt to cause tangible increases of amplitude.

Beginning with 1951, however, two other reason have contributed to accentuate the high waters in the Venetian lagoons:

1) The more frequent repetition of the flood-waves in the Venetian rivers (*): Tagliamento and Livenza (February and November 1951, Oct. 1953, Dec. 1954, Nov. 1959, Nov. 1961 and the most violent of Nov. 1965 and Nov. 1966), Piave and Brenta (Nov. 1951, Oct. 1953, Oct. 1960, Nov. 1965 and the strong one of Nov. 1966), Adige and Bacchiglione (Nov. 1951, Oct. 1953, Aug. 1966 and the rather heavy one of Sept. 1960, Sept. 1965 and Nov. 1966). The data are taken from Piccoli's mentioned work, Table I. The progressive accentuation and frequency of flood phenomena with the consequent progressive increase of conveyance of material into the sea, as gathered from the Hydrographic Service of the Magistrato alle Acque, is attributed to the "recurrence of intense rainfalls in periods always closer to each other" (Piccoli, l.c., p. 157).

2) The beginning and the progressive accentuation until 1964 and later of the bending of the Delta area and, hence, of the opposite stretch to sea bottom, especially in the section Porto Corsini-Chioggia. For the reasons given under 6. this fact has created always better conditions of the amplification of free or forced waves propagating toward the coast.

9.3. *Consequences of sudden variations of salinity in the High Adriatic.*

Let us now consider another aspect of the physical conditions of the Northern Adriatic Sea which is linked to abnormal afflux of (soft) water: salinity. It is known that the saltness in the inner seas is the lower the smaller is their communication with the Ocean, the lower is their evaporation and the higher is the amount of river water. While for instance the salinity of the Red Sea is in the order

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(*) Concerning the filling action of the Gulf of Venice by the Venetian rivers in flood conditions (and thus concerning the higher hydrodynamic precondition of "high waters") I would recall that on the basis of data supplied by L. Dorigo [(68), page 7] a first group of "high waters" from 1879 to 1883 must be added to the periods from 1951 until today and from 1926 to 1938, so that in 1879 there was one of the strongest floods of the Po of the last century (Giandotti, l.c., p. 7). The autumn of 1882 was long remembered for the tremendous floods of all Venetian rivers, beginning with the Adige (Piccoli, l.c., pages 156-157).

of 45‰, that of the Baltic Sea is around 15‰, but it is well apt to fall under 10‰ in the Gulfs of Bothnia and of Finland.

The flood periods bring therefore further influences on the properties of the High Adriatic Sea. The enormous quantity of the water unloaded by the swollen rivers into the Gulf of Venice in the rainy periods apply deep changes to the salinity of the sea water. The reduced salinity carries with it, among other things, a reduction of *density*, of *molecular viscosity* and of *surface tension* (66). In other terms it makes the water *lighter and more fluid*. The extensiveness of this phenomenon concerns in the long run the whole High Adriatic, where the salinity is always considerably reduced after large floods (67). If the atmosphere influences remain unvaried (pressure variation in mms of mercury), the relation mercury/water is no longer 13.2, as with normal salinity, but tends to 13.5. The static level variation tends to increase, and be it only to a very light extent, but the increase becomes more appreciable on the *dynamic field*, when the trend is toward resonance conditions. In these cases (in which the static effect may be multiplied by ten to a hundred times) the decreasing molecular viscosity, density and surface tension may facilitate level increases in the order of several centimetres.

Furthermore, isostasy presupposes that per area unit on a conventional surface (compensation surface) acts a vertical column of equal mass in any point of the considered surface. Therefore, that column has a different height according to its density: it is higher if the matter is less dense and lighter. Pattullo (39, 40) proves that the major part of deviation from the mean sea level is a function of isostatic effects resulting among the sea pressure and density changes (or volumetric changes). These effects maintain a constant pressure on the compensation surface (which may be the bottom surface). In collaboration with E. Lisitzin, Pattullo proves that according to the results of tide gauge graphs recorded in the "International Geophysical Year" the seasonal variation of the sea level is chiefly *isostatic* (58), at least in the larger portion of the Pacific.

As recalled before, an accurate research work on the variations of the sea level in the Atlantic areas of Iceland and the Bermudas was conducted by Shaw and Donn (n. 7) based upon data of 1958-1962. Among the other results, a particular interest regarded the isostatic effect deriving from the "steric effect" (linked to the variations of the water specific volume) and from the barometric effect:

the "steric effect" is by far predominant (in its positive values) in the months around October (September-December), especially in the years 1955-1957 and 1961 (in September 1955 with more than 24 cms), as appears by the way also from the monthly averages of the entire period shown in fig. 16.

What happens in the High Adriatic during and after the great floods? The "steric effect", associated particularly to the strong lessening of salinity values, must reach considerable proportions and lead to a level lifting of several cms. A transition and compensation area on a subvertical layer is probably building up in these anomalous intervals toward the Middle Adriatic, between Pesaro and Ancona, where even in normal times salinity (for instance in the coastal water opposite to Fano) is lower toward NW and increases toward SE, as a consequence of the afflux of the waters from the Venetian rivers and particularly from the Po (69).

In the flood periods of the rivers flowing into the High Adriatic and in the closely following ones the "lightening" of waters due to reduced salinity may bring about rises of the sea level under the isostatic effect, and also prepare dynamic phenomena of amplification of water motions, remaining the other conditions unchanged. This explains why the years of major floods are also characterized by a higher frequency of high waters (*) marked in the last tens of years as a consequence of heavier rainfalls.

What is expressed in this paragraph may appear partly contrasting with par. 9.2, but it must not be forgotten that these waters are "lightened" and particularly suitable to suffer and to enhance the dynamic barometric effects; their *mass* is in any way that of the liquid layer of normal seasons.

10. CONCLUSIONS.

a) From what is observed under n. 5, and since the mean thickness of the sea in correspondence to the deep basin of the Southern

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(*) The opposite effect takes place, of course, when salinity grows after rainfalls are scarce and rivers carry little water. The density increase may be such as to cause "an effective contraction of the sea volume which may be controlled also through the permanently lowered sea levels with respect to the normal level" [Mosetti (67), page 4].

Adriatic may be considered constant, in view of the clearly larger extension of that basin and the minor afflux of turbid material from the small rivers flowing into it, in view of the gradually thinning out mean thickness of the High Adriatic, it follows that (the other conditions remaining unchanged) the amplitude of the slow movements of the sea — with forced or free waves — in the neighbourhood of the Venetian coasts is subject to a slow but continuous relative growth.

b) But the depth decrease of a basin (or of part of it) brings forth another consequence: ***the progressive increase*** (the other conditions remaining unchanged) ***of the period of the basin's free oscillations.***

As I said, the theory values the period as inversely proportional to the square root of depth. Therefore, a decrease of the mean depth of the High Adriatic provokes an increase of the period of natural oscillations of the said sea (*) which is all the more appreciable if the natural oscillation of 23 hours can be attributed — according to Oddone (21) — to the free movement of the High Adriatic considered as a gulf open to the large basin in the South.

In any case, the increase of the period of the free oscillations gives way to a very slow, but unavoidable approach of [10] to resonance conditions, especially as far as referred to the diurnal and semidiurnal tides (**).

(*) If the period of the uninodal free oscillations of the stretch of sea between the Venetian coasts and the line between the Tremiti Islands and the Island of Pelagosa is 11.8 hours for a mean depth of 60 ms, the period of the uninodal becomes 12.00 hours if the mean depth is reduced by 2 ms.

(**) Concerning the propagation of waves through the High Adriatic, the effect of friction on the sea bottom should also be considered. However, with the exception of narrow canals and of very long periods, it is extremely low.

Referring to equations [9] or [10], if we consider the λ_j corresponding to natural oscillations, in the case of friction they will be no more purely imaginary, but take a real part, always negative as the energy decreases. The roots in λ will be still imaginary, conjugated in twos, but no longer in twos equal and of opposite sign.

Let us look at the consequences. With forced oscillations we have $q_r = \varepsilon_r\, e^{\lambda t}$ which is a particular solution, while the general solution of the unhomogeneous equations is $q_r = \varepsilon_r\, e^{\lambda t} + \sum A_j\, a_{rj}\, e^{\lambda_j t}$.

The A_j's depend on the initial conditions. Applied to the tides, these

Moreover, it was observed on other occasions that in basins subject to forced oscillations there is a tendency toward the unification of the periods of such waves or of some of them with the periods of the free oscillations which the basin is capable to produce: uninodals, binodals..., or of some of them. In 1910 Oddone (70) proved by experiments that a basin is able to change its configuration until the creation of a proper period in the order of the one pertaining to the perturbing force.

As far as the Adriatic is concerned, it is certainly not fortuitous that the uninodal of about 23 hours is close to the daily tide and that the free wave of 11,8 hours (approximately) is in the order of the half-daily tide.

In its natural course, this process is undoubtedly very slow. It is true that the basin's period may be lengthened by the slow raising of the bottom through deposits of turbid material, but such lengthening may at the same time be contrasted by the advance of the shore line.

This equilibrium is in any case unstable, sometimes failing; they can be easily upset by slight changes of the participating forces. For instance, changes in the conditions of some rivers, caused by arti-

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terms disappear rapidly: as λ_i has a negative real part, $e\lambda_j t$ decreases constantly until zero: during the development of the tides, the movement due to free oscillations must be considered finite: there remains only the forced oscillation properly speaking.

Secondly, friction produces a light decrease of amplitude and a little phase displacement (11). We see, besides, a less perfect resonance. We have in fact

$$\varepsilon_r = \Sigma \frac{D_j}{\lambda - \lambda_j}$$

and the resonance is realized for $\lambda = \lambda_j$ which provokes the tendency toward the infinite of one of the terms which prevails therefore decidedly on all the others. Due to friction the resonance is no more as perfect. In fact, while λ is purely imaginary since the perturbing forces are essentially periodical, λ_j yet has one negative real part. Therefore, $\lambda - \lambda_j$ is never annulled.

Practically, however, the difference is not large, since the real part of λ_j is always extremely small as an absolute value, from which follows that $\lambda - \lambda_j$ can become very small, so that an almost perfect resonance is enabled.

ficial barrages, prevent an efficient counteraction by way of advancement of the beach without changing the slow reduction of the basin's mean depth by sand depositing, as in the specific case of the High Adriatic (*).

c) As was pointed out repeatedly, a vast part of the Polesine region, anyway slowly sinking down in itself, suffered considerable subsidences of over 3.5 ms in some places as a consequence of the disorderly extraction of methane-waters in the Delta area, begun in 1948 and continued up to 1960 and still in course in places hardly outside the Delta.

These sinkings have necessarily spread also to the coast area and to the sea bottom close to it (**). An analogous process due to concurring causes and in part to the same cause, took place on the High Adriatic coast from Venice to Ravenna (***).

Beginning with 1951, a progressive light decrease of the angle between the sea bottom and the water surface near the shore is thus going on along the West coast of the Gulf of Venice. Within the dynamics of slow sea-motions (linked to the transit of pressure va-

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(*) The amplitude of oscillations in the High Adriatic may become subject — the other conditions remaining unchanged — to an increase also for other reasons: the progressive restriction of the basin (26). This is what actually (though very slowly) happens, in spite of the acting bradiseism, with the advancement of the delta on a front of several tens of kms which is piling up on the sea (at the rate of some 70 ms per year in the phase of lobated delta) (71).

(**) This is proved by the isokinetics (from —20 to —70 cms/year) opened on the sea, but not only during the strenuous milkings, but also after their interruption in the delta area (isokinetics from —10 to —50 cms/year), with some still in course in 1967 [figs. 2-5 of (72)].

(***) Beginning in 1950, at Porto Corsini the annual frequency of high waters increases, certainly also on account of ground subsidence. This is proved by the observation that the high waters of over or equal to 1,00 m follow a curve of always higher frequencies, lower than that of Venice in the beginning, but turning steeper and steeper beginning with 1962 and surpassing widely the annual number of high waters observed in Venice. Thus, while from 1950 to 1961 (in a twelve year span) the number of high waters in Venice was 52 and at Porto Corsini 26, it rose from 1962 to 1969 — in eight years — to 66 in Venice and to as many as 144 in Porto Corsini [page 54 of (73)]. In a few years' time, hence, the frequency relation of the two places was inverted.

riations) this is translated into a relative increase of the motion's amplitude, pursuant to the theory put forth under N. 6, which says that resonance phenomena may take place in the propagation of a wavy motion toward the coast when the sea bottom falls slowly down with respect to it (*), and that such phenomena are the more large the more the sea bottom tends to flatten out parallel to the water surface.

The case observed by the Japanese (32) is summarized in fig. 12. From many points of view it seems to fit for the High Adriatic: in fact, the depths occurring are of the same amount. Also in the High Adriatic the transit velocities of weather perturbations, corresponding to resonance phenomena, are of the order of $\sqrt{gh_0}$ (for h_0 varying between 20 and 25 ms) (2). In two respects, however, the situation of the High Adriatic is definitely worse: 1) the case examined by the Japanese involves a (projected) distance of only 20 kms for the extreme depths of 40 ms and 8 ms, while in the High Adriatic the distance varies between 40 and 90 kms (75) (**), and presents thus a mean slope bottom clearly below that considered by the Japanese, which involves — the other conditions remaining unchanged — a much more accentuated amplitude of the liquid intumescence proceeding toward the coast; 2) with the aggravating circumstance of a

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(*) Of course, the slope may vary from one area to another. As far as the delta is concerned, for instance, a faster increase of depth from the coast toward the open sea is observed "in the offshore strip from Porto Caleri to Punta della Maestra. More precisely, while the isobates up to 15 ms maintain themselves more or less at the same distance from the coast, the isobates between 15 and 25-30 ms progressively go away proceeding from North to South. In fact, the 25 m isobate North of Punta della Maestra averages a distance of 6 kms from the coast, and in the South it reaches a maximum of 11 kms off Porto Volano" [Ciabatti (74), page 191]. This depends on the properties of the material flowing into the sea and on the action of the sea-currents. Thus, North of Punta della Maestra the deposits have a less fine grain than in the South, while the large sand area "develops toward North in a different nature and a coarser grain. This fact suggests that the water-ways North of the Po carry coarser material to the sea, of a different nature, even if toward South a finer material carrying by the subcoastal currents can be seen" [(74), page 208].

(**) On a front of some 100 kms the 50 m isobate is apart from the 40m one by 25-50 kms; the area between the two isobates may therefore be considered a wide horizontal plain.

progressive increase of the resonance effect as a consequence of the considerable sinking of the West coast since 1950, the other conditions remaining unchanged.

If we consider, for instance, the high water occurred in Venice between November 3 and 5, 1966, fig. 23 shows us that in those days the pressure variation was about 8 mm of mercury to which corresponded, as is shown by fig. 24, a lifting of the sea level of about 90 cms, that is about nine times the static value!

d) As expressed in N. 7, we have an inversion of the air temperature trend on the Earth since 1940, parallel to which an accentuation of weather phenomena, particularly of rain happened.

Although these important phenomena are not reflected in what has been written and said about Venice, it is a fact that the Magistrato alle Acque (Water control board) ascertained in the last decades always more frequent repetitions of weather precipitations in the area to the High Adriatic associated (N. 9.2); besides, the frequency and duration of winds was growing, especially the winds from SE-SSE (scirocco), as is proved by the fig. 24 published by Prof. Giordani Soika, Director of the Meteorological Observatory of the Ospedale al Mare (Lido) and taken from (48). More recently [1970, v. (73), page 55] Giordani Soika and D. Meneghini stated that "these variations, which have been more accentuated and more significant in the last fifteen years, express themselves in a heavy increase of the Bora wind in autumn (...) and in an increase of the Scirocco throughout summer and autumn". The authors believe that this brought about an increase of the seiches. In this regard it must be believed — as is explained further — that the intesification of the phenomenon of free (or forced) oscillations should not be attributed so much to the higher wind frequency but rather to the accentuation of their first reason, identified in the variations of atmospheric pressure.

At any rate, the accentuation of meteorological phenomena, linked to the inversion of the mean air temperature trend in the world since 1940, is accompanied by an accentuation of the causes of perturbations of the sea level in connection with weather events (*).

(*) Strictly speaking, in order to obtain a mean sea level that can be taken as a sure reference, this should be corrected from the alterations associated with atmospheric pressure, with wind, evaporation, temperature variations etc... not an easy task, indeed. The most sizeable alterations, This accounts for the interest of the studies of atmosphere and hydrosphere interaction.

It is still a widespread belief that the wind is a fundamental reason of the formation of free oscillations in liquid basins, either closed or open. It is often said that these oscillations appear when the wind suddenly mitigates its intensity, after having blown for a long time in the same direction toward a coast. If this cause really exists, it is altogether casual and anyway of a secondary effect. In the long years dedicated to the study and observation of this phenomenon, I was able to prove that the chief cause, if not the only one, of the free oscillations ("seiches") can be found in the gradients of atmospheric pressure. Quite often the transit of atmospheric pressure variations over a basin is accompanied by more or less high winds and it is owing to this coincidence that one prefers to attach to the winds a great importance to the developing free or forced oscillations. This importance, however, is chiefly the outcome of pressure perturbations; rather, sometimes the wind has a slackening effect on existing oscillations (30).

When pressure variations, even of minimum extent, pass over any kind of basins, of the most diversified shapes, dimensions and depths, they excite there coperiodical oscillations, proper of the basins themselves (5, 78) or forced oscillations (77), also if there is no wind (5) or if winds are very weak (figs. 1, 2, 3, 6). I had the opportunity to

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of course, are those linked to pressure, also because the wind is a consequence As far as pressure variations are concerned, in order to eliminate corrections or to reduce them to a minimum, one uses to report to mean decennial values. However, this is valid for *static* variations. In the case of air-sea interactions in the field of resonance, such corrections are no longer valid: in any case they will be insufficient. The fact that in two consecutive decades the atmospheric pressure averages vary of only tenths of millibars does not justify the conclusion that the *lmm* did not become subject to sizeable *dynamic* variations; when they are masked and *averaged*, they lead to *lmm* alterations which should not happen in reality. A dynamic alteration of the selected type in fig. 24 of an elongated form — moreover masked in a complex recording as per fig. 23, is only partially corrected in usual practice. If these alterations increase then in the course of time, as in Venice and Porto Corsini, the mean sea level (valued with traditional methods) is bound to be fictive and to change even more with time. It is therefore more appropriate to define the mean sea level of the past decades as a mean *apparent* level.

see this confirmed both in small closed basins and in wide seas. When the rhythm of pressure variation is very close to that of the free oscillations of the underlying water, the negligible baric gradients, in the order of fractions of *Torr* (and recordable, therefore, only with highly sensitive microbarographs), are sufficient to cause for lack of wind, large coperiodical movements in the basins (⁵). And such motions can happen with a very wide range of rhythms, with periods from few tenths of a second — which, if they take place on the surface of the two interacting media, may originate the microseisms (⁷⁹) — to very slow ones which are able to put in motion all the water of a big lake (such as the Garda Lake which in the Summer and Autumn months, after formation of the surface of the thermal-leap, oscillates for weeks and weeks with periods of about 24 hours, that is of his internal binodal excited by the daily coperiodical barometrical oscillation) (⁴).

Let us return now to the Adriatic.

In a recent study F. Mosetti, one of the most active and prolific experts of the so-called "Comitatone", Accerboni and Castelli looked into the influence of the wind on the lifting of the North Adriatic level by applying to that sea some models that had been already used by other authors on other basins (⁸⁰). The authors affirm that "the solution of the problem gives evidence of the lifting of the level as an effect of the wind and of the consequent appearance of the seiches with periods of about 21 hours, which are in perfect agreement with the observation" (l.c., page 18). The application to the rough sea of November 3, 4, 5, 1966, referred to Venice, is summed up by fig. 26. Its caption says "if one neglects the effect of the seiches with an about half-daily period, which have not been taken into account, a considerable correspondence of the two diagrams is noted" (l.c., page 29). Yet, this correspondence is only apparent. Mosetti himself proves it in another work (done with the collaboration of M. T. Carrozzo), published in the same number of the "Bollettino di Geofisica" (⁷⁶). In it a new, truly efficient method of tide analysis is presented. The application of this method to the heavy sea of early November 1966 led to the separation of the various components (fig. 24). The figure gives full evidence that *the high water at Venice is largely associated to the intumescence* which develops in approximately three days *as a consequence of the simultaneous reduction of atmospheric pressure and is enhanced by resonance phenomena*, prevailing the conditions set forth in N. 6. It appears as an elongation conforming to the recalled theory (fig. 12). As is shown by fig. 24, the principal intumescence is overlapped by an entire series of seiches. Clearly predominant among these are the half-daily ones, which develop with the characteristic of ample isolated impulses (typical of open basins), while the oscillations of about 22 hours, equally discontinuous, show limited amplitudes and overcame by the half-daily ones. In any case, the ones as well as the others are justified by the presence of coperiodical pressure variations, which is evidenced by the barometrical curve of Venice (fig. 23) (*).

Therefore, the pressure variations are sufficient to explain the phenomenon of high water in Venice, at least in its principal aspects. Moreover, the figure 23 shows clearly that the wind was subject to sudden changes of intensity and direction in several of the observation

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(*) That the wind is no determining factor in the formation of high waters is also proved by the other heavy seas if due consideration is given to the meteorological conditions in which they took place. L. Dorigo (^{81}) compares 11 high tides occurred in Venice (Punta della Salute) with the meteorological factors prevailing during them; April 16, 1936: high water 147 cms, pressure at tide peak 742,5 mms, wind 54 kms/h from SSW (with a strong seaward component) (fig. 27a); March 12, 1937: high water 119,5 cms, pressure at tide peak 752,0 mms, wind 66 kms/h from the 3rd quadrant, crosswise to the Adriatic; Dec. 5, 1946: high water 104 cms, peak pressure 746,8 mms, wind 24 kms/h from ENE; Dec. 9, 1946: high water 136 cms, peak pressure 741,8 mms, light wind, from the 3rd and first quadrants; Nov. 29, 1947: high water 126,5 cms, peak pressure 747,8 mms, very light winds (8 kms/h) from SSW; Jan. 27, 1948: high water 119,5 cms, peak pressure 750 mms, eastern moderate winds; Jan. 28, 1948: high waters 126 cms, peak pressure 742 mms, wind 20 kms/h crosswise to the Adriatic (WSW); Nov. 12, 1951: high water 151 cms (fig. 27b), peak pressure 742 mms, wind 48 kms/h from SSW; Dec. 24, 1958: high water 124 cms, peak pressure 746,8 mms, south-wind 18 kms/h; Jan. 15, 1960: high water 126 cms, peak pressure 750 mms, wind 34 kms/h from NE (thus tending to depress the *lmm*); Oct. 15, 1960: high water 145 cms, peak pressure 748,2 mms, wind 48 kms/h from SSE (actually, on the whole winds prevailed from the 3rd quadrant, moderate to almost strong; fig. 27c); Nov. 5, 1960: high water 123 cms, peak pressure 745,5 mms, north-wind 8 kms/h (fig. 27d).

The joint element of all these high tides is exclusively the low pressure. The generally light wind blew from the most different directions.

The water is the higher the deeper is the reduction of atmospheric pressure, and therefore, the higher is its gradient before and after the minimum and the closer it approaches to the resonance conditions. This was exactly the case on November 3, 4, 5, 1966 which may be considered, under such a standpoint, a limit case.

stations along the Adriatic West coast, so that its action gives rise to multiple solutions. That the seiches are not connected to the wind is proved by the fact that they are *not present when the wind falls* [as is affirmed in page 32 of (80)] but *before it* begins to blow from SE and when its local action is strongest, and that they reach maximum amplitudes in agreement with overcame coperiodical pressure variations and of abrupt inversions of the pressure behavior, due to phenomena similar to those shown in figs. 1-6.

As a matter of fact, the frequency of high waters in the Venetian Lagoon increased strongly after 1951. The sudden alterations of the sea bottom in connection with the large flood of the same year and of following years which tended to raise the amplitude of sea motions and to lengthen the period of free oscillations of the High Adriatic, the lifting of the water, due to reduced salt content, in flood periods which stimulated the intensification of water motions in the dynamic field, together with the reinforcement action following the sinking of the West coasts, both of which enhanced by meteorological perturbations, may well be summoned among the chief reasons of the alarming phenomenon.

In front of events of such grandiosity, the question should be raised up to which extent a limited work in the Lagoon may be able to counteract the heavy seas, when the latter appear with the amplitude proper to the open sea. The drama of Venice must be seen, therefore, in the whole of natural phenomena which cannot be easily controlled by man. Ignoring this aspect of the problem, would be equivalent to renouncing a priori on a solution, incomplete as it may be.

REFERENCES

See at page 229.