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Analysis of a storm surge in the Adriatic sea by means of a two-dimensional linear model

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Geofisica. — *Analysis of a storm surge in the Adriatic sea by means of a two-dimensional linear model.* Nota di FRANCO STRAVISI (*), presentata (**) dal Socio A. MARUSSI.

RIASSUNTO. — La mareggiata verificatasi nell'Adriatico nel novembre 1966 è riprodotta e studiata con un modello matematico bidimensionale, che comporta la soluzione delle equazioni lineari di storm surge per mezzo di uno schema alle differenze finite. Oltre all'innalzamento del livello marino per effetto del vento e del gradiente della pressione atmosferica, ed alla circolazione orizzontale del bacino, si calcola l'andamento dell'energia meccanica totale, il lavoro delle forze agenti, il volume e lo scambio di volume attraverso il canale di Otranto.

INTRODUCTION

In this paper the reproduction of a storm surge in the Adriatic sea is obtained by means of a two dimensional mathematical model leading to linear equations numerically solved with a difference scheme. The model is the same as has already been used in a preceding numerical experiment [7].

The conservation laws for the total mechanical energy, and for the total volume of the displaced water are checked.

The results obtained show the efficiency of the model used for the study of storm surges in the Adriatic.

THE STORM SURGE EQUATIONS

The vertically integrated linearized storm surge equations for an adjacent sea at mean latitudes are, in transport form:

$$\left\{ \begin{aligned} &\frac{\partial \eta}{\partial t} = -\nabla \cdot \mathbf{U}, &(1)\\ &\frac{\partial \mathbf{U}}{\partial t} = -gh\,\nabla \eta - \mathrm{K}\mathbf{U} + \mathbf{C} + h\mathbf{F}, &(2) \end{aligned} \right.$$

with the symbols:

η	sea level elevation from the surface at rest;
$\mathbf{U} \equiv \{\mathrm{U}, \mathrm{V}\}$	vertically integrated horizontal velocity (horizontal transport per unit section);
$\mathbf{C} \equiv f\{\mathrm{V}, -\mathrm{U}\}$	vertically integrated Coriolis acceleration;
$\frac{1}{2}f$	mean vertical component of Earth's rotation vector;

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(**) Nella seduta del 13 gennaio 1973.

K	constant bottom friction coefficient;
$\mathbf{F} \equiv \{X, Y\}$	external force per unit mass on the sea surface;
h	depth of the basin;
g	mean gravity;
$\nabla \equiv \left\{\frac{\partial}{\partial x}, \frac{\partial}{\partial y}\right\}$	horizontal gradient operator.

Sea water is assumed to be homogeneous and incompressible. The position and the extension of the basin are such that the convergence of the meridians is negligible, and the equipotential sea surface at rest can be approximated by an (x, y) plane, normal to a uniform mean gravity field and to the z axis, positive upwards. An appropriate right orthogonal set of cartesian coordinates is adopted accordingly, the storm surge equations (1, 2) being invariant for rotations around z. All the physical variables are functions of (x, y, t).

The external force in the transport equation (2) accounts for the wind stress and for the atmospheric pressure gradient:

$$\mathbf{F} = \gamma h^{-1} w \boldsymbol{w} - \rho^{-1} \nabla p_a , \tag{3}$$

with:

$\boldsymbol{w} \equiv \{w_x, w_y\}$	wind velocity near the sea surface;
p_a	atmospheric pressure;
γ	wind stress constant coefficient;
ρ	mean density of sea water.

A quadratic dependence from the wind velocity, and a constant coefficient γ are here assumed, as usual in this kind of computations.

Neglecting shore effects, the coast of the basin is approximated by a vertical rigid wall, with normal $\boldsymbol{n}$, at which the boundary condition:

$$\mathbf{U} \cdot \boldsymbol{n} = 0 \tag{4}$$

is applied. At the open end, a normal level is imposed:

$$\eta = 0 , \tag{5}$$

in the assumption that no surge propagates from the external sea, and that it has an infinite capacity.

The volume and energy equations

Integrating the continuity equation (1) over the surface S of the basin, making use of the divergence theorem and of the boundary condition (4), and integrating in time from the beginning $t = 0$ of the storm surge, the volume balance is obtained:

$$V(t) = V(0) + V_e(t)\,, \tag{6}$$

with:

$$V(t) = \int\limits_S \mathrm{d}S\eta\,, \tag{7}$$

$$V_e(t) = \int\limits_0^t \mathrm{d}t \int\limits_{\mathcal{A}} \mathrm{d}\mathcal{A}\,\mathbf{U}\cdot\boldsymbol{n}\,. \tag{8}$$

The actual volume of the basin, referred to the volume of the basin at rest ($\eta = 0$), is defined by (7); (8) is the volume of the sea water exchanged through the open end $\mathcal{A}$, with inwards directed normal $\boldsymbol{n}$.

Taking the scalar product of the vertically integrated momentum equation (2) by the velocity $h^{-1}\,\mathbf{U}$, integrating over the surface S of the basin, using (1) and (4, 5) and integrating with respect to time, the energy balance is easily obtained:

$$\mathrm{E}(t) = \mathrm{E}(0) + \mathrm{W}(t)\,. \tag{9}$$

The total mechanical energy, referred to the energy of the basin at rest ($\eta = 0$, $\mathbf{U} = 0$), is the sum of the potential and kinetic energy:

$$\mathrm{E}(t) = \mathrm{P}(t) + \mathrm{T}(t)\,; \tag{10}$$

$$\mathrm{P}(t) = \frac{1}{2}\,\rho g \int\limits_S \mathrm{d}S\eta^2\,, \tag{11}$$

$$\mathrm{T}(t) = \frac{1}{2}\,\rho \int\limits_S \mathrm{d}Sh^{-1}\,\mathbf{U}^2. \tag{12}$$

The total work:

$$\mathrm{W}(t) = \mathrm{W_F}(t) + \mathrm{W_K}(t) \tag{13}$$

is the sum of the work of the applied force $\rho\mathbf{F}$:

$$\mathrm{W_F}(t) = \rho \int\limits_0^t \mathrm{d}t \int\limits_S \mathrm{d}S\mathbf{F}\cdot\mathbf{U}\,, \tag{14}$$

and of the work of the bottom friction $-\rho\mathrm{K}h^{-1}\,\mathbf{U}$:

$$\mathrm{W_K}(t) = -\,\rho \int\limits_0^t \mathrm{d}t \int\limits_S \mathrm{d}S\mathrm{K}h^{-1}\,\mathbf{U}^2. \tag{15}$$

It must be noted that there is no energy exchange through the open boundary, because of the condition (5).

Assuming as initial conditions $\eta = 0$, $\mathbf{U} = 0$, i.e. the basin at rest for $t = 0$, it follows that:

$$V(0) = 0 \quad ; \quad E(0) = 0 . \tag{16}$$

The computation of the volume and energy functions (7, 8), (11, 12), (14, 15), along with η and $\mathbf{U}$, has a twofold purpose. Firstly, it is interesting to know their behaviour during a storm surge, since there is no way to deduce them from the observed data; secondly, equations (6) and (9) provide an extremely valuable check of the convergence of the numerical computations [5, 6, 7].

The difference scheme

The difference scheme, applied to the Adriatic sea, makes use of the grid shown in fig. 3 *b*. The η points alternate with the U points in the x direction, and with the V points in the y direction, so that two points of the same kind are $2\,\Delta x$, $2\,\Delta y$ apart.

The initial values η^0, U^0, V^0 are prescribed; then the η, U, V matrices are separately evaluated, in this order at the corresponding grid points, at the time $(i+1)\,\Delta t$, as follows:

$$\eta^{i+1} = \eta^i - \Delta t \{ D_x(U^i) + D_y(V^i) \} ; \tag{17}$$

$$U^{i+1} = (1 - K\Delta t)\, U^i - gh\Delta t D_x(\eta^{i+1}) + f\Delta t V^i + h\Delta t X^i ; \tag{18}$$

$$V^{i+1} = (1 - K\Delta t)\, V^i - gh\Delta t D_y(\eta^{i+1}) - f\Delta t U^{i+1} + h\Delta t Y^i . \tag{19}$$

The operators D_x, D_y indicate central differences in the x or y direction, i.e., at the grid point $(k\Delta x, j\Delta y)$:

$$D_x \equiv [\ ]_{k-1}^{k+1}/2\,\Delta x \quad ; \quad D_y \equiv [\ ]_{j-1}^{j+1}/2\,\Delta y .$$

In the case of no rotation ($f = 0$), equations (18) and (19) are independent; otherwise, the missing transport component in (18) and (19) is evaluated by an arithmetical mean from the four nearest points. The use of mean transport, instead of mean velocity components, represents the only departure from the model used previously [7], when the depth is variable.

At the coastal points, indicated in fig. 3 *c* according to the legend, the following boundary conditions:

$$U = 0 \quad , \quad V = 0 \tag{20}$$

are applied instead of (4), as discussed in [6]. The level η is computed again by (17), where D_x, D_y can now indicate also forward or backward differences, as required.

At the open end, the normal level condition (5) is prescribed. Furthermore, since the opening of the Adriatic sea at Otranto is rather narrow and deep, the transverse transport is also assumed to vanish. This is simply done in the adopted coordinate system, in which y has the direction of the flow at the open end, by putting for $y = 0$:

$$\eta = 0 \quad , \quad U = 0 \,, \tag{21}$$

$$V_{k,0}^{i+1} = (1 - K\Delta t)\, V_{k,0}^{i} - g \frac{\Delta t}{\Delta y} h_{k,0}\, \eta_{k,1}^{i+1} + h_{k,0}\, \Delta t Y_{k,0}^{i} \,, \tag{22}$$

with a forward difference for the y component of the gradient of η.

The energy and volume functions are computed evaluating the integrals (7, 8), (11, 12), (14, 15) by summation over the appropriate finite elements (fig. 3 *c*):

$$P^{i} = \frac{1}{2} \rho g \Delta S_{\bigcirc} \sum_{\bigcirc} [\eta^2]_{\bigcirc}^{i} \,, \tag{23}$$

$$T^{i} = \frac{1}{2} \rho \Delta S_{+} \sum_{+} h_{+}^{-1} [U^2 + V^2]_{+}^{i} \,; \tag{24}$$

$$W_{F}^{i} = \rho \Delta t \Delta S_{+} \sum_{n=1}^{i} \left\{ \sum_{+} [XU + YV]_{+}^{n} \right\} , \tag{25}$$

$$W_{K}^{i} = - K \rho\, \Delta t \Delta S_{\times} \sum_{n=1}^{i} \left\{ \sum_{-} h_{-}^{-1} [V^2]_{-}^{n} + \sum_{|} h_{|}^{-1} [U^2]_{|}^{n} \right\} ; \tag{26}$$

$$V^{i} = \Delta S_{\bigcirc} \sum_{\bigcirc} \eta_{\bigcirc}^{i} \,, \tag{27}$$

$$V_{e}^{i} = 2\, \Delta t \Delta x \sum_{n=1}^{i} \left\{ \sum_{k} \alpha_k V_{k,0}^{n} \right\} . \tag{28}$$

The α_k in (28) are suitable weights applied to the line elements $2\,\Delta x$; they are introduced to account for the real width of the open end of the basin.

The Courant–Friedrichs–Lewy stability criterion is a guide to the choice of the time interval Δt related to the given mesh sizes $\Delta x\,, \Delta y$. Once the Coriolis parameter f has been assigned, the stability increases with the bottom friction coefficient K.

THE STORM SURGE OF NOVEMBER 1966

a) *Analysis of the observed surge.*

The abnormal storm surge that occurred in the Adriatic sea in the first week of November 1966, is now described and discussed in order to compare the observed data with the results given by the mathematical model.

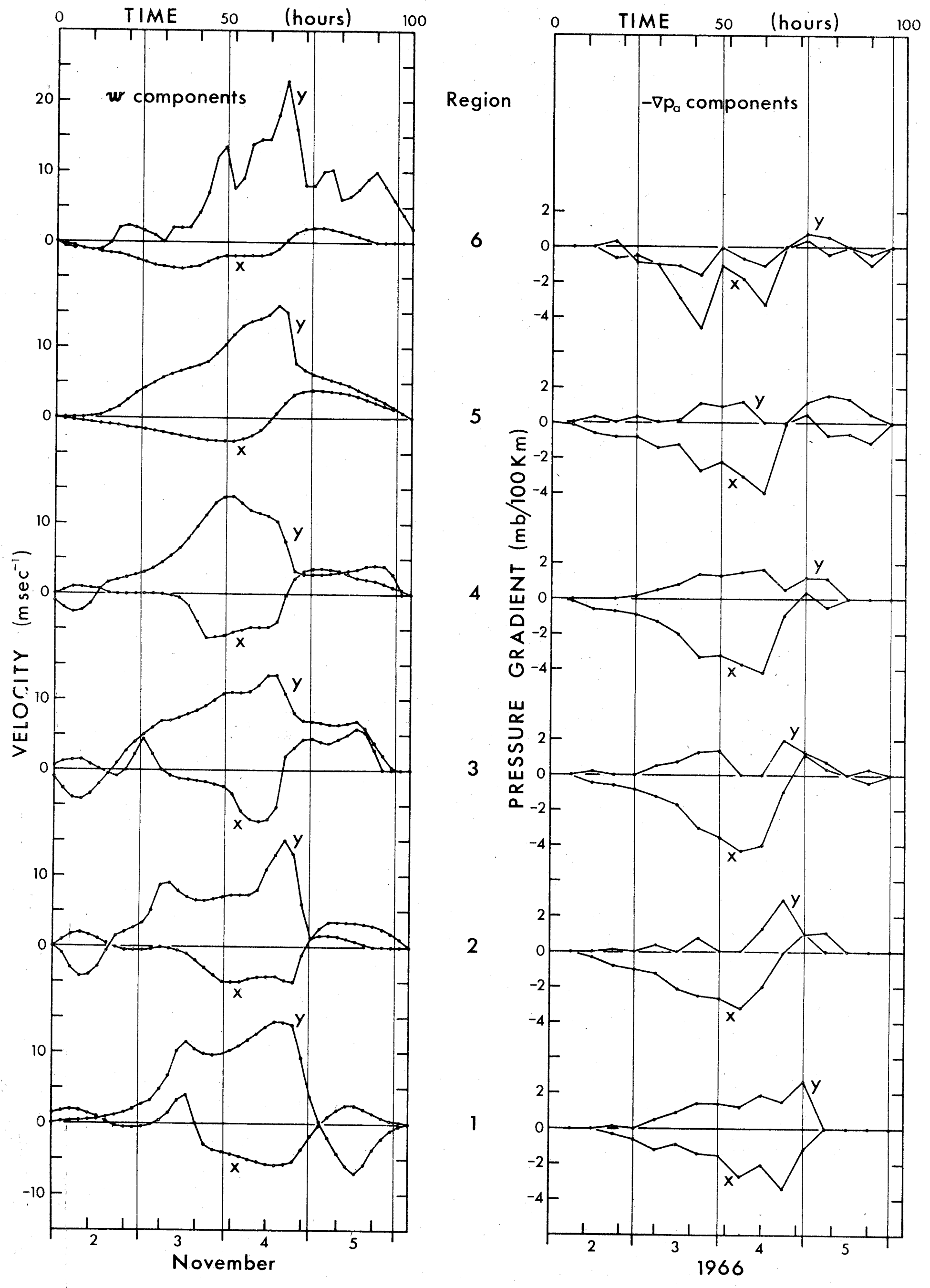

Fig. 1. – November 1966 storm surge in the Adriatic sea: wind velocity and atmospheric pressure gradient components (reference axes and region partition as in fig. 3).

The meteorological situation over the Italian peninsula is summarized by the weather charts reported in [11], which yield the wind speed and direction at several ground stations, and the isobars at the sea level, every six hours from 7^h of November 2 to 19^h of November 5 (C.E.M.T.). The wind records of Venezia, Ravenna and Brindisi are reported also in [1]. From these data, the wind velocity and atmospheric pressure gradient components have been deduced (fig. 1) for six regions covering the Adriatic basin (fig. 3).

The mean wind field acts along the principal axis of the Adriatic, and high velocities, above 10 m/sec, are reached and maintained for about 65 hours; after 18^h of November 4 the wind decreases rapidly and vanishes in one day. The horizontal pressure gradient is likewise directed along the same axis.

The sea level records at the harbours of Trieste, Venezia, Ortona, Manfredonia and Otranto are analyzed. The astronomical tide is computed with seven components (M_2, S_2, N_2, K_2, K_1, O_1, P_1), using the harmonic constants given by [4, 8]. The storm surge obtained by difference is shown in fig. 2, from 0^h of October 31 to 24^h of November 9; at each harbour, the mean sea level in the interval $0^h \pm 5^h$ of November 2 is taken as the reference level.

According to the previous knowledge about wind effects in a basin [6, 7], the mean sea level (fig. 2) follows the long period component of the driving force, and free modes are excited by the jumps of the force. When the wind stops, the accumulated water is released, and the free sea surface is restored through a marked series of damped seiches. These have been separated by means of the Vercelli filtering technique [9, 3]: the resulting mean periods of the first three seiches are 21.5, 11.2, 7.1 hours respectively; other periods are about 5, 4.5, 4, 3.5, 3, 2 hours. Assuming a damping factor exp $(-1/2\ Kt)$, the mean damping coefficient for the first and second seiche results in 1.1 and 1.7×10^{-5} sec^{-1} respectively. The amplitude of the first seiche, which is the dominant mode, decreases towards the open end; the surge at Otranto (fig. 2) is indeed rather small, and the hypothesis (5) is quite justified for the computations. The Coriolis force induces a counterclockwise rotation in the basin, which appears as a phase lag from Trieste to Otranto.

The Venezia record refers to a point (Punta Salute) inside the lagoon, so there is a delay of about 1.5 hours with respect to the open sea, because of channel propagation.

The barometric surge is still present in the graphs of fig. 2; it has to be eliminated before the comparison with the storm surge reconstructed in the model.

b) *The computed storm surge.*

The storm surge is reproduced by means of the model and the difference scheme presented in this paper. The grid used to represent the Adriatic sea is the same as in [7, fig. 1]: the mean depth is defined at each grid point

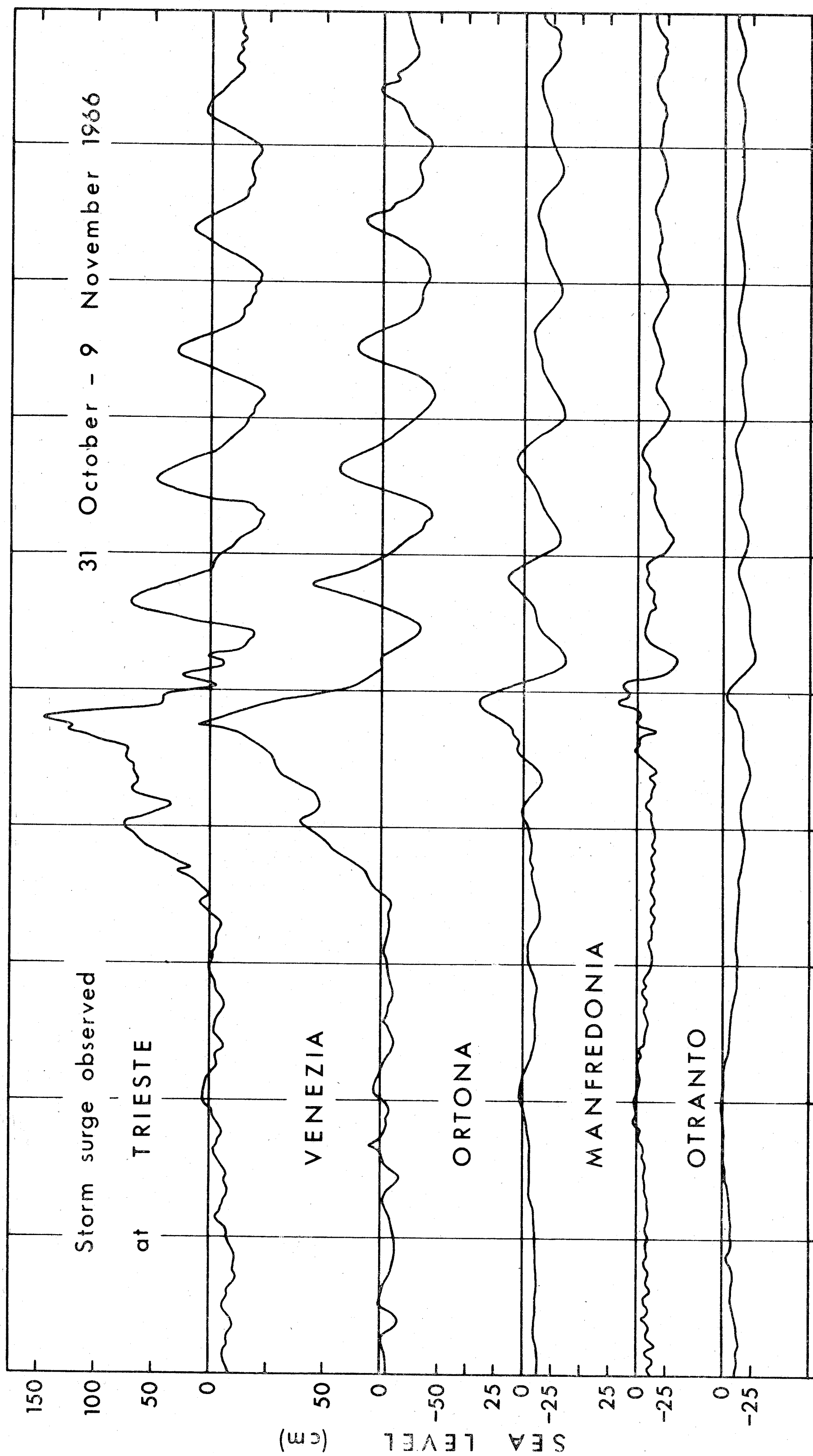

Fig. 2. – November 1966 storm surge in the Adriatic sea: observed sea level along the Italian coast, after removal of the astronomical tide.

(fig. 3). The state at rest is assumed at $t = 0$:

$$\eta^0_{\bigcirc} = 0 \quad , \quad U^0_{-} = V^0_{|} = 0 \, ,$$

since the real initial values are not known; the boundary conditions are expressed by (20, 21). The wind velocity and atmospheric pressure gradient components are given after fig. 1, every 2.5 and 6 hours respectively; at each time-step they are evaluated by a linear interpolation, and the force $\mathbf{F}$ (3) is computed after them.

It is known [2] that the vertically integrated storm surge models give lower elevation peaks, and this defect is accentuated in linear models (constant bottom friction coefficient K); to balance this deficiency, a higher value is used for the wind stress coefficient γ(3), and K is kept a little smaller than the observed mean value.

The following parameters have been used:

$$g = 9.8 \text{ m sec}^{-2}$$

$$f = 9.9 \times 10^{-5} \text{ sec}^{-1}$$

$$\mathrm{K} = 1.0 \times 10^{-5} \text{ sec}^{-1}$$

$$\gamma = 5.0 \times 10^{-6}$$

$$\Delta x = \Delta y = 20.6 \text{ km}$$

$$\Delta t = 3 \text{ min.}$$

The storm surge is followed from 0^h of November 2 to 24^h of November 6, for a total of 120 hours, i.e. 2400 time steps. Computations are performed on a CDC 6200 computer (Centro di Calcolo, Trieste University). A Fortran program provides the following outputs: (*a*) sea level every hour, and transport components every ten hours, for the whole basin; (*b*) sea level and transport components every 30 minutes at some grid points of interest; (*c*) sea level differences between the east (+) and west (—) coast, for five transverse sections (fig. 3 *a*); (*d*) potential and kinetic energy (23, 24), active and resistent work (25, 26), volume and volume exchange (27, 28), every 30 minutes. The computing time is about 80 seconds for 100 grid points and 1000 time steps.

The results are presented in figs. 4, 5, 6, 7 and 8.

The total potential energy of the Adriatic grows initially with time (fig. 4 *a*), reaching a maximum value of 11.8×10^{20} erg after 66.5 hours. When the wind force drops, the potential energy decays oscillating with a period of 10.8 hours, i.e. half the period of the first longitudinal free mode ($\mathrm{P} \sim \eta^2$). The total kinetic energy $\mathrm{T}(t)$ oscillates in antiphase; its maximum value (after 73.5 hours) is about 9×10^{20} erg, and the mean period is 10.7 hours ($\mathrm{T} \sim \mathbf{U}^2$).

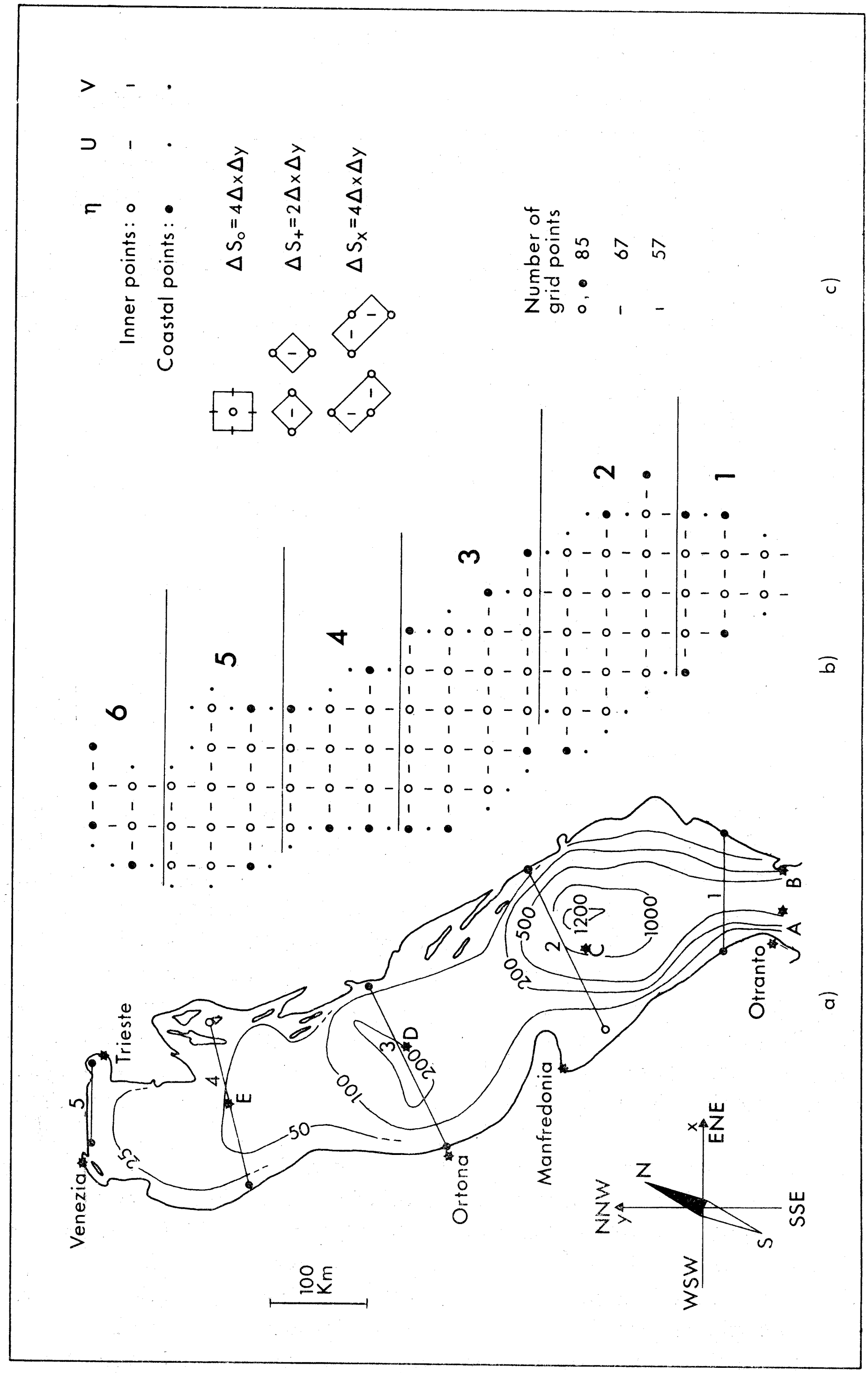

Fig. 3. – Adriatic basin with bottom topography (depth in meters), reference points and transverse sections (*a*). Grid points for storm surge computations, and region partition for the input data of wind and pressure (*b*). Surface elements for the computation of integral quantities (*c*).

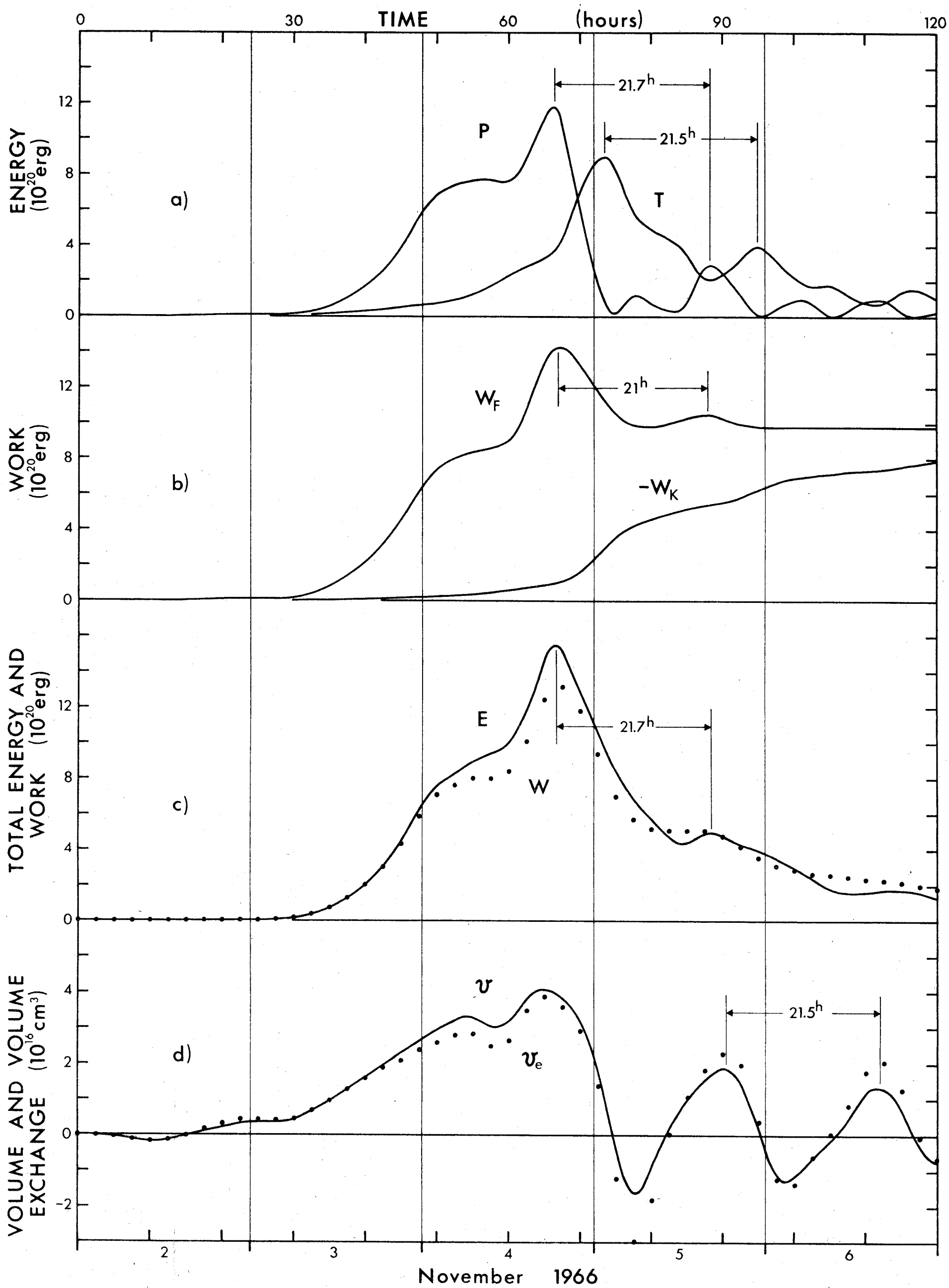

Fig. 4. – November 1966 storm surge computations: Adriatic potential and kinetic energy P (t), T (t) (a). Work of the meteorological force, $W_F(t)$, and of the bottom friction, $W_K(t)$ (b). Energy balance (c): $E(t) = P(t) + T(t)$ and $W(t) = W_F(t) + W_K(t)$. Volume balance (d): $V(t)$ is the actual volume of the Adriatic referred to the rest state, $V_e(t)$ is the volume exchanged through the open end.

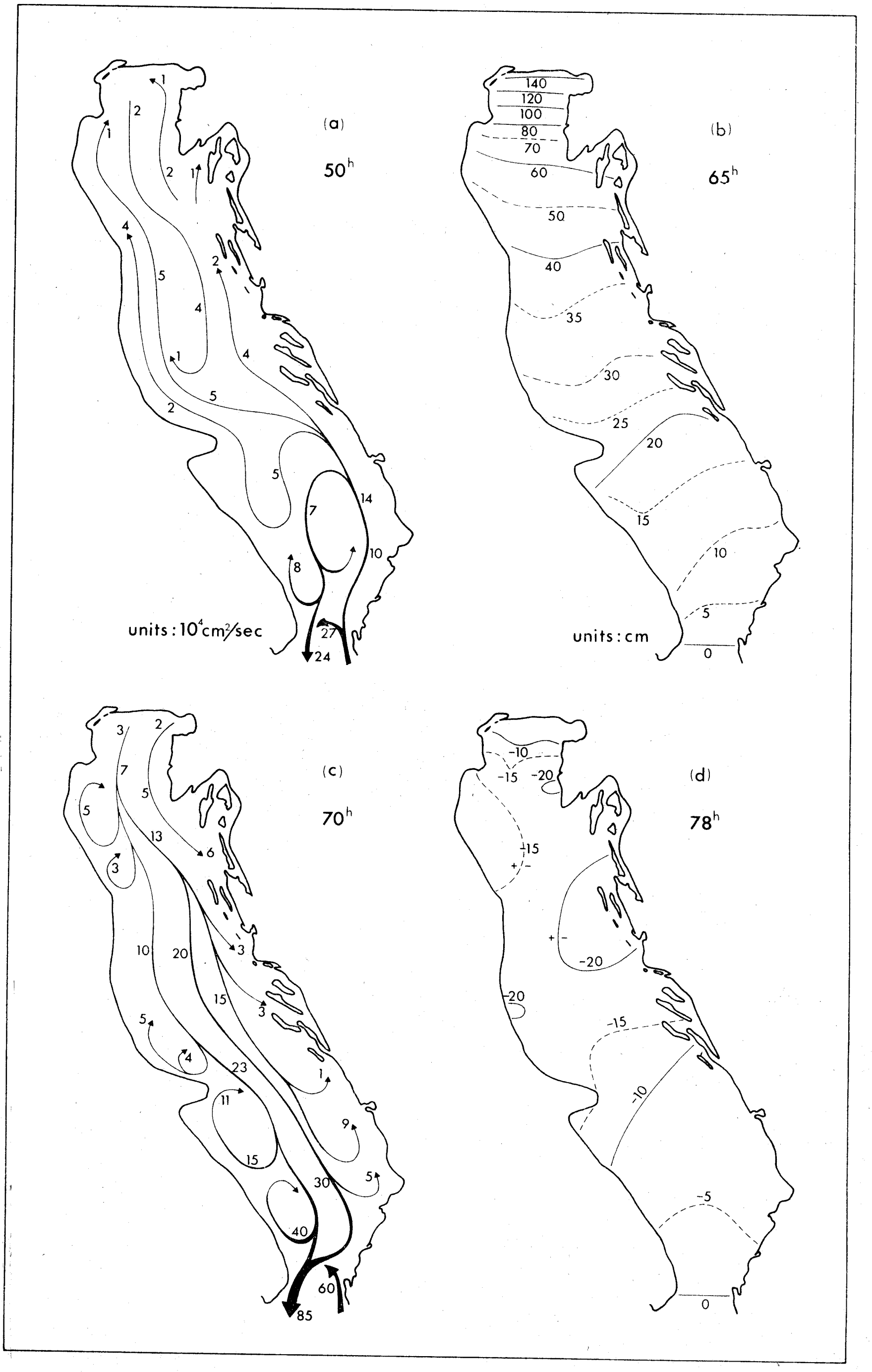

Fig. 5. – November 1966 storm surge computations: water motion in the Adriatic. Filling currents (*a*), equal level contours at maximum volume (*b*), outflowing currents (*c*) and equal level contours at minimum volume (d). Horizontal transport per unit transverse section is in 10^4 cm^2/sec; sea level elevations are in cm.

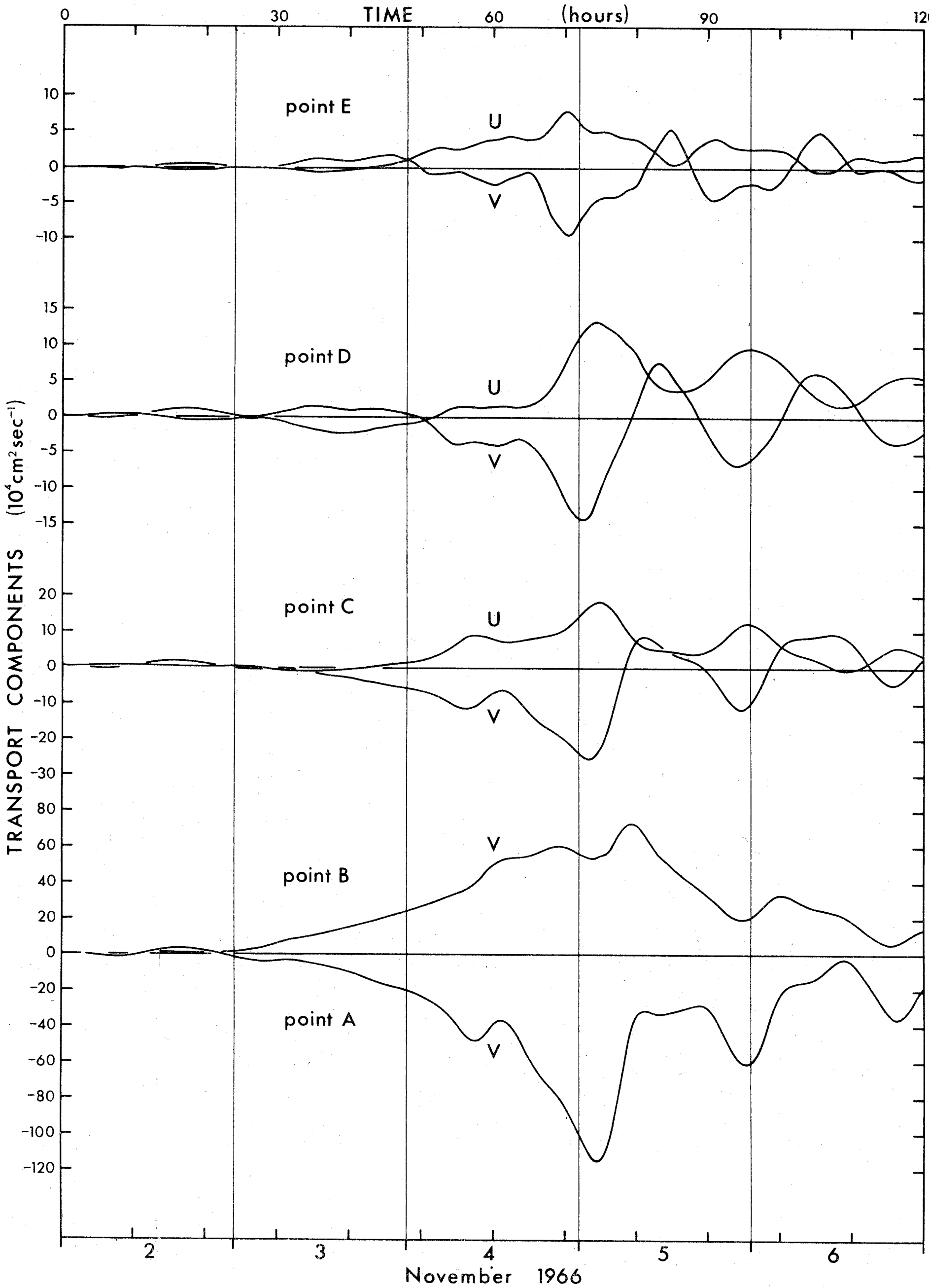

Fig. 6. – November 1966 storm surge computations: transport components U (t), V (t) at the grid points A, B, C, D, E (fig. 3 a).

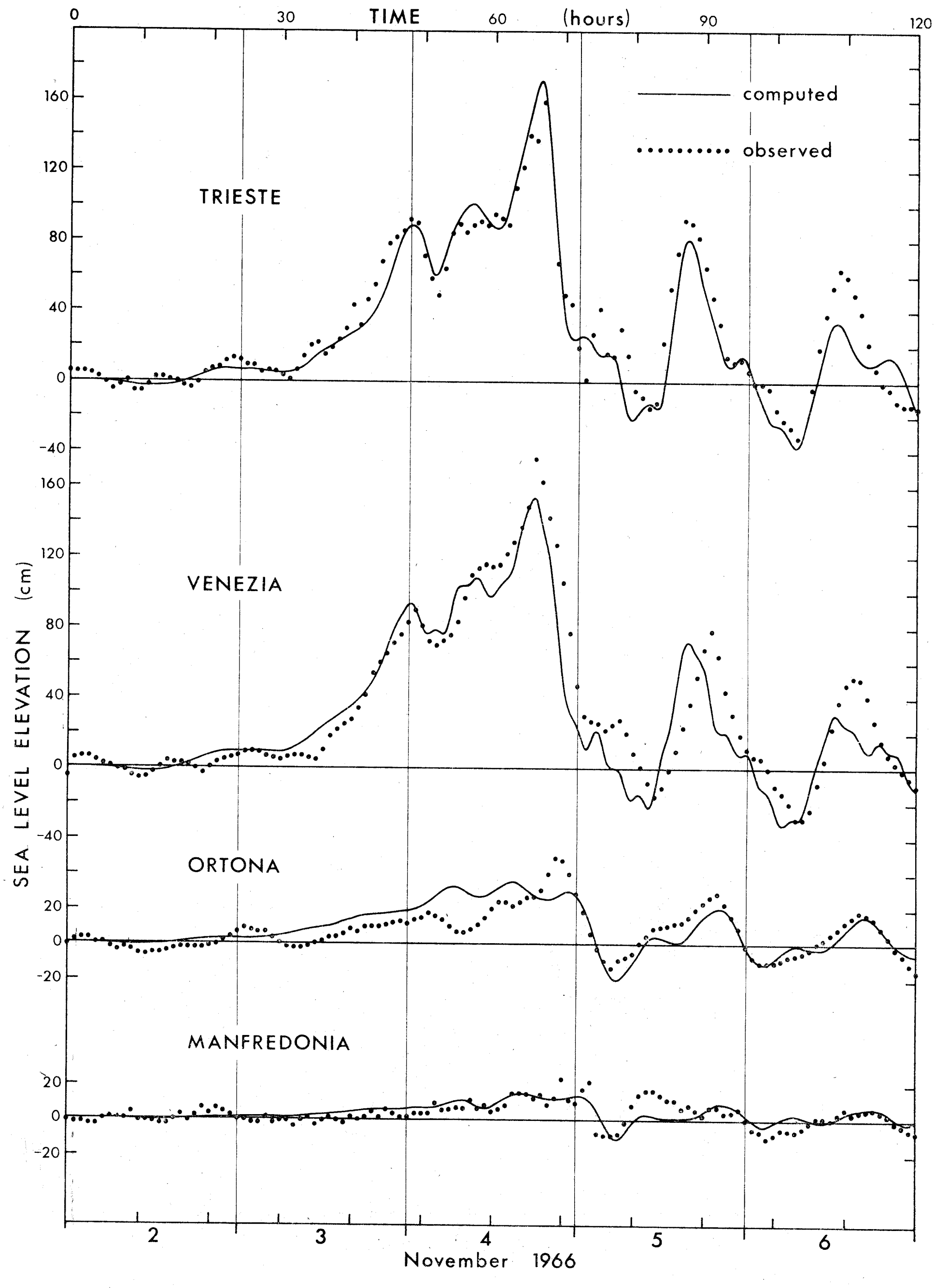

Fig. 7. – November 1966 storm surge in the Adriatic: comparison between computed and observed $\eta(t)$ sea levels.

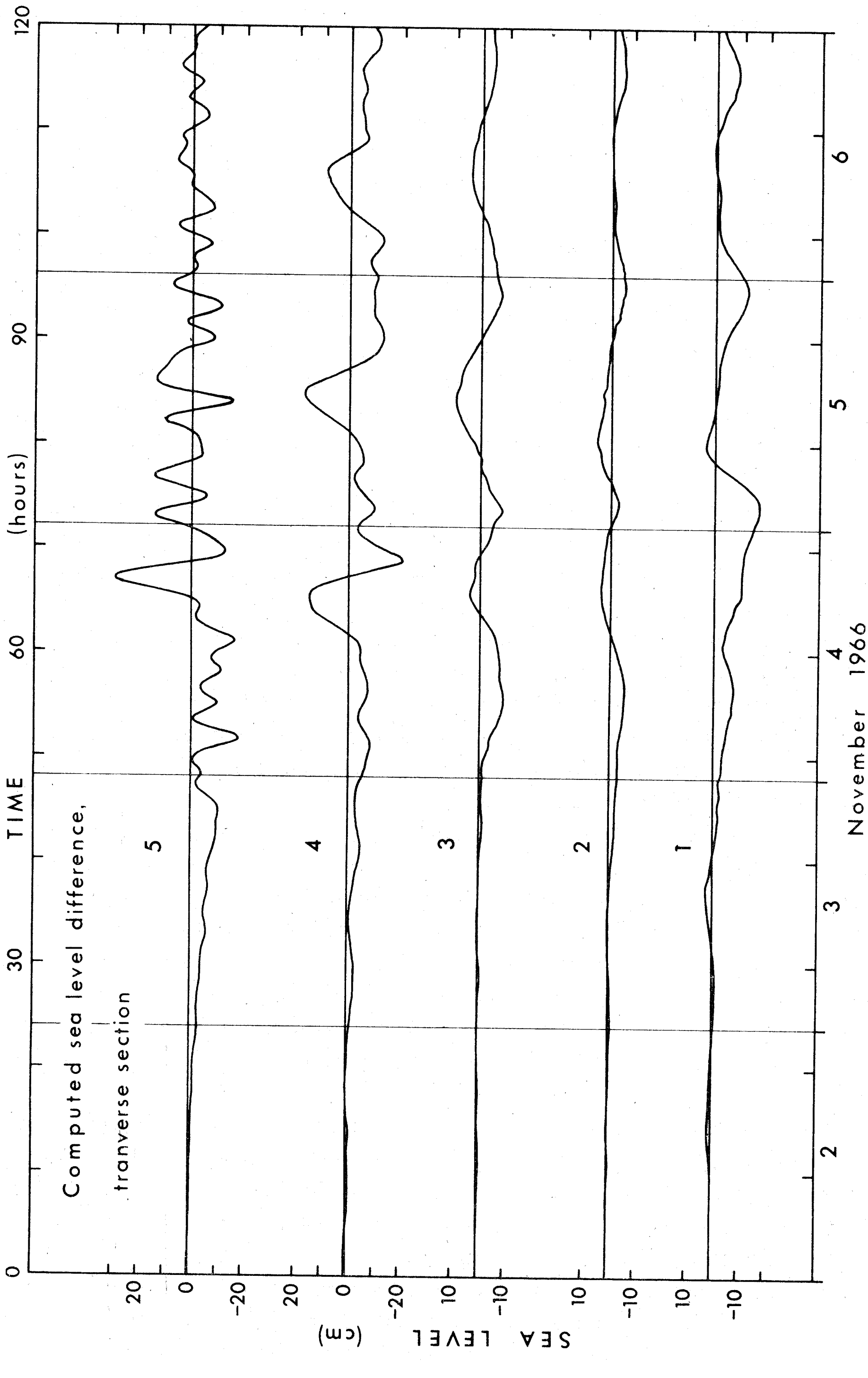

Fig. 8. – November 1966 storm surge computations: sea level difference between the east (+) and west (—) coast of the Adriatic, as a function of time, for five transverse sections (fig. 3 *a*).

The total work W_F of the applied force $\mathbf{F}$ (fig. 4 *b*) reaches its maximum after 67 hours (14.3×10^{20} erg); it decreases afterwards when the basin is emptying, since the mean transport is opposite to $\mathbf{F}$. W_F is constant after 100^h, since the force is no longer defined, for lack of data. The bottom friction work W_K must tend to the same value with time; W_K grows more rapidly when the transport is more intense (after 70–75 hours).

The energy balance is satisfactory, as can be seen from fig. 4 *c*.

The volume $V(t)$ of the Adriatic is shown in fig. 4 *d*; the basin is slowly filled during the first 65 hours: at that instant (17^h of November 4), about 4.2×10^{16} cm^3 of sea water are accumulated in the Adriatic. The whole mass is then released, and the basin is rapidly emptied; oscillations follow, with the first seiche period of 21.5 hours.

Also the volume balance is satisfactory (fig. 4 *d*), provided the α_k weights in (28) are determined by a least squares fitting between the V^i and V_e^i time series: the values $\alpha_1 = 1.27$, $\alpha_2 = 1.35$, that are quite acceptable, have been obtained.

The transport situation after 50 and 70 hours represents the typical current pattern during the filling and the emptying stage of the basin respectively (fig. 5 *a*, *c*); arrows indicate the path of the mean flow, and numbers the transport intensity per unit transverse section, in 10^4 cm^2/sec. Sea water enters the Adriatic, and part of it flows out along the Italian coast at Otranto. The main current deviates towards the west coast over the Gargano promontory and reaches the Gulf of Venice; another branch follows the east coast of Dalmazia, and enters the Gulf of Trieste. A descending current is present in the axial region of the basin; a strong counterclockwise circulation is characteristic of the mouth region.

The outflowing currents are much more intense (fig. 5 *c*): the main transport (about 20×10^4 cm^2/sec) is along the valley-way; weak currents depart eastwards between the Dalmatian islands, and large scale countercurrents take form in the recesses of the coast. The southeastern coast of the basin stops and deviates the descending water flux westwards, through the narrow Otranto channel; a minor current turns back along the east coast. At the mouth region, a strong east entering flux, which combines with the outflowing current giving again a counterclockwise circulation, is still present.

The circulation in the basin during the storm surge is such that, in the axial points C, D, E (fig. 3 *a*), the mean transport is always directed towards the open end (fig. 6); the persistent circulation in the mouth region is here evident (points A, B), [7]. Alternating currents are superimposed to the long period trend: their direction is along the axis of the Adriatic.

The equal level contours after 65 and 78 hours, at the time of the maximum and minimum volume respectively, are drawn in fig. 5 *b*, *d*; the strong shallow water effect in the Gulfs of Venezia and Trieste clearly appears.

Computed sea level elevations as a function of time are compared with the corresponding observed at Trieste, Venezia, Ortona and Manfredonia;

the grid points representing these localities are shown in fig. 3 *a*. Since in the model the sea level at Otranto is taken to be zero, the observed surge of Otranto has been subtracted from the other surges in fig. 2; in this way the barometric surge, assuming it uniform, in a first approximation, over the whole basin, is eliminated. The reproduction of the surge is fairly good (fig. 7); differences are due partly to the model approximations, to the rather wide mesh size used, and to condition (5), but partly also to the input data of $\boldsymbol{w}$, ∇p_a. The periods desumed from the graphs for the first three seiches are 21.5, 11, 7.5 hours; periods of about 8.5, 5, 3.5, 3 hours are present at Trieste and Venezia.

Computed east-west sea level differences for the five transverse sections of fig. 3 *a* are shown in fig. 8; an oscillation with the period of the first seiche has a positive initial peak, and is delayed from south to north. This indicates a counterclockwise progression of the seiche along the coasts, due to the rotation of the Earth, according to the observations.

A comparison with the sea levels obtained in [10] for the same storm surge, but using a one-dimensional model, is instructive.

CONCLUSIONS

The general correctness of the results and the satisfactory energy and volume balances obtained for the critical meteorological situation that has just been examined, proves that the difference scheme used to solve the storm surge equations is efficient, and that the vertically integrated linear model is applicable to the Adriatic sea.

Besides reproducing the sea level elevations, the deterministic model here examined throws light on physical aspects of a storm surge, like the large scale horizontal circulation and the energy and volume balance, that are yet little known.

Further numerical experiments with typical meteorological situations that could arise might be of interest for the forecasting of storm surges in the Adriatic sea.

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