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A numerical simulation of transport and sedimentation of suspended particles in Lake Neuchâtel[1]

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Key words: Numerical simulation, Lake Neuchâtel, general circulation, thermal stratification, large scale dispersion, transport of suspended particles, sedimentation

ABSTRACT

The dispersion and sedimentation of suspended particulate matter in Lake Neuchâtel are studied with a numerical model. To simulate the currents in the lake, a three dimensional general circulation model is applied. A six weeks run is performed under late autumn conditions, in which the particle load of rivers entering the lake is high. Meteorological wind data and realistic thermal stratification are included in the model. At the Areuse river output, particles are injected into the lake. In addition to their advection by the currents, the particles possess a vertical settling velocity. The simulation indicates that privileged deposition areas for suspended particulate matter which is discharged by the Areuse river, are confined to the north-east region of the lake.

RESUME

La dispersion et la sédimentation de particules en suspension dans le Lac de Neuchâtel ont été étudiées à l'aide d'un modèle numérique. L'usage d'un modèle tridimensionnel de circulation générale a permis de simuler les courants dans le lac. Une simulation de dispersion de particules dans des conditions tardi-automnales a été menée sur une période de six semaines. A cette saison, la charge particulaire des affluents du lac est relativement importante. Des relevés météorologiques de vent ainsi qu'une stratification thermique réaliste ont été utilisés dans le modèle. A l'embouchure de l'Areuse, des particules ont été injectées dans le lac. Les particules sont transportées par les courants et, à ce transport advectif, on ajoute une vitesse de chute en raison de leur densité plus importante que le fluide. La simulation a fait apparaître que les sites de dépôt privilégiés pour le matériel particulaire apporté par l'Areuse se répartissent dans la partie nord-est du lac.

Introduction

Lake Neuchâtel is a quasi-rectangular body of water in western Switzerland (Fig. 1). Its longest axis is directed SW-NE. The bathymetry of the lake is "elongated bath-tub" like with a hill centred in the north-east region (Fig. 2). This underwater hill ("la Motte") is rather steep and reaches its highest point only 9 m under the water surface. Morphological characteristics of the lake are presented in Table 1. More detailed information is found in Bapst (1987) and Sollberger (1974). The lake has been the subject of several geochemical and sedimentological studies. The analysis of coprostanol and other sterols reveal a faecal contamination in surface sediments (Pittet et al. 1990). The contamination is limited to the north-east part of the lake, not far away from the wastewater treatment plant of Neuchâtel. Another contaminant of anthropogenic origin is talc, whose distribu-

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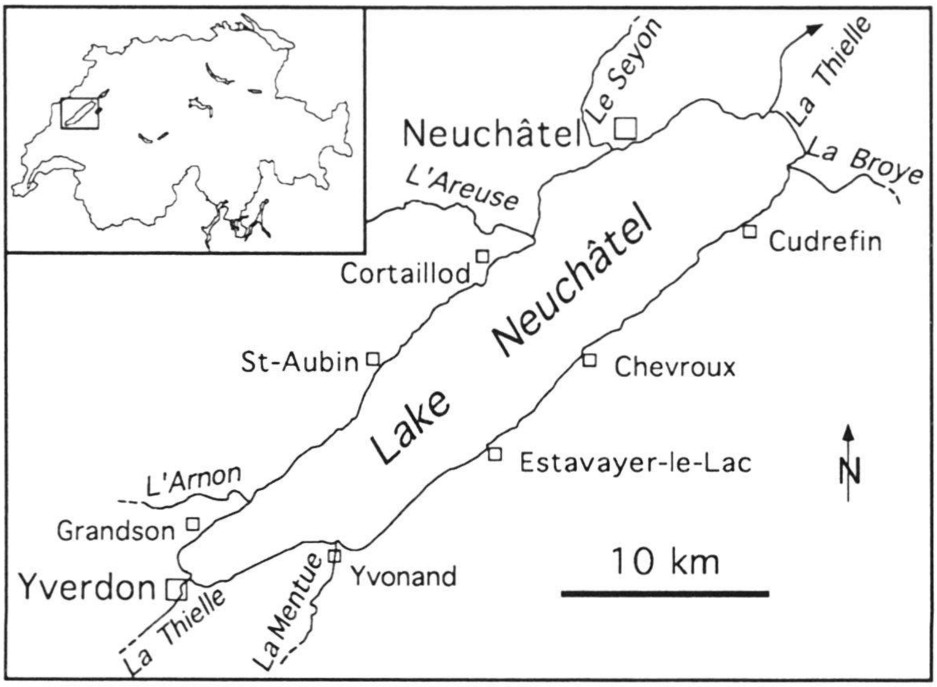

Fig. 1. Location of Lake Neuchâtel in western Switzerland. Its longest axis is directed SW-NE. Its main tributaries are the Areuse, the Arnon, the Broye, the Mentue, the Seyon and the Thielle. This latter is also the sole emissary.

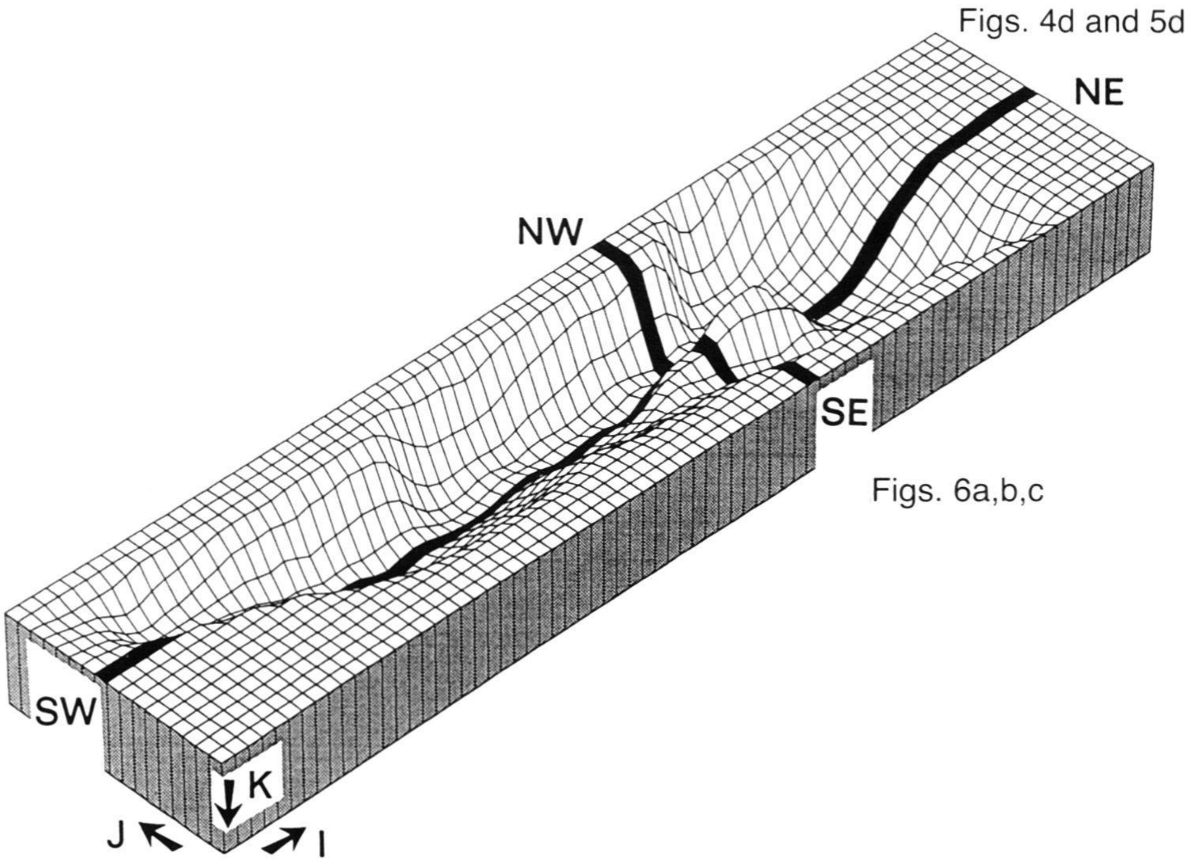

Fig. 2. A 3D perspective view (from the south) of the lake topography with location of the vertical sections displayed in Figures 4d, 5d and 6. The underwater hill "la Motte" is clearly apparent.

Tab. 1. Morphological characteristics of the lake.

Surface area	214 km2
Length	38.3 km
Mean width	5.68 km
Maximal depth	153 m
Mean depth	64.2 m
Volume	13.8 km3
Residence time of water	8 years

tion in the lake has been studied by Bapst (1987). These studies, as well as the one of Beck (1987), have permitted to raise the hypothesis of the existence of three or four sub-basins in the lake which would have their own physico-chemical and sedimentological characteristics. Bapst formulated this hypothesis on the base of a differentiated distribution of talc and kaolinite, minerals the origin of which is anthropogenic for talc and partially anthropogenic for kaolinite. This and the fact that the different sub-basins have different sedimentation rates (Schwalb 1992) put up the question if some of them are privileged deposition areas for suspended particulate matter which is discharged into the lake.

The dispersion of particles released into a lake is primarily governed by water motion. The prediction of the direction of their transport requires the computation of both the water circulation and the advection of the particles. On that basis, a 3D general circulation model is applied to simulate the currents in Lake Neuchâtel and the particle transport is integrated. Figure 3 schematically presents the structure of the model. In the principal box (the hydrodynamic model), temperature (or density) and velocity are state variables whose evolution is described by conservative equations. These two state variables interact through the advection and buoyancy processes: the currents move water masses

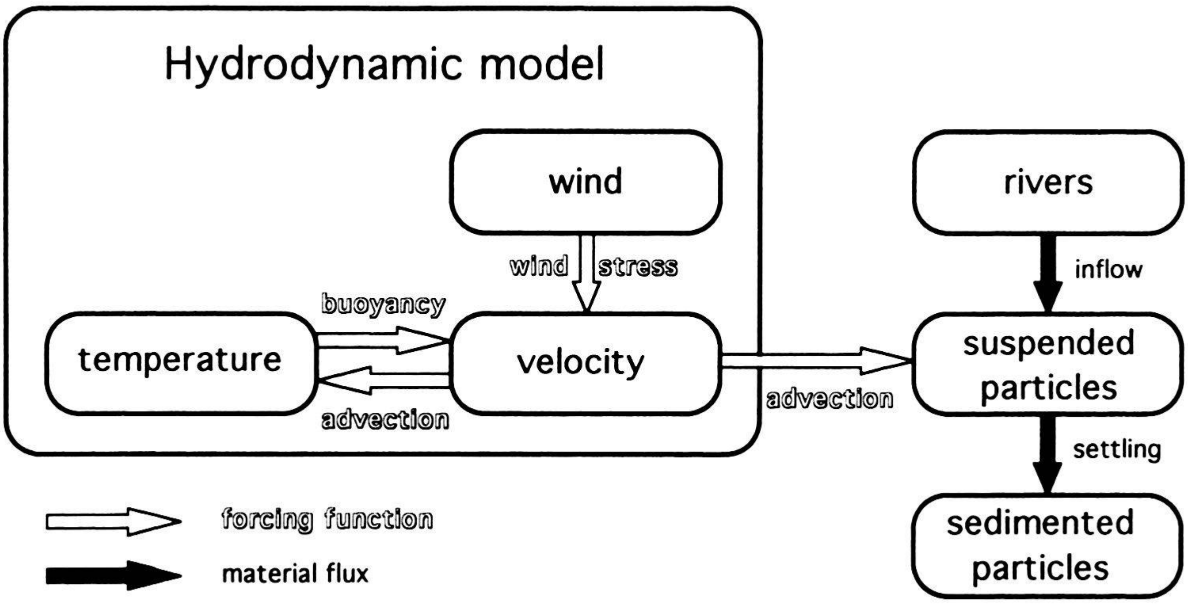

Fig. 3. The structure of the model. Forcing processes are indicated by double arrows. Material fluxes are indicated by heavy arrows from the river to the water column and to the bed of the lake. In the principal box, the hydrodynamic model is schematically represented. The hydrodynamic model determines the advective transport of the particles. In addition, while particles are assumed to have a higher density than the fluid, they possess a vertical settling velocity with respect to the surrounding fluid and gradually sink until sedimentation.

of different densities and differences in density between water masses generate buoyant forces. These forces add to other ones like Coriolis in the momentum balance. The wind box represents the main forcing in establishing the velocity field. Composed as such, the hydrodynamic model drives the particle transport through the advection of the particles by the currents (see Fig. 3). In addition, while particles are assumed to have a higher density than the fluid, they possess a vertical settling velocity with respect to the surrounding fluid and gradually sink until sedimentation. One of the main tributaries of the lake, the Areuse river, is chosen as the particle source.

Several authors have investigated the influence of currents produced by inflowing rivers on sedimentation of particulate matter in lakes. Depending on the relative density of the lake and river water, the intrusions of the river inflows can take the form of overflows, underflows or interflows (Wright & Nydegger 1980). Overflows consist in the spreading of lighter river waters over the lake surface. Underflows are currents carrying waters loaded by particulate matter along the lake bottom. These are exceptional and sporadic events but they can deposit a non negligible part of sediments. Interflows are water intrusions in intermediate layers, where gravity and buoyancy are balanced. They are observed during summer when the thermal stratification is pronounced. As mentioned by Giovanoli (1990) who has studied the inflow of the Rhone river into Lake Geneva, the momentum of the interflow dampens only a few hundred meters from the river mouth, after which, the influence of the lake currents upon the transport becomes predominant. In Lake Neuchâtel, the Areuse discharge is about 6 m^3/s during summer, compared to several hundred m^3/s for the Rhone river (Giovanoli & Lambert 1985), and the particulate load is much lower. For this reason, we assume that the interflows extent is relatively small and that the transport of particles is essentially controlled by the larger scale circulation.

The present study is composed of two distinct parts. In the first part, the hydrodynamic model is applied to Lake Neuchâtel to simulate some typical features of its circulation under autumnal conditions. An idealised daily wind cycle and thermal stratification are introduced in the model. Comparison with a measured temperature field is supplied. In the second part, a simulation of dispersion and sedimentation of particles is performed. In the latter case, observed wind data are used to force the hydrodynamic model. The integration of the particle transport enables us to trace the particles released at the Areuse outlet and to determine where the particles are incorporated into the sediment.

Hydrodynamics

A study of some hydrodynamic features of Lake Neuchâtel under representative wind and stratification conditions for the autumnal season is performed with the PROSPER General Circulation Model (PGCM). The PGCM is based on the incompressible Navier-Stokes (NS) equations, an equation of state and a heat equation. The following approximations which are justified by scaling estimates of the terms that appear in the NS equations (Pedlosky 1987, Gill 1982) are used:

- The Boussinesq approximation: density variations are neglected in computing rates of change of momentum from accelerations but are taken into account when they give rise to buoyancy forces.

- The hydrostatic approximation: the vertical momentum equation is reduced to hydrostatic equilibrium.
- The "rigid lid" approximation.
- The turbulence closure approximation: the Reynolds stresses are assumed to depend in a linear way on the spatial derivatives of the large-scale flow velocity. In particular, constant eddy viscosity coefficients are used.

The resulting system of equations is integrated in time and space with a finite difference method. A numerical description of the original scheme is found in Zuur (1991) and a recent modification of a part of the algorithm in Zuur (1993). The spatial discretisation is based on the staggered Arakawa-C control volume approach: while the computational points for the scalar quantities (pressure and temperature) are located at the centre of each control volume, the ones of the velocity components are staggered at the cell interfaces (Arakawa & Lamb 1977). Here, a horizontal plane of the lake is divided in 70 × 18 control volumes, the area of each one being 549 × 497 m^2. In the vertical direction there are 20 layers of control volumes with a thickness of 7.10 m.

Over Lake Neuchâtel, the prevailing wind during autumn is "le Vent", a south-westerly wind blowing along the main axis of the lake. In order to identify some typical hydrodynamic features of the lake in this first simulation, an idealised daily wind cycle and thermal stratification are used in the model. Each day, during 12 hours, a uniform wind is blowing over the lake from the south-west with a constant speed of 7.5 m/s. During the next 12 hours, the wind is turned off. This sequence is repeated 10 times, by which an integration over 10 days is performed. At the start of the run, the lake is at rest and is thermally stratified: the temperature decreases linearly from 10.5°C at the surface down to 5.5°C at maximum depth. When the wind starts to blow, it exerts a surface stress which puts the superficial layers of water into motion. As a result of the vertical eddy viscosity, the kinetic energy penetrates more deeply and a current grows in the upper layers. Near the downwind shore, the currents converge, giving rise to vertical downwelling motions. The amplitude of the vertical motions strongly depends on the thermal structure of the water column: the stratification generates buoyant forces balancing the vertical motions of water masses of different density. The sinking water masses feed a countercurrent in the deeper layers and, at the upwind border, there is an upwelling zone. This circulation is accompanied by a vertical shift of the isotherms, which sink within a downwelling zone and rise within an upwelling zone. When the wind is turned off, the water masses are redistributed in the basin producing readjusting currents and internal waves.

Velocity and temperature fields at two points in time are presented in Figures 4 to 6b. The longitudinal and transverse vertical slices which are displayed are indicated in Figure 2. Figures 4 and 6a show the fields at the end of a period of 12 hours of wind forcing. Near the surface away from the shore, the velocity field is deflected to the right relative to the wind direction (Fig. 4a). This deflection results from the Coriolis' force. The angle of the deflection agrees with the theoretical value, being 45 degrees, which is the limiting angle in the Ekman layer when the surface is approached (Pedlosky 1987). As the net horizontal flow near the surface is directed eastward, it induces upwelling in the west part and downwelling in the east part of the lake. The water flux in the upper layers is balanced by a countercurrent in the deeper ones (see Fig. 4c). The topography and in particular the hill "la Motte" channels the countercurrent along the northern slope of the lake. The ve-

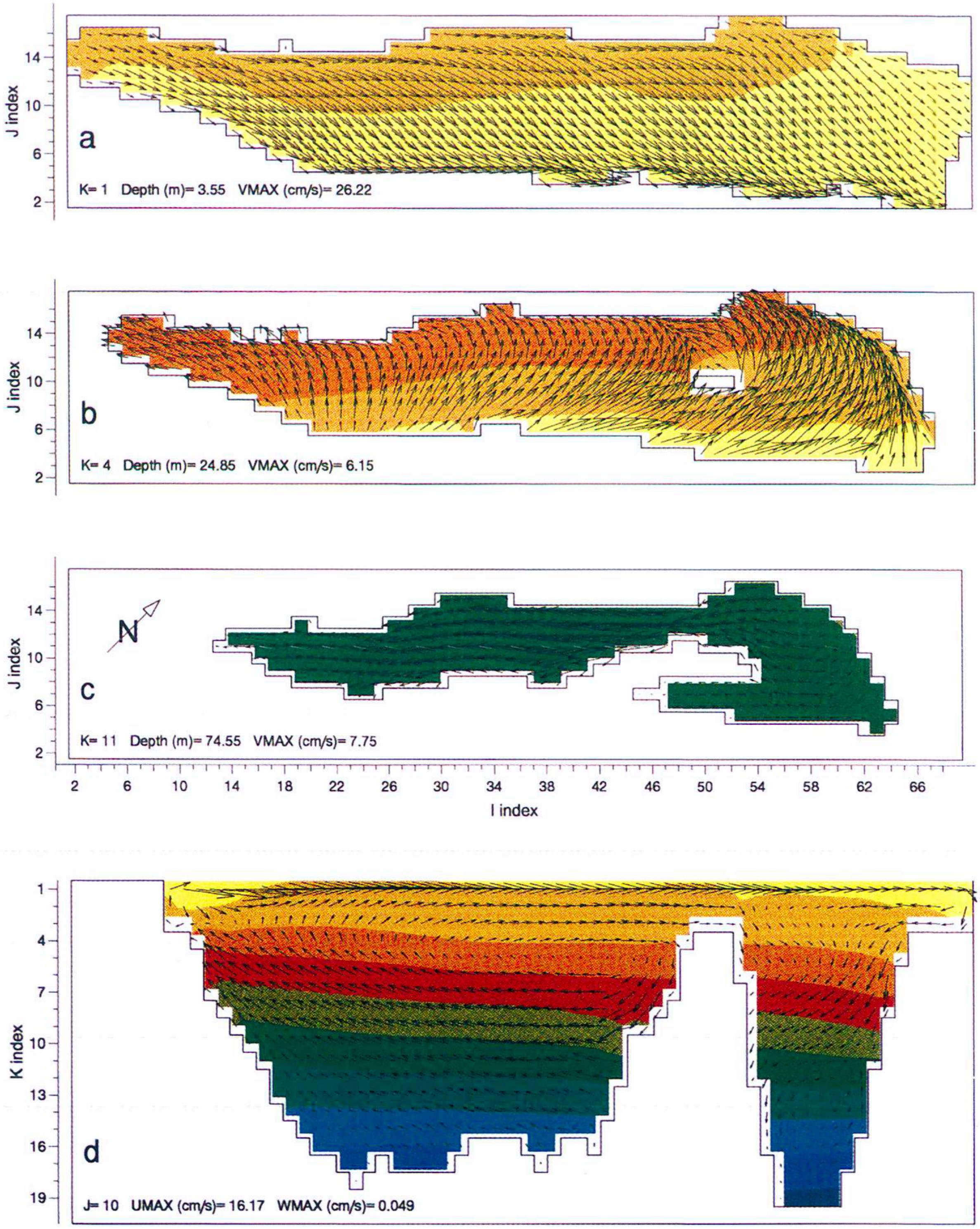

Fig. 4. Temperature and velocity fields (4a, b, c: horizontal sections, 4d: vertical section) at the end of a period of 12 hours of SW wind forcing with constant speed of 7.5 m/s. Colours refer to the temperature (see Fig. 7). For convenience and readability, scaling factors for velocity arrows are adjusted in each plot according to the maximum velocity that occurs at that level or slice. The magnitude of the longest vector is denoted under the corresponding plot. The depth-level is indicated by the K value and the slice by the J value (see Fig. 2). The south-west wind drags the surface currents eastward, inducing upwelling in the west part and downwelling in the east part of the lake. The water flux of the upper layers is balanced by a countercurrent in the deeper ones.

locity increases abreast of "la Motte", where the passage narrows. When examining the vertical slices of Figures 4d and 6a, one sees the vortex in the vertical W-E plane which has been built up by the wind and one recognizes the characteristic vertical shift of the isotherms accompanying upwellings and downwellings. This feature also clearly appears in the horizontal sections.

Figures 5 and 6b show the situation six hours later, during which period the wind was turned off. Near the surface (Fig. 5a), the current is directed towards the north-west coast and the water masses sink to feed a south-westward current in the deeper layers. This current is quite observable in Figure 5c as well as in Figure 5d from the section k=6 to section k=11 (from 40 to 80 m in depth). The underwater hill "la Motte" profoundly affects the circulation, separating two hydrodynamic sub-basins (NE and SW) of the lake. Moreover, in the longitudinal (Fig. 5d) and transverse (Fig. 6b) sections of the lake, one notices the subdivision into two opposite rotating cells, epilimnetic and hypolimnetic, which is a typical feature of thermally stratified flows. The latter feature will be of particular importance on particle disperison, producing reciprocating motions in the successive layers during settling. Notice the relative similitude between the thermal structures of Figures 4d and 5d as well as between the ones of Figures 6a and 6b, while the velocity fields appreciably differ. Only six hours without wind have elapsed between the two states visualized in these figures. In view of the order of magnitude of the vertical velocities, notable displacements of the isotherms would require a longer period between the repeated south-west wind events.

Vertical temperature profiles were measured at five stations along a SE-NW transverse section (Chevroux-Cortaillod). The interpolated field (measures on 5-11-92) is shown in Figure 6c. The wind conditions prior to the measurements were close to the simulation conditions (a calm period following a period of south-west wind) and the observed temperature field may be compared with the computed one displayed in Figure 6b. The comparison brings out the similitude of the thermal structures: two opposite inclinations appear up and down the 9°C isotherm. One can see in Figure 5d that the 9°C isotherm draws the boundary between the two rotating cells obtained by the model.

Particle dispersion

The second simulation is performed to illustrate the dispersion of particles released in the lake by the Areuse river. In this case, meteorological wind data from the "Observatoire Cantonal de Neuchâtel" are used to force the model (Fig. 8). The particle dispersion is performed by injecting suspended particles into the circulation model. During the first two weeks of the run, particles are released at a constant rate of 400 particles per day. They are continuously injected into the surface cell adjacent to the Areuse entrance. The starting position of each particle in this cell is chosen at random. After 15 days, a total of 6,000 particles is released and no more particles are added during the next 27 days. Once injected, the particles are transported by advection by the surrounding fluid.

In addition, while particles are assumed to have a higher density than the fluid, they possess a vertical settling velocity with respect to the surrounding fluid, which is set to 0.25 m/h. This value is estimated from sediment traps experiments. The total sediment fluxes divided by the mean particulate matter concentrations in the lake water above the traps provides a mean settling velocity. Values obtained for the stratified period average

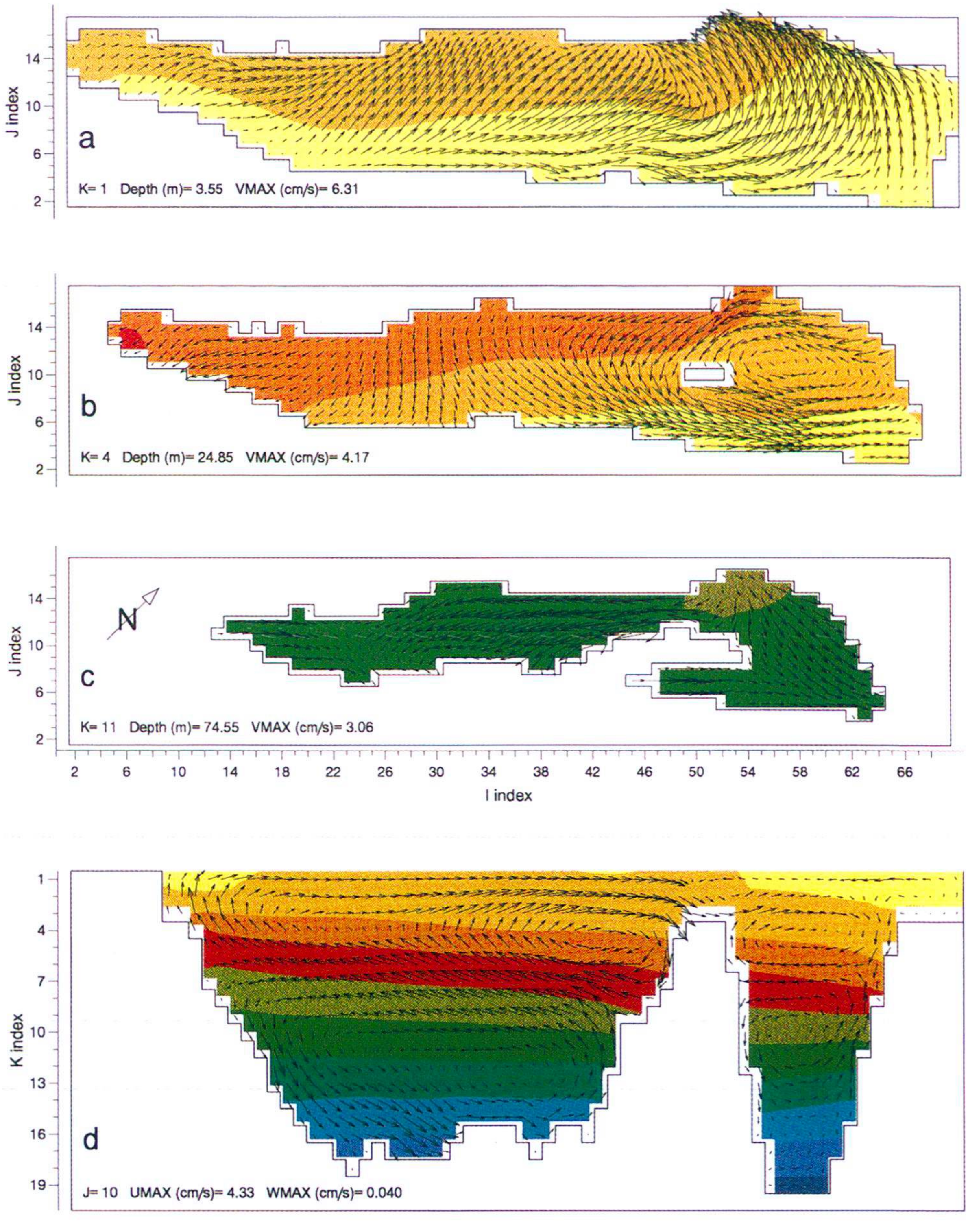

Fig. 5. Temperature and velocity fields (5a, b, c: horizontal sections, 5d: vertical section) six hours later the time corresponding to Figure 4. During this period, the wind has been turned off. Near the surface, the current is directed towards the NW coast and the water masses sink to feed a south-westward current in the deeper layers. In the vertical section, one notices the subdivision into two opposite rotating cells, epilimnetic and hypolimnetic.

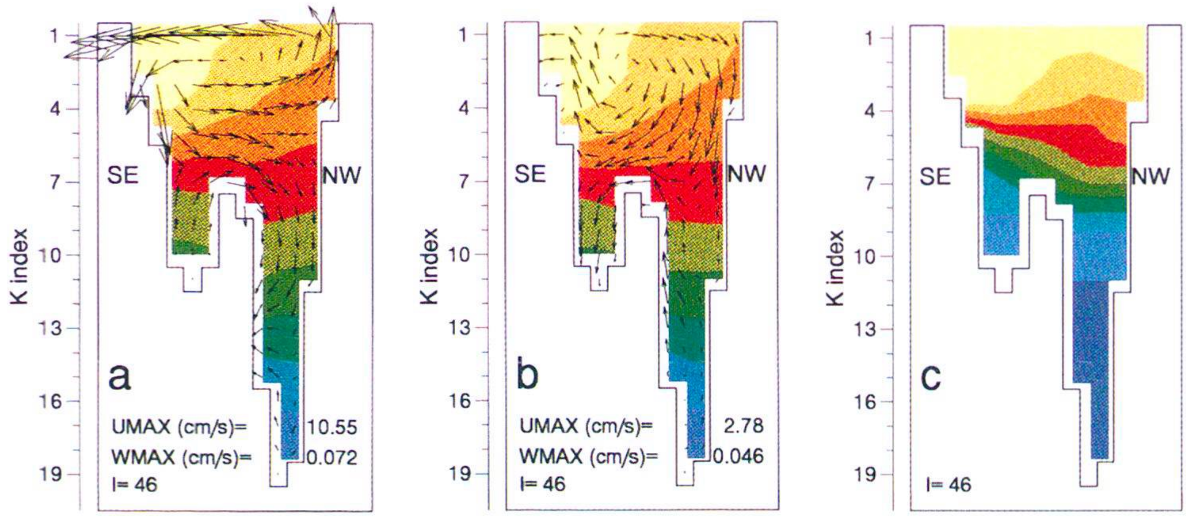

Fig. 6. Temperature and velocity fields (SE-NW transverse section) after a period of 12 hours of SW wind forcing with constant speed of 7.5 m/s (Fig. 6a) and six hours later, during which the wind has been turned off (Fig. 6b). Temperature field interpolated from measurements along the transverse section (Fig. 6c). The corresponding slice is indicated by the I value (see Fig. 2).

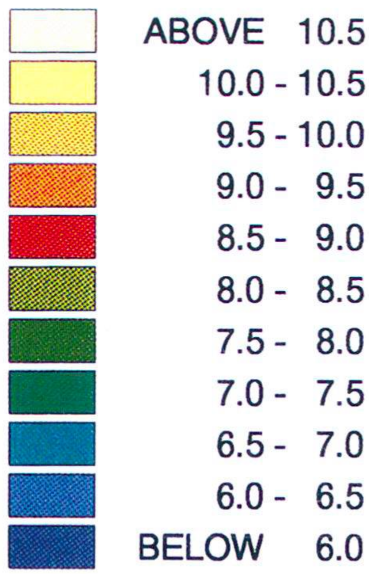

Fig. 7. Colour scale for temperature fields (°C) of Figures 4, 5 and 6.

0.183 m/h in the epilimnium and 0.245 m/h in the hypolimnium. This way of calculation provides an order of magnitude estimate of the mean particle sinking velocity and doesn't attempt to provide settling velocities for individual particles. On this basis, settling velocities were calculated in other Swiss and North-American lakes. For example, Eadie et al. (1990) obtained mean values of 0.21 m/h for the three Laurentian Great Lakes, Lakes Michigan, Huron and Superior for the unstratified period. These values, however, are lower by an order of magnitude for the stratified period (0.0217 ± 0.0067 m/h).

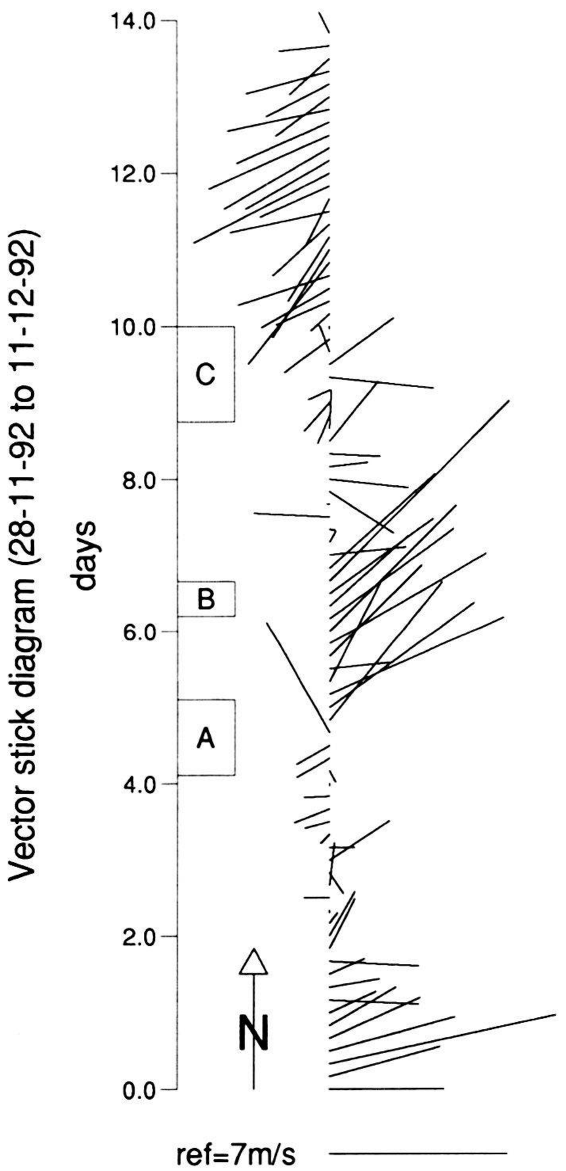

Fig. 8. Vector diagram of wind conditions prevailing during the particles inflow. Each stick is oriented in accordance with the wind direction. The wind vector is updated every four hours. The capital letters A, B and C refer to specific episodes of particle release. Different wind regimes can be distinguished. The run starts with nearly two days of west wind. After three days' rest, the south-west wind ("le Vent") blows during two days. Then, changing winds follow, before the north-east wind ("la Bise") prevails during four days.

Figure 9a shows a horizontally projected distribution of the suspended particles at different times (day 4 to day 14). As already mentioned, in the upper layers near the surface, the circulation is particularly sensitive to the wind conditions and its variations, and so is the bulk transport. In the deeper layers, particles are advected by the undercurrents which are less sensitive to the wind variations but depend more strongly on the lake morphology. The major obstacle constituted by the underwater hill "la Motte" clearly appears on the isobath map of Figure 10. Dispersion of the particles is the result of the combined effect of settling and advection by the currents under varying wind conditions. The complex way in which the particles are dispersed from the river outlet is illustrated by the successive plots of Figure 9a. Until the sixth day, the particles go along rather similar trajectories. From the eighth day onwards, the look of the plots radically differs. The particles are spread in all directions and, while some particles seem not to be influenced by the wind variations any more, other ones continue to disperse. Figure 9b shows the distribu-

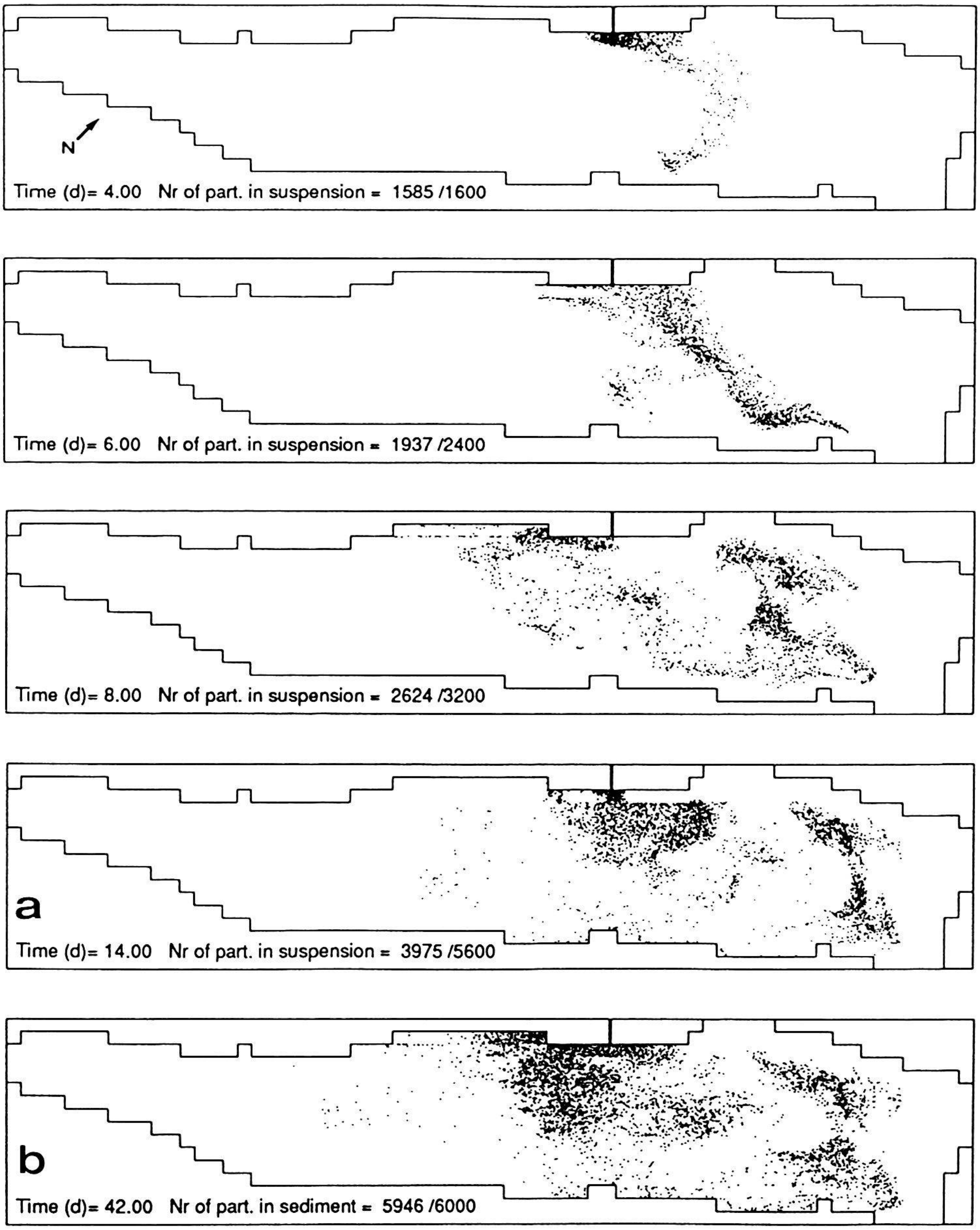

Fig. 9. Spatial distribution of the suspended particles at different times (Fig. 9a) and of the deposited ones at the end of the run (Fig. 9b). The suspended ones are viewed from the lake surface to the bottom (tomography). During the first two weeks of the run, particles are released at a constant rate of 400 particles per day. They are continuously injected into the surface cell adjacent to the Areuse entrance. After 15 days, a total of 6,000 particles is released and no more particles are added during the next 27 days. The vertical settling velocity with respect to the surrounding fluid is set to 0.25 m/h. In each but the last plot, the time (in days) and the number of particles in suspension are mentioned. The difference accounts for the deposited ones.

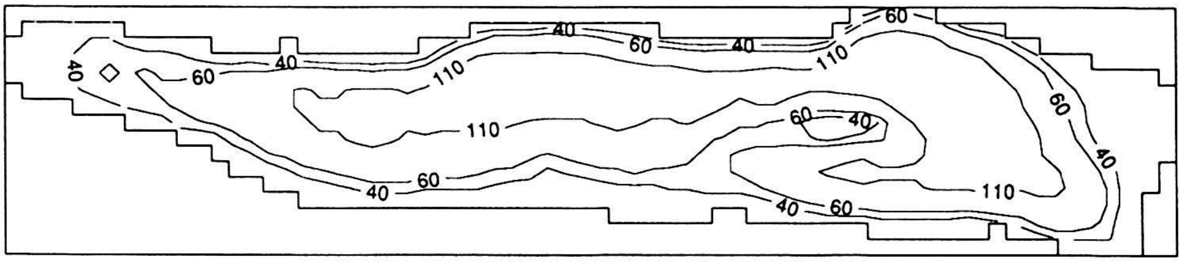

Fig. 10. Topography of the lake bed. The isobaths (m) delimit the coastal slopes, the bathyal plain and the ridge of "la Motte".

tion of the particles in the sediment at the end of the run (day 42). In shallow areas exposed to particle fluxes, the material is deposited first. Consider the case of "la Motte" and its west side, which, stopping some particles getting past, deposit them. Some other particles, carried by intense surface currents, cross the lake and reach the opposite shore. Closer to the Areuse outlet, the coastal slopes collect a non negligible amount of particulate matter and this, in various ways: either the particles are released during a calm period when currents are weak, and stay near the outlet until sedimentation (see Fig. 9a, day 4, for particles released after day 2); or alternatively the particles are brought back by undercurrents (see Fig. 9a, day 8, after a period of south-west wind); or finally they are confined along the shore by westward currents. In these two latter cases, the sediments are localised west of the outlet. In the most north-eastward part of the lake, one can distinguish two deposition areas. Particles have settled in the bathyal plain and on the north and south-east slopes. Between these two deposition areas and "la Motte", the bathyal plain is free of particulate matter. A last deposition area appears in the bathyal plain and on its slopes, south of the Areuse outlet. There, all the particles which have not been carried beyond "la Motte" by the surface currents settle. An overall view of the sedimentation map allows to conclude that sedimentation occurs mainly in the north-east half of the lake, the south-west half being almost free of any deposition.

Interpretation of the results of Figure 9 has made conspicuous the great variability of particle pathways and of sedimentation areas, depending on wind conditions. In order to illustrate this dependance in a more evident way, three groups of particles taken out of all the ones released have been traced. These groups correspond to specific wind episodes which are indicated by a capital A, B and C in Figure 8. The particles of group A are released after a calm period and just before a two days period of south-westerly wind. At the end of this period which precedes a period of changing winds, particles of group B are released. Finally, the ones of group C come after two more days, just before a period of north-east wind.

First, we consider group A in Figure 11. These particles are released during a calm period and therefore they remain grouped and form a patch. Once the wind has risen (see Fig. 8), they are quickly transported by the surface current induced by south-west wind (day=6). When they reach the deeper layers, primarily as a result of their settling velocity, they are swept along towards the north slope (day=8). It may be verified that this current corresponds to the one shown in the previous section (Fig. 4b). Afterwards, the wind drops and the particles continue to settle. The deeper the particles sink, the less sensitive to the wind conditions their transport is and until their sedimentation they re-

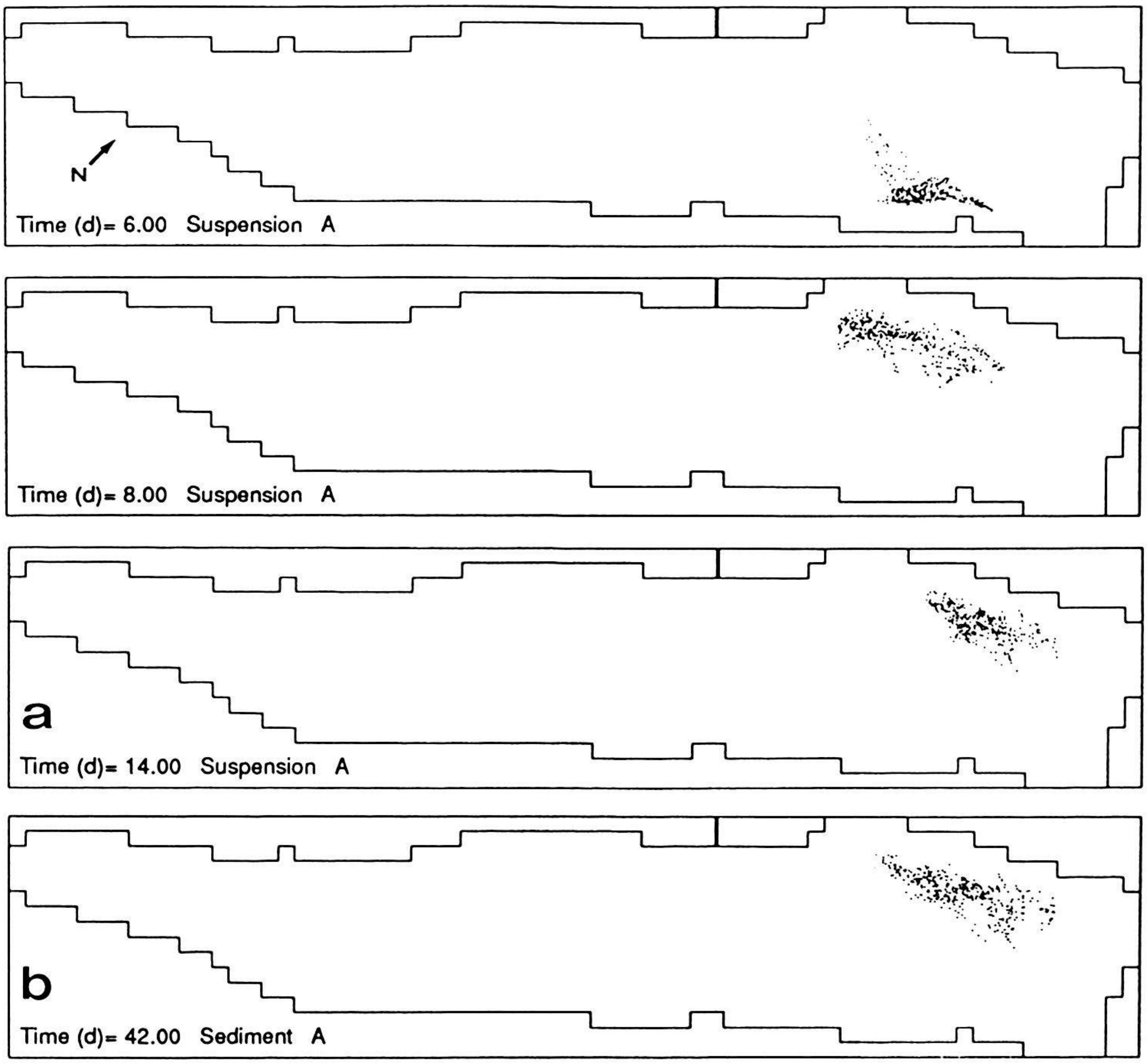

Fig. 11. Spatial distribution of the particles of group A, in suspension (Fig. 11a) and in sediment (Fig. 11b). This group collects, out of all the particles of the run illustrated on Figure 9, the ones which have been released during the specific episode indicated by a capital A on Figure 8. This episode corresponds to a calm period preceding two days of SW wind. The suspended ones are viewed from the lake surface to the bottom (tomography).

main located in the same part of the lake. Next, we consider group B in Figure 12. This time, the south-west wind has been blowing for more than a day when the particles are released (Fig. 8). They are immediately swept along by the current, making a slender streak (day=8). The changes in wind conditions have a strong dispersive effect on particles transport in the upper layers. Given the reduced time interval of discharge of this group B, the effect of dispersion is quite spectacular. Note that these particles are among the ones which settle at the most westward location (compare with Fig. 9). Finally, Figure 13 shows the fate of the particles of group C released before a period of north-east wind ("la Bise"). At the beginning, the particles accumulate near the Areuse outlet (day=10). When this wind starts blowing, the shore confines the induced surface current (day=12) and the particles sink with water. Because downwelling accelerates the settling, the par-

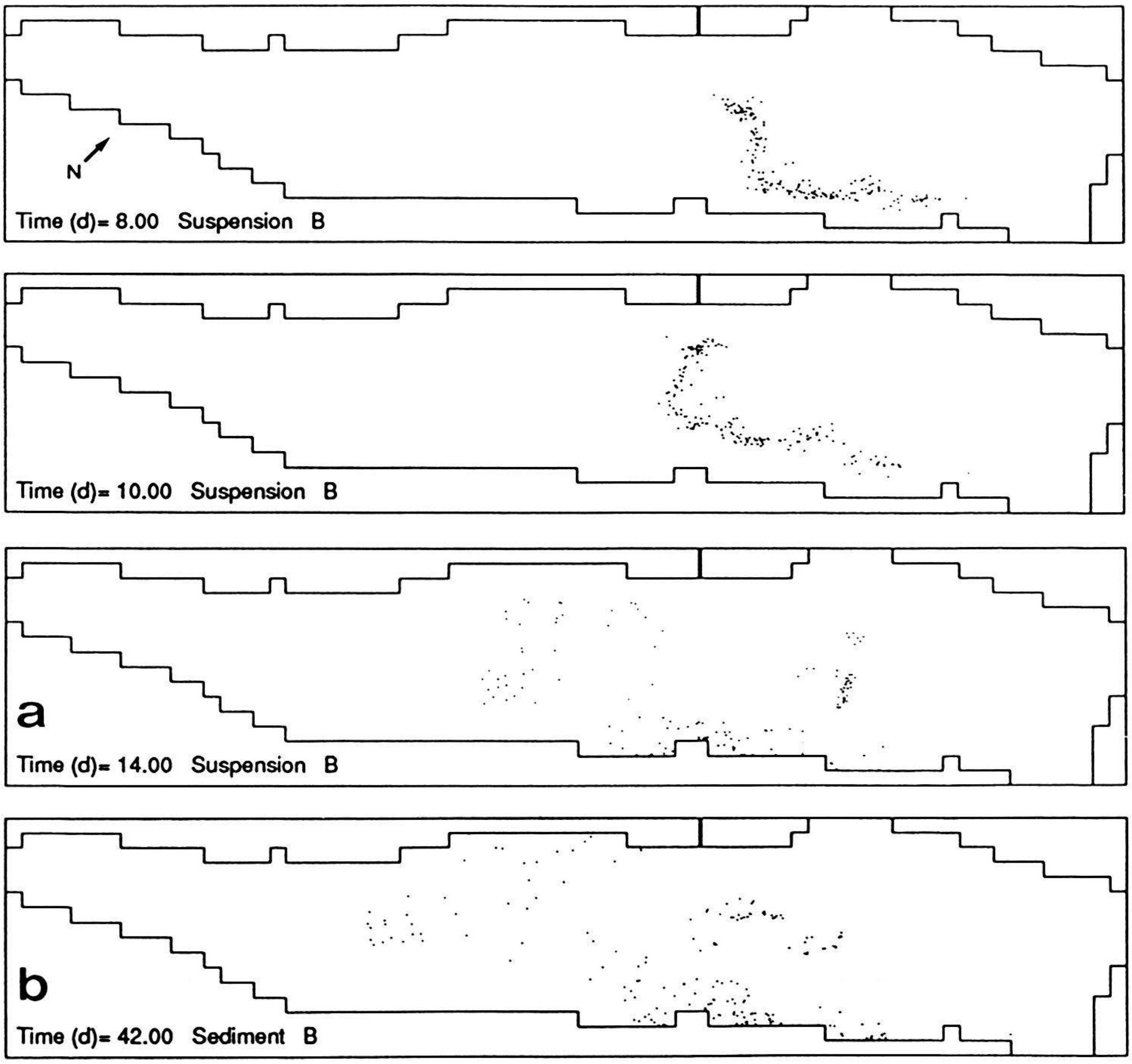

Fig. 12. Spatial distribution of the particles of group B, in suspension (Fig. 12a) and in sediment (Fig. 12b). These particles have been released at the end of a two days period of SW wind before a period of changing wind (see Fig. 8). The suspended ones are viewed from the lake surface to the bottom (tomography).

ticles quickly reach the deeper layers. Less than two days later, they are advected by an eastward countercurrent (day=14). Examining the last plot (day=42), one notes that the particles have come back and settled opposite the Areuse outlet. Comparison between the sedimentation maps of Figures 11, 12, 13 and Figure 9 allows to identify the particles of each group among the whole.

In experimental work, it is a major difficulty to recognize the particulate matter in the sediment from the Areuse outlet because it doesn't have a distinct signature. The reason for this is the mixing in the sediment with other material that has a similar composition, but which originates from autochthonous production or other river inlets. Nevertheless, a comparison between sedimentation rates in various sites of the lake may supply some information. Figure 14 shows the results of measurements of total carbon content in two cores taken in the bathyal plain at respectively 1 km (LN04) and 5 km (LN01) away from

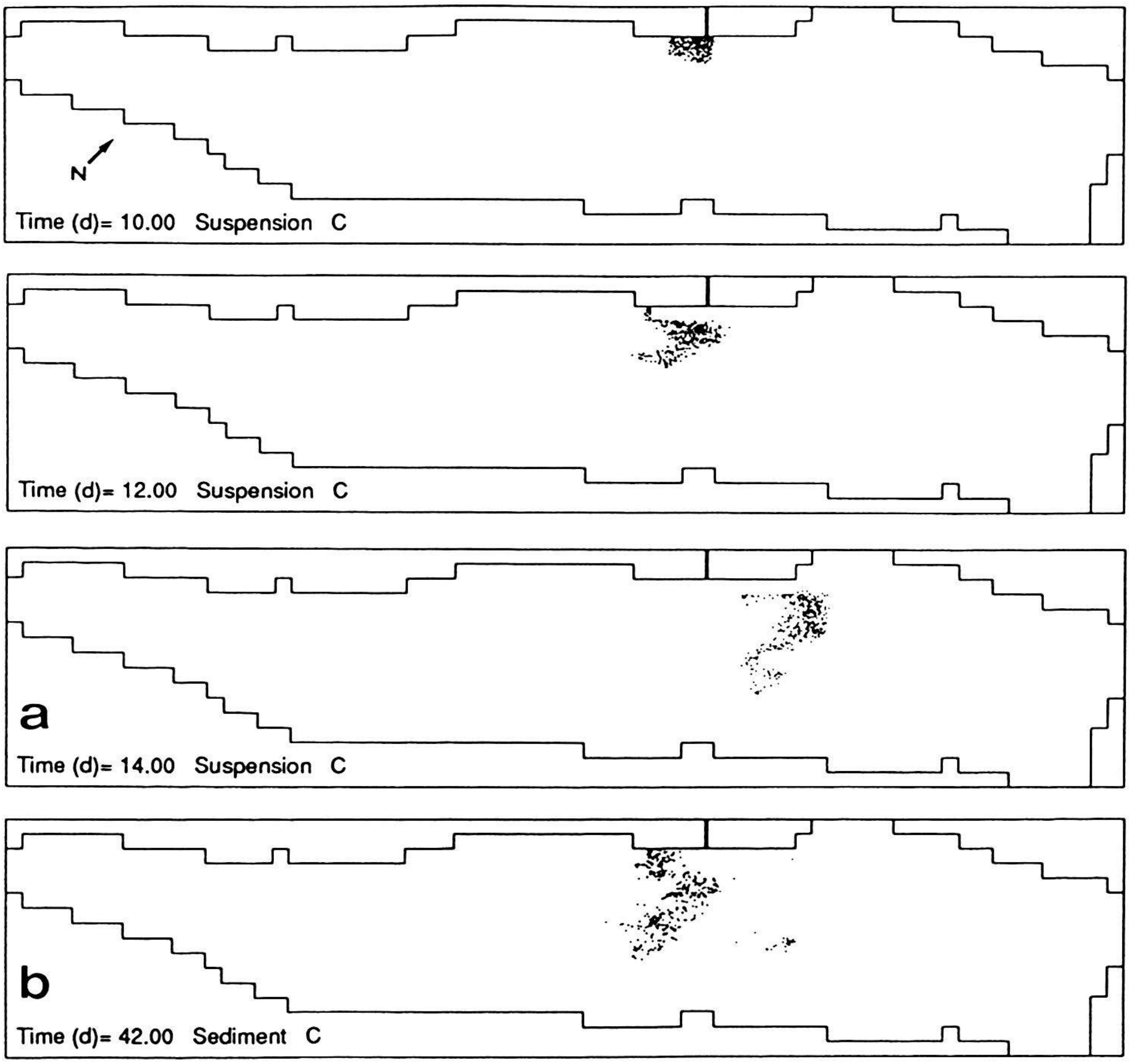

Fig. 13. Spatial distribution of the particles of group C, in suspension (Fig. 13a) and in sediment (Fig. 13b). These particles have been released just before a period of NE wind (see Fig. 8). The suspended ones are viewed from the lake surface to the bottom (tomography).

the Areuse outlet. In Younger Subatlantic, four sub-units limited by minima of total carbon content are distinguished. The inferred accumulation rate, although fluctuating, is of the same order of magnitude in the two cores and the mean accumulation rate over the entire period is not more than 10% superior at 1 km than at 5 km away from the outlet. So, a strong decrease of sedimentation with distance from the outlet is not observed. This fact would confirm that the dispersion takes place on a large scale which is induced by the lake currents.

Concluding remarks

Two simulations have been performed in Lake Neuchâtel. The first simulation has made conspicuous some characteristics of its general circulation. One noticeable feature which

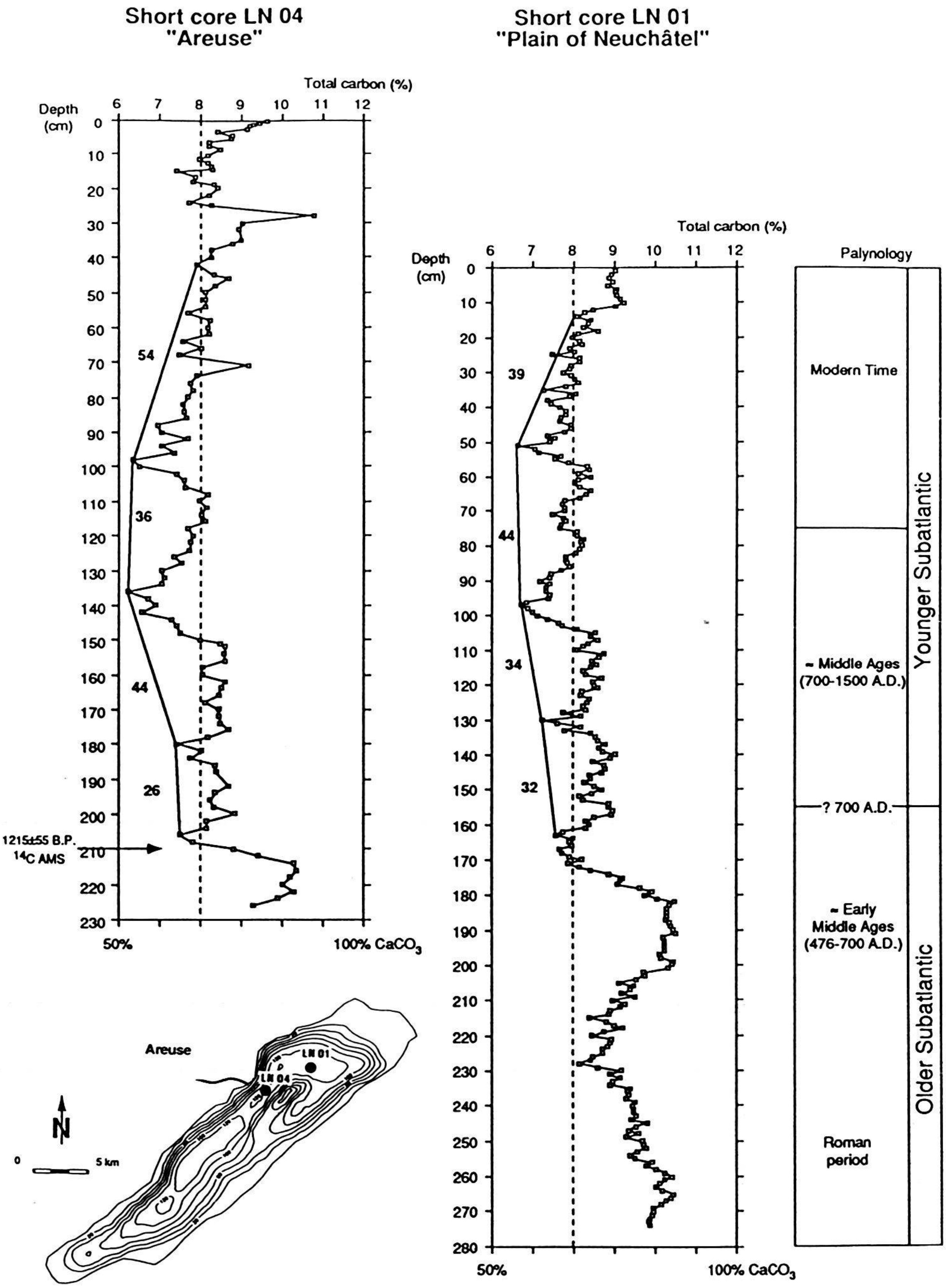

Fig. 14. Variations of total carbon content (%) versus depth (cm) in two short cores taken, the first one (LN04) just in front of the Areuse outlet and the second one (LN01) in the plain of Neuchâtel. The bold numers indicate the thickness of each of the four sub-units. They allow to compare the sedimentation rates between the two cores. On the right side of the figure, a chronological scale is supplied by palynology.

significantly affects the particle transport, is the build up of two vertical cells rotating in opposite directions due to the thermal stratification of the lake. The second simulation has illustrated the complex way in which the particles are dispersed from the river Areuse outlet under realistic wind conditions.

The presented results are clearly based on over-idealized assumptions. Therefore no quantitative accuracy can be expected from them. More refined results could be obtained by including a sophisticated particle transport model, which takes relevant physical, chemical and biological processes into account. The objective here, however, was merely to identify the preferred location and the spatial scale of the sedimentation of the bulk part of the suspended particulate matter that is realeased from the Areuse outlet. The results show that the sedimentation area, during the season in which the particle load of the Areuse is particularly high, is restricted to the NE part of the lake. This would support the observations of several studies that show the dependence of the rate and composition of sedimentation on geographic location in the lake. Longer term simulations appear to be promising in order to understand the geographical distribution of suspended particulate matter released into the lake from various sources.

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