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UNUSUAL DEEP MIXING OF LAGO MAGGIORE DURING THE WINTER 1980-1981 (**)

ABSTRACT: AMBROSETTI W., BARBANTI L. & MOSELLO R., *Unusual deep mixing of Lago Maggiore during the winter 1980-1981* (IT ISSN 0084-8948, 1982).

The main hydrodynamic characteristic of L. Maggiore, as well as the other deep sudalpine lakes, is their oligomixis, i.e., full circulation, with the consequent thermal and chemical homogeneity of the whole water column, does not occur every year. Since 1960, this situation has been observed only in the late winter of 1963, 1970 and 1981. The last occurrence was particularly well studied, with weekly measurements of the vertical distribution of temperature and oxygen concentrations, supplemented by monthly analyses of the main chemical variables.

The results showed at the beginning of February a wind induced drift of superficial water and a deep water counter current with the formation of a three layers situation: the superficial mass, from a depth of 0 to 120 m, with an oxygen concentration of 8,5-9,0 mg l^{-1}; a middle layer (120-220 m), with a concentration of 6,5 mg l^{-1}, and a lower layer (220-370 m), with a concentration of 9,0 mg l^{-1}, well above the values measured on 23[rd] January, which ranged from 5,7 and 6,6 mg l^{-1}. This situation was observed also at other points of the lake, which indicates a « conveyor belt » mechanism of circulation. In the subsequent days the wind and the convective movements caused a progressive oxygenation of the water mass down to 200 m. In this paper the water mass dynamics are discussed in relation to the main meteorological and hydrological variables, as well as the morphology of the lake.

RIASSUNTO: AMBROSETTI W., BARBANTI L. & MOSELLO R., *Il non comune mescolamento profondo del Lago Maggiore durante l'inverno 1980-1981* (IT ISSN 0084-8948, 1982).

La caratteristica idrodinamica principale del Lago Maggiore, come del resto quella degli altri laghi profondi sudalpini, è la loro oligomissi, cioè il fatto che la completa circolazione, con la conseguente omogeneità termica e chimica dell'intera colonna d'acqua, non si verifica tutti gli anni. A partire dal 1960 quest'ultima situazione è stata osservata soltanto nel tardo inverno degli anni 1963, 1970 e 1981. L'ultimo evento è stato studiato nei particolari, con misure settimanali della distribuzione verticale della temperatura e delle concentrazioni di ossigeno, integrate da analisi mensili delle principali variabili chimiche.

I risultati hanno permesso di constatare come all'inizio di febbraio il vento abbia indotto correnti di deriva superficiali e correnti di gradiente in profondità con la formazione di una struttura a tre strati: la massa superficiale (da 0 a 120 m di profondità) con concentrazioni di ossigeno di 8,5-9,0 mg l^{-1}; uno strato intermedio (120-220 m) con una concentrazione di 6,5 mg l^{-1}, ed uno strato inferiore con una concentrazione di 9,0 mg l^{-1}; quest'ultimo valore è risultato ben superiore a quelli misurati il 23 gennaio che variavano da 5,7 a 6,6 mg l^{-1}. Una tale situazione fu osservata anche in altri punti del lago, il che indica un meccanismo di circolazione del tipo « a nastro trasportatore ». Nei giorni successivi il vento ed i movimenti convettivi hanno determinato la progressiva ossigenazione della massa d'acqua sotto i 200 m. In questo lavoro la dinamica della massa d'acqua viene discussa in rapporto alle principali variabili meteorologiche ed idrologiche, ed anche in rapporto alla morfologia del lago.

TERMINI-CHIAVE: Limnologia fisica; mescolamento; oligomissi. Lago Maggiore.

The Istituto Italiano di Idrobiologia of the Consiglio Nazionale delle Ricerche has studied for some years the winter overturn of the deep sudalpine lakes (Maggiore, Lugano, Como, Iseo and Garda), to establish the relationships between hydro-meteorological variables and water circulation, and its bearing on the trophic conditions of the lakes.

These lakes (fig. 1) are normally classified as oligomictic (*sensu* HUTCHINSON & LOEFFLER, 1956), that is, full circulation, thermal and chemical homogeneization of the whole water column, do not occur every year, but only in coincidence with particularly cold and windy years (for L. Maggiore see e.g. VOLLENWEIDER, 1964; TONOLLI V. L. & BONOMI, 1967; TONOLLI, 1969). Previous observations on the effects of the overturn on the chemical pattern of the water of the sudalpine lakes have been presented by BONOMI, CALDERONI & MOSELLO (1979); they pointed out that, among different physical and chemical variables, vertical distribution of temperatures and of oxygen concentrations are the most indicative of the depth of the maximum extent of the vertical mixing.

Restricting the discussion to L. Maggiore, fig. 2 shows the mean oxygen concentrations in the water layer be-

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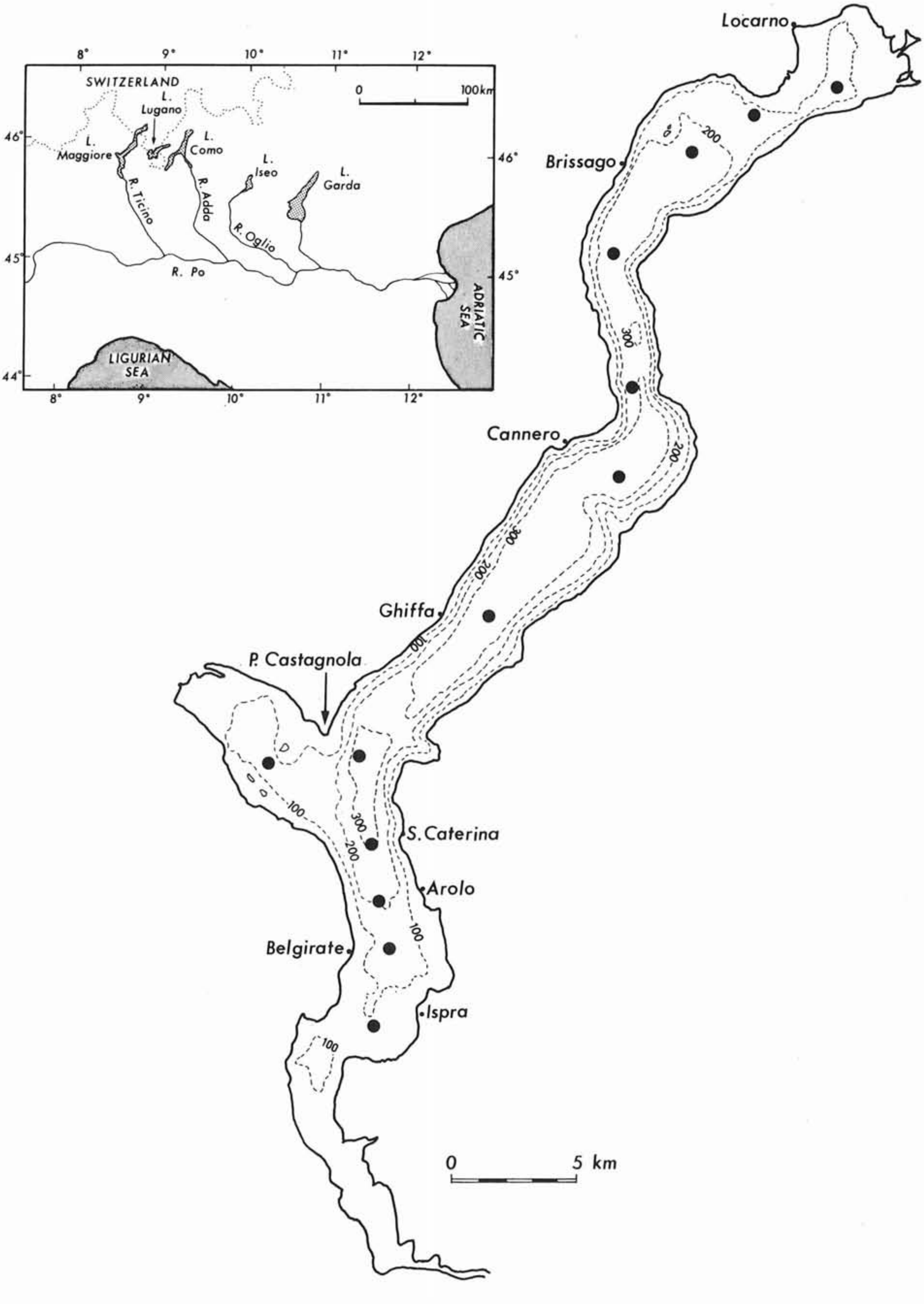

FIG. 1 - Lago Maggiore and location of Italian sudalpine lakes.

tween 200 and 370 m, measured since 1960 in different periods of the year. The highest concentrations were formed in the late winter of 1963 and 1970, in coincidence with unusual meteorological conditions. As shown by AMBROSETTI, BARBANTI & ROLLA (1979) and AMBROSETTI, BARBANTI & MOSELLO (in print), variations in the depth of mixing in different years depend on main meteorological variables such as atmospheric temperature, total solar radiation and total wind-run. However, January. These general meteorological conditions could not justify to definite the 1980-81 winter as very harsh.

From January on, water temperature of the lake (fig. 4) decreased on the whole column during the sampling period, showing an initial small gradient at the depth of 120 m; this difference diminishes afterwards, but a ΔT of 0.1-0.2 °C is always present at depths of between 200 and 250 m. From these observations we may conclude that temperature is not a suitable variable for

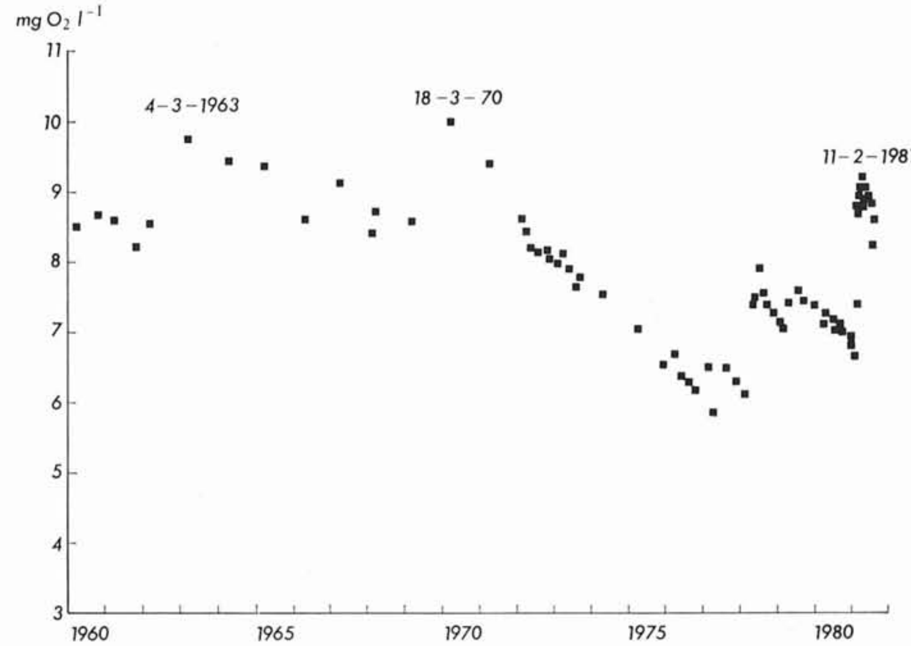

FIG. 2 - Oxygen trend in Lago Maggiore water below 200 m.

the dynamics of the phenomenon are not completely understood; therefore an intensive study on Lago Maggiore during the winter 1980-1981 was carried out, taking biweekly measurements of the vertical distribution of temperature and oxygen near the point of maximum depth (370 m, Ghiffa station) supplemented by monthly analyses of the main chemical variables.

The prevailing meteorological events during winter 1980-81 are summarized in fig. 3, which shows the total daily wind-run (W), the ten-day mean temperature of the air (Ta) and the ten-day total solar radiation (R), measured at the meteorological station of Pallanza in comparison with the mean values of the years 1951-1979. The figure further shows lake water temperatures (Tw) at depths of 0, 50, 100, 200 and 300 m, measured at the Ghiffa station. Wind, with the exception of a few limited periods (e.g. at the beginning of January and at the end of March), was always below the mean of the reference period. Atmospheric temperature also showed a similar trend, with the exception of the first ten days of January and February; from the beginning of December to the middle of February high negative differences were measured (more than 2 °C). Accordingly, the two parameters had opposite effects on the vertical mixing. On the other hand, solar radiation from the last ten days of December to February was higher than the mean, with maximum differences in describing a phenomenon such as that observed in the winter 1980-81 in Lago Maggiore.

A better description of the event is given by the vertical distribution of oxygen, as shown in fig. 5. On 15th January and even more clearly on 23rd of that month, oxygen distribution indicated a well defined stratification of the water: the superficial mass, from 0 to 120 m depth, had concentrations higher than 9 mg l^{-1}, while the water below showed concentrations ranging from 6 to 7 mg l^{-1}. On 5th February the situation was fundamentally changed, so that it was possible to distinguish three different water layers: the upper (0-120 m) with oxygen concentrations of 8.5-9.0 mg l^{-1}, slightly below the values of the previous sampling; a middle layer (120-220 m), with concentrations of 6.5 mg l^{-1}, very close to the values measured on 23rd January; and a lower layer (220-370 m), with concentrations of 8.0 mg l^{-1}, only sligthly below the values of the upper water layer. On 11th February the vertical distribution of the oxygen showed again a two-layer pattern, with an upper water mass (0-220 m) having concentrations slightly below 8 mg l^{-1}, while the lower water showed concentrations higher than 9 mg l^{-1}. A concentration of 7.7 mg l^{-1} at 220 m was probably the remainder of the poorly oxygenated middle layer of the previous sampling. The two layers were still distinguishable in the days between 18th February and 4th March, but the differences slowly

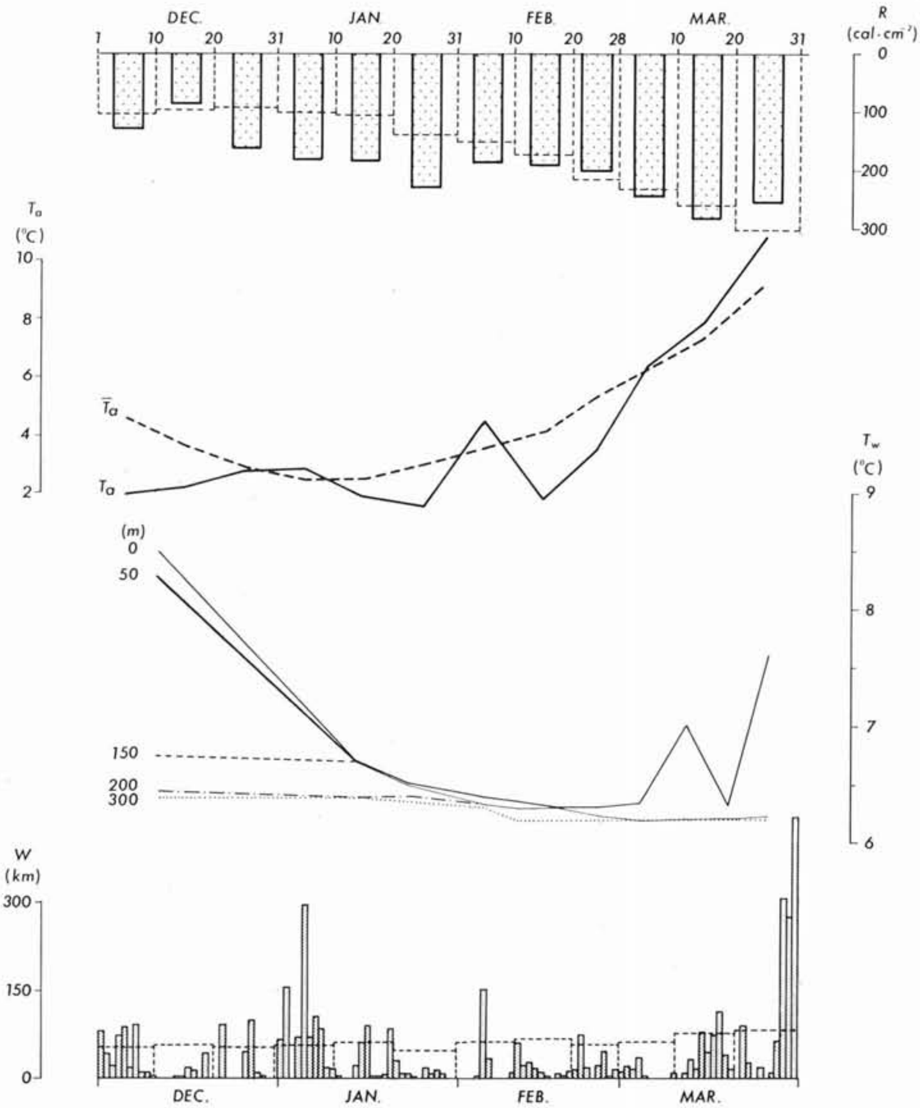

FIG. 3 - Solar radiation (R), air temperature (Ta), total wind-run (W) in the period December 1980 - March 1981 (continuous line) and comparison with the mean of the years 1951-1979 (broken line); water temperature (Tw) at different depths.

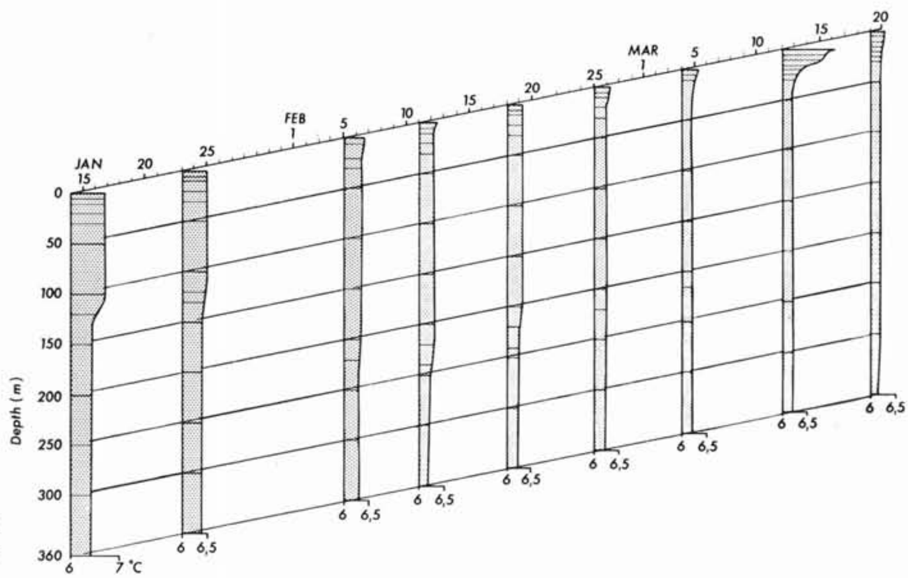

FIG. 4 - Vertical distribution of water temperature measured at Ghiffa, L. Maggiore.

decreased; the whole water column reached a rather high oxygen concentration, from 8.6 to 9.0 mg l^{-1}. Mixing was completed on 19th March.

The vertical distribution of oxygen observed on 5th February is explainable only assuming a drift of superficial water to deep strata. According to all the evidence, wind, the main force for dynamic processes in lake water, was the external cause of this event. Fig. 5 shows the chronological succession of the total wind-run (km/day) measured at Pallanza. Between 23rd January and 5th February winds were low. On February 5th wind-runs suddenly rose to more than 150 km in 24 hours, afterwards the wind-run slowed down, and only in the second half of March values increased to 50-100 km. Fig. 6 further shows wind speed and direction measured at Pallanza, Ispra (southern part of the lake) and Locarno Monti (northern part) on 4th, 5th and 6th February. Considering the different location of the stations and the different instruments used, these values agree well. Blowing from the northern directions, the type of wind can be considered a « föhn »: this is evident from the opposite trends of the air temperature (Ta) and relative humidity (U) curves drawn in the same figure. The strongest wind, which caused the movements of the water mass, began at 24th of the 4th February and continued until the last hours of 5th February. Since the oxygen distribution was observed at 13th of the same day, we can estimate exactly the wind energetic aspects. As to its intensity, the values are not exceptional: indeed, the mean hourly speed is 4-6 m s^{-1}. However, this is the range of speed that may give rise to the strongest drift currents (Haines & Bryson, 1961; Smith, 1979; George, 1981): winds with higher intensity dissipate part of their energy in waves, breakers and « white horses ».

In conjunction with wind conditions, thermal conditions of the lake were optimal for strong water movements: waters were practically homothermic, slightly above 6 °C, presenting therefore low resistence to mixing.

The morphology of the lake is also important in determining the dynamics of the turnover: the Lago Maggiore basin is long and narrow, with steep slopes and a relatively wide platform. The wind induced drift currents in direction of the principal axis amass the water on the lee-shore, causing a deep water counter current (gradient current), according to the mechanism known as the « conveyor belt » type of circulation (Boyce,

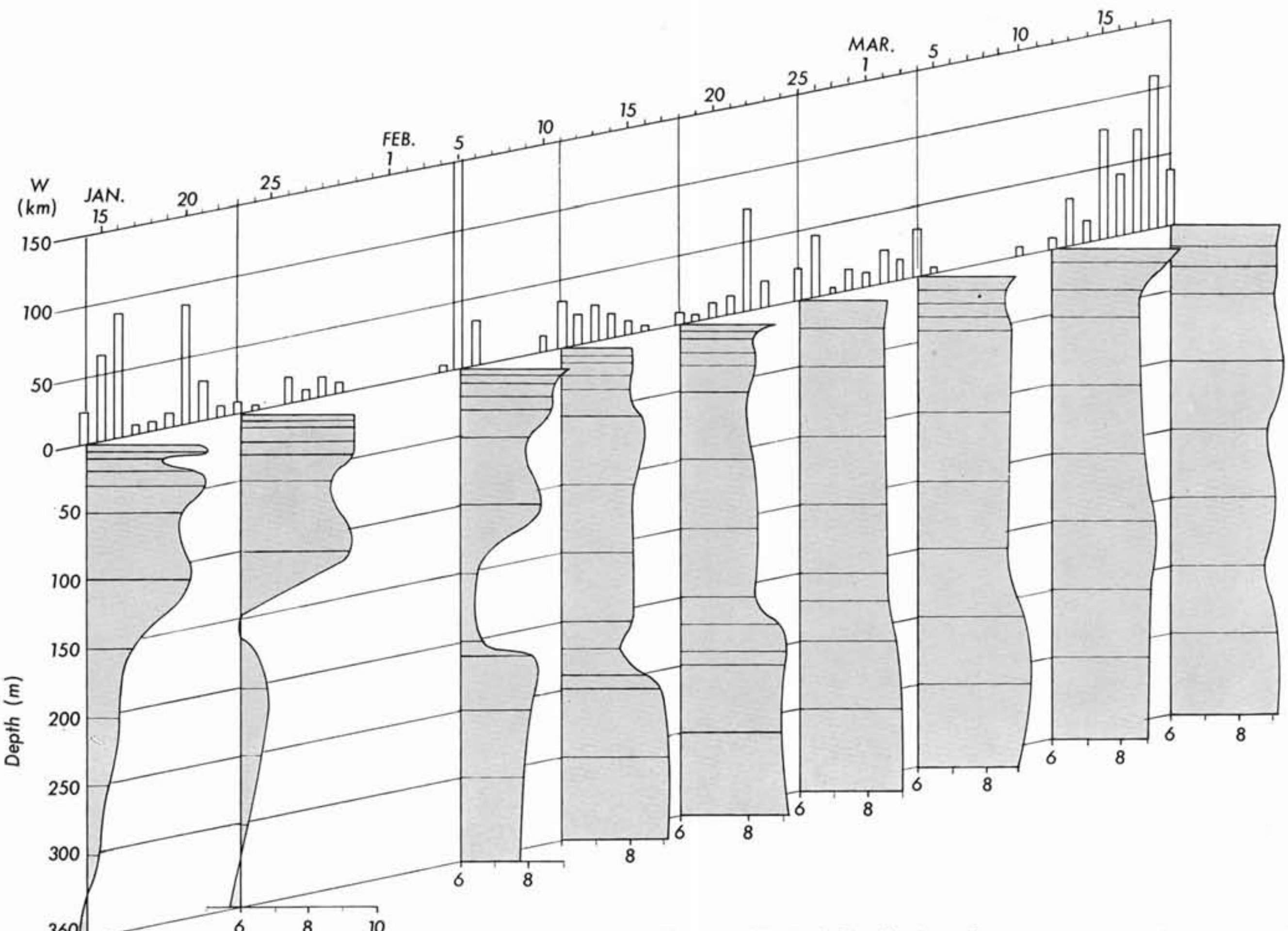

Fig. 5 - Vertical distribution of oxygen concentration measured at Ghiffa, and total wind-run daily measured at Pallanza.

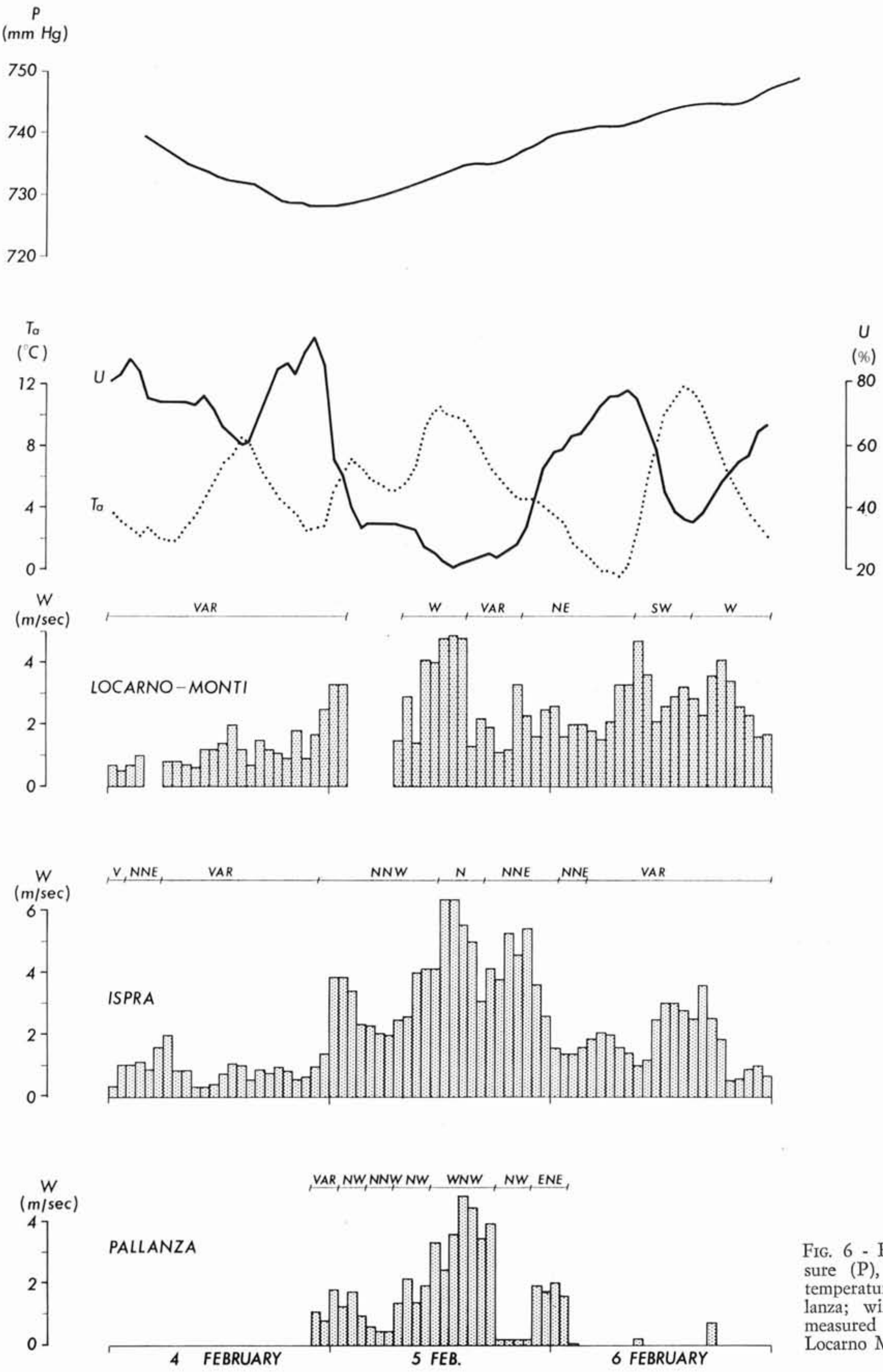

Fig. 6 - Hourly atmospheric pressure (P), humidity (U) and air temperature (Ta) measured at Pallanza; wind speed and direction measured at Pallanza, Ispra and Locarno Monti during 4th, 5th and 6th February.

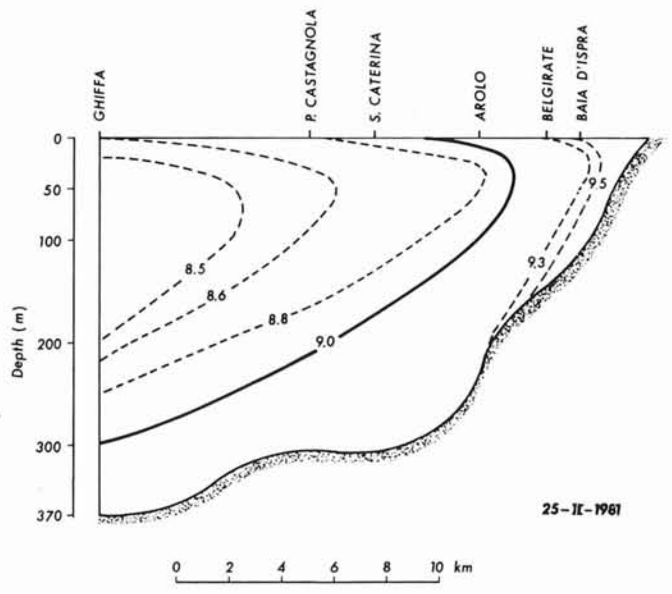

FIG. 7 - Oxygen concentrations in the southern basin of L. Maggiore measured at 25.II.1981.

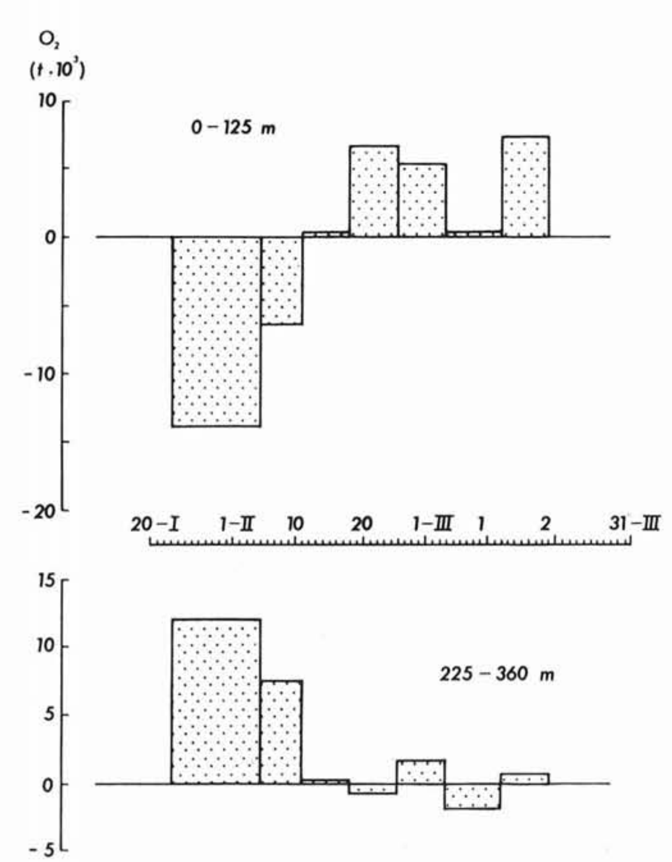

FIG. 9 - Oxygen balance in the successive samplings in the water layers between 0-125 m and 225-360 m.

1974; CSANADY, 1978; SIMONS & LAM, 1978; SMITH, 1979). Because of the narrowness of L. Maggiore, Coriolis force effects are probably negligible.

In regard to oxygen enrichment, we exclude water oxygenation due to inputs from the tributaries: the winter 1980-81 was characterized by low precipitation and consequently low discharges in all the inflowing rivers. However, some perplexity remains considering the short time in which the water movements occurred: only 12 hours from the beginning of the wind to the sampling time, requiring a current speed well above the highest values known up till now in L. Maggiore (BARBANTI & CAROLLO, 1965).

After 5th February winds showed low intensities and different directions, coming prevalently from the South; the superficial drift currents probably turned in a direction opposite to that of the event described above, but certainly they could not induce a turnover involving

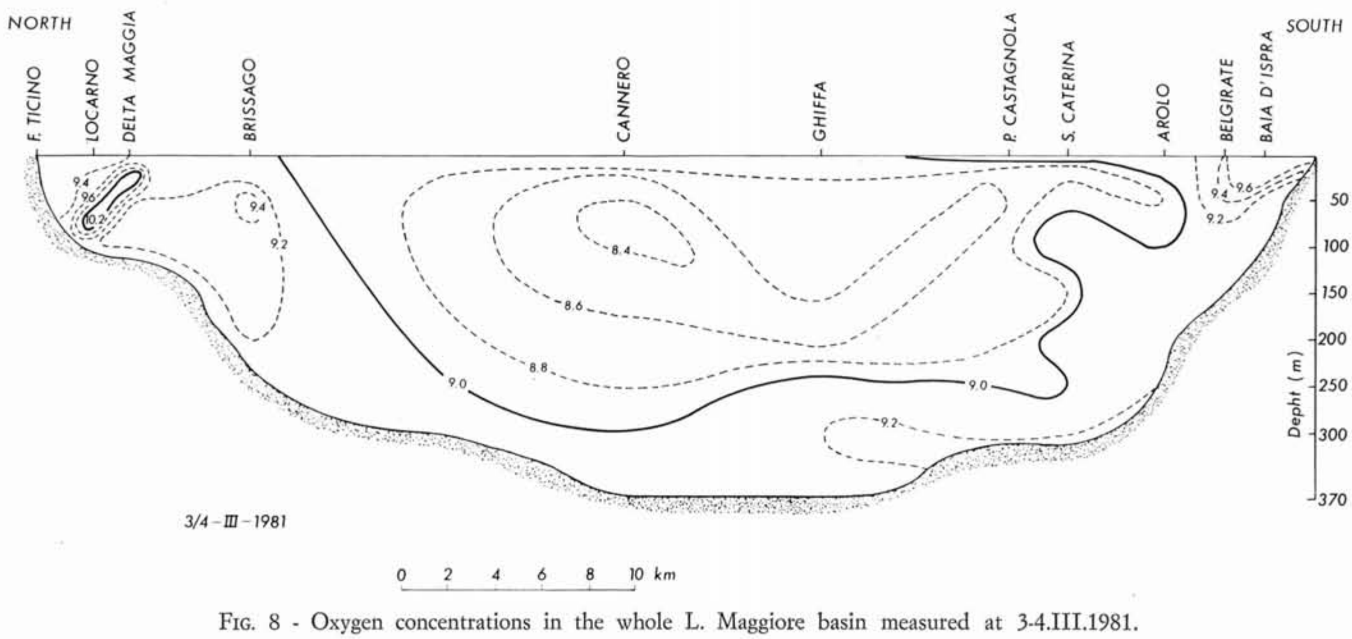

FIG. 8 - Oxygen concentrations in the whole L. Maggiore basin measured at 3-4.III.1981.

the deeper water. The vertical distribution of the oxygen indeed indicates that the values below 220 m did not change from 9 mg l^{-1}, resulting from the event of 5[th] February. The southerly winds of the following days must have contributed to the convective movements, always present during the phase of cooling, and to a progressive oxygenation of the water mass down to 200 m.

The isoline of dissolved oxygen along the principal axis of the lake confirm this situation: fig. 7 shows the situation in the southern part of the lake on 25[th] February; fig. 8 considers the whole basin, on the days 3[rd] and 4[th] March. Furthermore, the two figures show that the vertical distribution of the oxygen found at the point of maximum depth was similar in the whole basin, with the exception of the northernmost and southernmost parts of the basin. In the northernmost part the situation is complicated by the presence of fluvial masses, coming from rivers Ticino and Maggia, two of the main tributaries of the lake.

The oxygen budget for the water layers between 0-125 m and 225-360 m (fig. 9) shows further that, between the samples of 23[rd] January and 5[th] February and 5[th] February and 11[th] February, the oxygen deficit found in the more superficial layer is nearly balanced by the increase calculated for the deeper layer. This is not true for the successive sampling dates, and it is a further proof that the transfer of the water masses happened on the first days of February.

This is also confirmed by other chemical variables (conductivity, nitrate, reactive and total phosphorus, reactive silica). During spring and summer 1980, as a rule, the concentrations of these factors show a notable decrease in epilimnion and an increase in the deeper water, as a consequence of well known biological processes. The chemical stratification thus established is partially reduced, during the winter time, by wind mixing, convective processes and the inputs from the tributaries, but only twice, in 1963 and 1970 (fig. 2), did we find chemical homogeneity in the whole water mass.

The concentration of the above listed variables, measured from September 1980 to February 1981 in the layers 0-20 m and 200-360 m, are set out in tab. 1. The upper layer (trophogenic) is characterized by the highest biological activity, with important consequences also for the chemical concentrations, while in the lower layer, which in L. Maggiore is not normally involved in the turnover, the tropholitic processes prevail. The values of conductivity and nutrients measured from September to January show no significant variations on the bottom and a gradual increase on the surface. This last aspect is to be related to watershed inputs, as verified from a budget relative to the period from September to January, a budget that also takes into consideration the mixing with the deeper layers, having higher concentrations. The values measured on 18[th] February, coincidentally with the double layer situation previously described, are practically the same on the surface and on the bottom. Furthermore, comparison with the previous samplings underlines a notable decrease in the nutrient concentration and a considerable increase in the oxygen content in the deeper layer; all these variations testify to the water transfer from surface to bottom and viceversa.

There is no doubt that this phenomenon greatly affects the biological condition of the lake, e.g. as shown by TONOLLI V. L. & BONOMI (1967) for L. Maggiore zooplankton. On the occasion of and after the event of 5[th] February, biological samplings were made, in order to measure the vertical distribution of chlorophyll, of particulated organic matter and of zooplankton; the first results confirm that the deep waters, in the weeks after this date, show values very close to those at the surface waters, while the waters in the middle layer are completely different (BERTONI & CALLIERI, pers. comm.; DE BERNARDI & GIUSSANI, pers. comm.).

TABLE 1

MEAN CONCENTRATIONS OF SELECTED CHEMICAL VARIABLES IN THE UPPER AND LOWER WATER LAYERS IN L. MAGGIORE

		Depth (m)	22-IX 1980	11-XII 1980	23-I 1981	18-II 1981
Dissolved oxygen	mg l^{-1}	0 - 20	9.3	9.3	9.4	8.5
		200 - 360	6.9	6.8	6.6	8.7
Conductivity	$\mu S\ cm^{-1}$	0 - 20	121.0	131.2	135.3	136.4
	(18 °C)	200 - 360	136.0	136.2	136.6	136.7
Nitrate nitrogen	mg N l^{-1}	0 - 20	0.61	0.70	0.80	0.76
		200 - 360	0.82	0.79	0.76	0.75
Reactive phosphorus	μg P l^{-1}	0 - 20	1	9	12	8
		200 - 360	21	23	26	7
Total phosphorus	μg P l^{-1}	0 - 20	9	16	21	24
		200 - 360	26	28	28	22
Reactive silica	mg Si l^{-1}	0 - 20	0.4	1.0	1.3	1.5
		200 - 360	1.6	1.6	1.6	1.5

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