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Origin and size of hypolimnic mixing in Urnersee, the southern basin of Vierwaldstättersee (Lake Lucerne)[1)]

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ABSTRACT

Urnersee and Gersauersee are two adjacent basins of Vierwaldstättersee (Lake Lucerne, Switzerland), seperated by a sill of 85 m depth, with similar topography (max. depth 195 and 213 m, respectively) but remarkably different exposure to "external forces", such as wind and river input. Urnersee is exposed to diurnal winds and to occasional strong storms from the south (Föhn) whereas the wind over Gersauersee is moderate or weak. Two rivers, both having very large discharges during storms, replace the total water volume of Urnersee about once a year; in contrast, no large river flows directly into Gersauersee. Between March and October 1986, meteorological parameters, water temperatures and currents were measured quasi-continuously with the aim to quantify hypolimnic water exchange and mixing in Urnersee and to assess the relative importance of wind mixing versus river-induced water exchange for the renewal of the deep water layers. Three periods could be identified: (1) in April, weak stratification and strong episodic storms exchange about 50% of the deep hypolimnion (DH, defined as layer below 110 m depth) leading to a mean heat flux of 36 Wm^2. Because of the large wind mixing the water of the exposed Urnersee below about 20 m depth becomes lighter than in the sheltered Gersauersee. (2) In May and June, the horizontal density gradient causes about 65% renewal of the Urnersee DH by the heavier Gersauersee intermediate water but does not affect the heat content. (3) Simultaneously with these processes are the episodic river floods adding another 20% to the DH water exchange and causing a heat flux of about 6 Wm^2. During the rest of the summer, water exchange remains below 10% and is mainly due to episodic flood while wind mixing has little influence. Yet, during floods water input into the DH per unit time can still be very large and heat fluxes reach 600 Wm^2 or more. The influence of lateral density currents between the two adjacent basins on hypolimnic mixing is of great ecological significance and explains the larger oxygen saturation found in the deep water of Urnersee compared to Gersauersee.

1. Introduction

1.1 *Ecological significance of mixing processes*

The state of a lake is influenced by various factors such as the spatial and temporal distribution of organisms, dissolved and particulate matter, thermal and mechanical

1) Supported by the Swiss National Science Foundation.

energy fluxes. These factors themselves are interrelated by physical, chemical, and biological processes among which mixing plays a central role by controlling the pace at which the reactants are brought into contact or delivered to the "scene of action". Heat exchange and wind stress at the water surface are the most important forces driving mixing in lakes. In addition, river inflows and density gradients caused by the temperature and the chemical composition of the water can induce currents in lakes. Investigations on the influence of anthropogenic perturbations on aquatic ecosystems require detailed knowledge regarding the effect of external forces on lake mixing.

This investigation deals with one particular aspect of lake physics which is still not fully understood, with water exchange and mixing in the hypolimnion of deep lakes. The importance of these processes becomes apparent by considering, for example, the transport of nutrients from the deep water layers into the trophogenic layer or, in reverse, the flux of oxygen from the surface into the hypolimnion. The former controls the productivity in the surface layer, the latter the redox potential in the hypolimnion and the chemical exchange fluxes at the sediment-water interface.

1.2 *Hypolimnic water exchange and mixing*

Water exchange and mixing are the two prototype processes which are responsible for the transport of water and its dissolved or suspended constituents. Water exchange means the flow of "bulk volumes" of water from one location to another where, in turn, the water is pushed away. In other words, water volumes exchange their places but keep their identity. In contrast, mixing means the "amalgamation" of adjacent water parcels into a parcel of new physical and chemical characteristics. Of course, the distinction between exchange and mixing is artificial to a certain extent: First, there is no water exchange without mixing, at least not at the boundaries of the water masses involved in the exchange. And second, it is ultimately a question of time and length scales whether some water movement is considered as exchange or as mixing. Let us assume, for instance, that by some mechanism two equivalent volumes of water exchange position across the thermocline. This is clearly an exchange process at first sight, but from some distance in space and time we observe that the physical-chemical properties of the water on either side of the thermocline have become more alike, i. e. that some mixing occured. In spite of this objections, the two terms will be used in the following discussion to describe and classify the various processes of water movement observed in the hypolimnion of deep lakes.

Mixing is caused by turbulent flow. In the absence of a vertical density stratification the turbulent kinetic energy brought into the lake by wind and rivers easily spreads in all directions throughout the lake. If the lake is stratified, the kinetic energy of the water is primarily concentrated in the horizontal plane. In this case turbulent mixing below the thermocline draws its energy from the external forces mainly in an indirect way. One mechanism is by the so-called Kelvin-Helmholtz instability: Internal waves and seiches at the thermocline produce horizontal currents in the hypolimnion. Provided that the vertical gradient of the currents, i. e. the vertical shear, exceeds a certain critical value determined by the vertical density stability, the interface between adjacent water layers may become unstable. Consequently, some of the stream lines are increasingly distorted until they turn over and irreversibly mix part of the water from different layers. Thorpe (1969) has beautifully illustrated this process. The effekt of a great number of such events can be described in a simplified manner by a vertical turbulent diffusion coefficient.

Not as well understood are mixing processes at the sediment-water interface. While in the ocean water velocities and shear stress were directly measured within the sediment-water boundary layer (Gust and Weatherly, 1985) and even within the viscous layer of some 10^{-3} m thickness (Caldwell and Chriss, 1979), no comparable data exist for lakes. Bottom current velocities in lakes are generally smaller than in the ocean; typical values for Baldeggersee in Central Switzerland are around 0.01 m s^{-1} (Lemmin and Imboden, 1987). It is not even known whether the bottom currents are generally turbulent or quasi-laminar.

In a stratified lake, water exchange in the hypolimnion can either be triggered from above or from below. The latter is caused by the subsurface intrusion of groundwater, the former by so-called density currents (Simpson, 1982), i. e. by the penetration of heavier water into the hypolimnion accompanied by a slow upwelling of the displaced hypolimnic water in the whole lake. Such densitiy currents are primarily induced by inflows or by inhomogeneous cooling or warming of the water body. As will be shown, lateral variation of the wind field over the lake may also be responsible for density currents. Although intrusions of surface water into the hypolimnion can be of greatest ecological relevance (especially in eutrophic and other polluted lakes), little is known about such phenomena (Imberger and Hamblin, 1982). Also, it is not known whether the chemical "loading" of the water near the sloping sediment surface (accompanied by a density increase) may lead to currents along the sediments thus concentrating certain compounds in the deepest part of the lake. Indications for non-diffusive exchange processes are found in most deep lakes, once the vertical distribution of water temperature is measured at high enough resolution and precision. For instance, water temperature in the deepest layer of Gersauersee rises during summer (Fig. 14). The added thermal energy can only partially be explained by the geothermal heat flux of about 0.1 Wm^{-2} (Finckh, 1981).

Another source of density currents are the rivers entering the lake. Density currents loaded by suspended particles, so-called turbidity currents, have been found at several river mouths such as the Linth in Walensee (Lambert et al., 1976), the Rhine in Bodensee (Lambert, 1982) and the Rhone in Lake Geneva (Lambert and Giovanoli, 1987).

1.3 *Objectives of investigation*

The aim of the field investigation in Lake Lucerne (Switzerland) described below was the identification and quantification of the different hypolimnic mixing and exchange processes. Time and location of the moorings for the instruments were

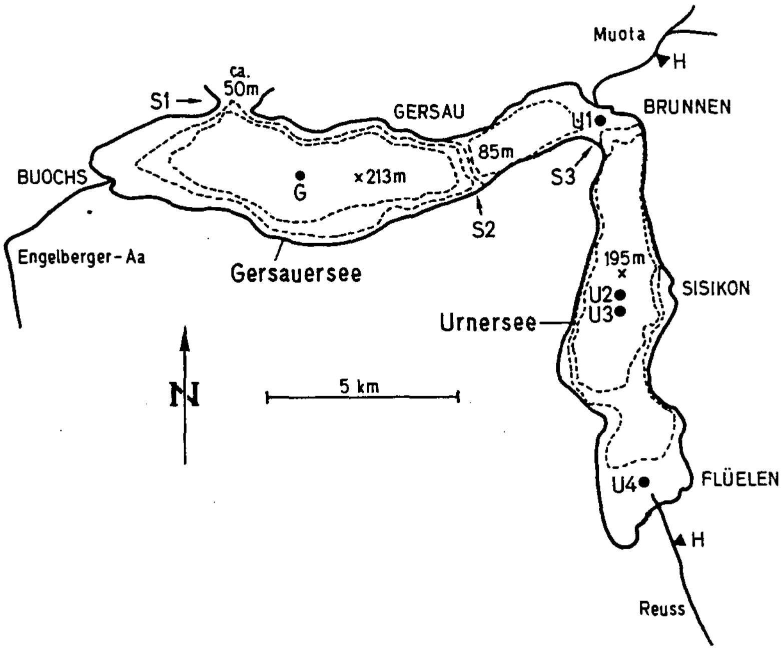


Figure 1. Map of southern basins of Lake Lucerne (Vierwaldstättersee), Urnersee und Gersauersee, showing the lake topography (contour lines at 100 and 150 m), the subsurface sills (S1, S2, S3), the main inlets mentioned in the text, and the sampling stations: U1, U4 = moorings containing thermistor chains and current meters, two at each location; U2 = meteorological buoy; U3 = thermistor chain 10 to 110 m; G = CTD-position in Gersauersee, H = recording stations of Swiss Hydrological Service.

chosen with the primary goal to compare the relative contributions from wind-induced and river-induced transport processes. More specifically, the following questions were asked:

- What is the relative contribution to hypolimnic mixing and exchange from the inlets compared to the influence from the wind and how does it change during the year?
- What is the rate of deep water renewal?
- How much heat is brought to the hypolimnion by density currents?
- What is the role of single wind storms to hypolimnic mixing?

Regarding the possible lateral water exchange between the two adjacent basins, Urnersee und Gersauersee, vertical profiles of water temperature and electric conductivity were occasionally taken in Gersauersee, as well. As we found out later, this information became very important for the interpretation of the dynamics in Urnersee.

In this article an overwiev of the different phenomena is presented which where found in Urnersee. More detailed physical discussions of some of the processes will be the subject of further publications.

2. Field program

2.1 *Urnersee and Gersauersee*

Urnersee and Gersauersee (Fig. 1) are two adjacent basins of Vierwaldstättersee (Lake Lucerne) with rather similar topography (Tab. 1) but remarkably different exposure to "external forces", such as wind and river input (Tab. 2). The basins are separated by two underwater sills; the shallower one (S2) reaches up to 85 m below the lake surface.

Table 1: Characteristic data of Urnersee and Gersauersee

	Urnersee	Gersauersee[1)]
Surface area [km^2]	22.0	30.3
Maximum depth [m]	195	213
Mean depth [m]	144	145
Volume [$10^6 m^3$] total	3160	4390
below 110 m	1070	1530
Mean residence time of water [yr]	1.4	1.5[2)]
Mean river input [m^3s^{-1}]	70	90[2)]

1) Including the small basin located between the underwater sills S2 und S3
2) Including input from Urnersee

Urnersee is located along the north/south axis of the upper Reuss valley which reaches far into the central alps and thus serves as a channel for the diurnal thermal winds. During the day, solar radiation causes the air along the mountain slopes south of Urnersee to warm and rise thus leading to a southward wind along the valley to replace the rising air. During the night, the air on the mountains cools faster than in the Reuss valley.
The Reuss valley is also the scene of action of the famous Föhn, an often very strong wind blowing across the alps from the south. Since the rising air loses most of its moisture on the southern slope of the alps, the Föhn is felt as dry and warm air on the northern side of the mountains. Föhn storms are responsible for the highest wind speeds measured in the Swiss mountains; they give rise to speeds at the bottom of the valleys which occasionally peak at 50 ms^{-1} and more. The traces of two such (moderate) storms can be seen in Fig. 3 (April 21/22 and April 26). Again, Gersauersee is much less affected by the Föhn than Urnersee.
The two basins also differ with respect to the amount of river water flowing directly into them (Tab. 2): The annual mean discharge into Urnersee from its three largest tributaries amounts to about 66 m^3s^{-1}; discharge into Gersauersee from its only larger river (Engelberger Aa) is only 12 m^3s^{-1}. Since the water from Urnersee later flows through Gersauersee, the mean residence time of the water is roughly equal in both basins, but the direct kinetic energy impact is much larger in Urnersee than in Gersauersee. Knowing these two differences one can intuitively conclude that vertical mixing and exchange must be stronger in Urnersee than in Gersauersee. Indeed,

Table 2: Characteristics of major tributaries of Urnersee and Gersauersee[1)]

River	Mean discharge [m^3s^{-1}]	Max. discharge [m^3s^{-1}]	Drainage area [km^2]	Mean altitude of drainage area [m a. s. l.]	Drainage area covered by ice [%]
Urnersee					
Reuss	45.0[2)]	550 (1939)	832	2010	11.4
Muota	19.0[3)]	330 (1977)	316	1360	0.05
Großtalbach	1.81[4)]	48 (1977)	43.9	1820	9.1
Gersauersee					
Engelberger Aa	11.7[5)]	57	227	1620	4.3

1) From Hydrologisches Jahrbuch der Schweiz, edition 1983
2) Mean value for years 1922–1983
3) 1923–1983
4) 1957–1983
5) Year 1983 only

the thermocline is generally deeper in the former basin. In addition, the large hypolimnic oxygen saturation which are common throughout the year (80% and more) seems to indicate that Urnersee is regularly turning over. In Gersauersee, however, mixing seems to be often incomplete. Undersaturation of oxygen in the deep water layer at the beginning of the stratification period may cause the oxygen concentrations to drop below 4 mg/l, in fall (H. Ambühl, private communication). As will be shown, there are other reasons for the different physical behavior of the two basins.

2.2 *Instrumentation*

The characteristics of the instruments used for meteorological parameters, water currents, temperature and electric conductivity are presented in Table 3. The CTD probe was used for single casts from a boat, the other instruments were moored in the lake at the locations shown in Figure 1. In addition to the data collected in the lake we used the flow rates and water temperatures of the tributaries to Urnersee measured by the automatic stations of the Swiss Hydrological Service. The response time of the instruments is given as the time for 63% response (corresponding to $[1-e^{-1}]$ provided that equilibrium value is reached exponentially). Note that the slow response of the Aanderaa thermister chains is due to the special design of the instrument: The thermistors are packed inside of a PVC tube filled with oil. Response is determined by heat diffusion through the tubing and oil.
Whereas the measurement of water temperature at the precision necessary to trace mixing in lakes is relatively easy to achieve with modern instruments, the detection of hypolimnic currents is still a big problem. The threshold of mechanical instruments such as the commercial one by Aanderaa or the type built by the Laboratory of

Table 3: Accuracy, resolution, sampling intervall, and response time of sensors

Sensor	Error of single measurement	Resolution	Response time (63%)	Sampling intervall
CTD probe [1]				
Temperature	0.0025 K	0.002 K	1.2 s	2 s
Conductivity [2]	0.2 μS/cm	0.2 μS/cm	–	2 s
Thermistor chain [3]	<0.02 K	0.022 K	6 min	20 min
Meteo sensors [3]				
Wind speed	~1 %	7.4 cm/s		20 min
Wind direction		0.35 degree	[4]	20 min
Solar radiation	1 % [5]	1.8 Wm^{-2}	2.5 s	20 min
Humidity		0.1 %	several min	20 min
Air temperature	~0.2 K [6]	0.043 K	8.5 min	20 min
Current meter				
VAW [7]	threshold of	0.5 cm/s		10 min
RC-5 [3]	2 to 3 cm/s [8]	0.5 cm/s		10 min

1) Producer: Meereselektronik, Trappenkamp, FRG
2) Calibrated with standard solution of KCl
3) Producer: Aanderaa-Instruments, Bergen, Norway
4) Sensor output represents actual value, not vectorial mean. Direction sensor is damped by oil.
5) Pollution (excrements from birds, aerosols etc.) cause unknown errors; temperature dependence is 0.6 $Wm^{-2}K^{-1}$
6) Air temperature can be influenced by convection and radiation from meteo buoy, especially during periods of low wind.
7) Producer: Laboratory of Hydraulics, Hydrology and Glaciology (VAW), Swiss Federal Institute of Technology, Zurich
8) Threshold can be increased due to sand deposition or biological coating

Hydraulics, Hydrology and Glaciology (VAW) is about 0.02 to 0.03 ms^{-1}, well above most hypolimnic current speeds (Lemmin and Imboden, 1987). However, since the field program was designed to detect events, i. e. periods during which the river water would plunge below the surface and lead to hypolimnic water exchange, we decided to use the robust mechanical instruments rather than more sophisticated ones such as acoustic current meters or the pendulum current meter designed by our group (Lemmin et al., 1985).

2.3 *Experimental setup*

When planning the moorings and sampling intervals of the various instruments we started from the following questions: (1) Where does one best observe mixing events and how long do they last? (2) How long does a field program have to last in order to get a representative picture on the average influence of events in the lake?
Reversible vertical displacements of the isobars due to internal waves and seiches have typical periods between several minutes (stability oscillations) and several hours (internal seiches). However, standing waves (seiches) have much larger amplitudes than the shorter internal waves. Meteorological events usually last for a

few hours (storms or strong rainfall leading to peak discharge in the tributaries) to a few days (transition of low or high pressure zones accompanied by the corresponding variations of heat flux and wind forcing). Finally, the vertical stratification of the lake follows a yearly cycle.

Taking these various changes into account, an observation period of at least half a year with a time resolution of 20 minutes (sampling interval for automatic instruments) was chosen. This setup should allow both the study of single events such as Föhn storms (Imboden et al., 1988) and the evaluation of the average mixing regime. With respect to spatial resolution three locations were selected, the mouths of the two major inlets (Reuss and Muota) for the river-induced events, the center of the lake for wind events and the recording of the general meteorological conditions (Fig. 1). Since we did not know how far into the lake the river water would keep its original direction, two moorings were installed at each inlet, about 300 m from the mouth and about 50 m (Muota) and 80 m (Reuss) apart (roughly corresponding to twice the width of the river channels), each equipped with a current meter and a thermistor chain. A meteorological buoy containing instruments to measure air temperature, wind velocity, humidity, and solar radiation was positioned at the center of the lake. Details about the buoy are given by Marti and Imboden (1986). A thermistor chain of 100 m length was moored close to the meteorological buoy to monitor the temporal evolution of the thermal structure in the lake. Except for some periods of instrument failure simultaneous records for all instruments exist for the period from April to October 1986.

3. Diffusive versus advective exchange of hypolimnic water

3.1. *Experimental evidence from hypolimnic temperature changes*

The effect of turbulent mixing on the flux of heat and dissolved or particulate components can approximatively be described by the familiar gradient-flux expression known as the first Fickian law:

$$\text{Flux} = -K_z \partial P/\partial z \qquad (1)$$

where we have chosen the flux of an arbitrary property with intensity (or concentration) P along the vertical z-axis taken as positive downwards. K_z is the so-called turbulent (or eddy diffusion) coefficient. As a consequence of eq. (1) the integrated sum of any conservative property (i. e. a property without in situ sources and sinks) below a given depth z_0 either steadily decreases in time, if the spatial gradient $\partial P/\partial z$ is positive, or increases in time if the gradient is negative.

As an approximation, water temperature in the hypolimnion can be treated as conservative. In most lakes light extinction in the surface layers is generally large; practically no light penetrates below the thermocline. Heat fluxes and in situ production of heat due to the decomposition of biomass are negligible compared to transport of heat. Since usually water temperature T decreases with depth, turbulent mixing is expected to add to the hypolimnic heat content. Figure 2 summarizes the temporal variation of the water temperature in Urnersee between 30 and 110 m. Whereas in

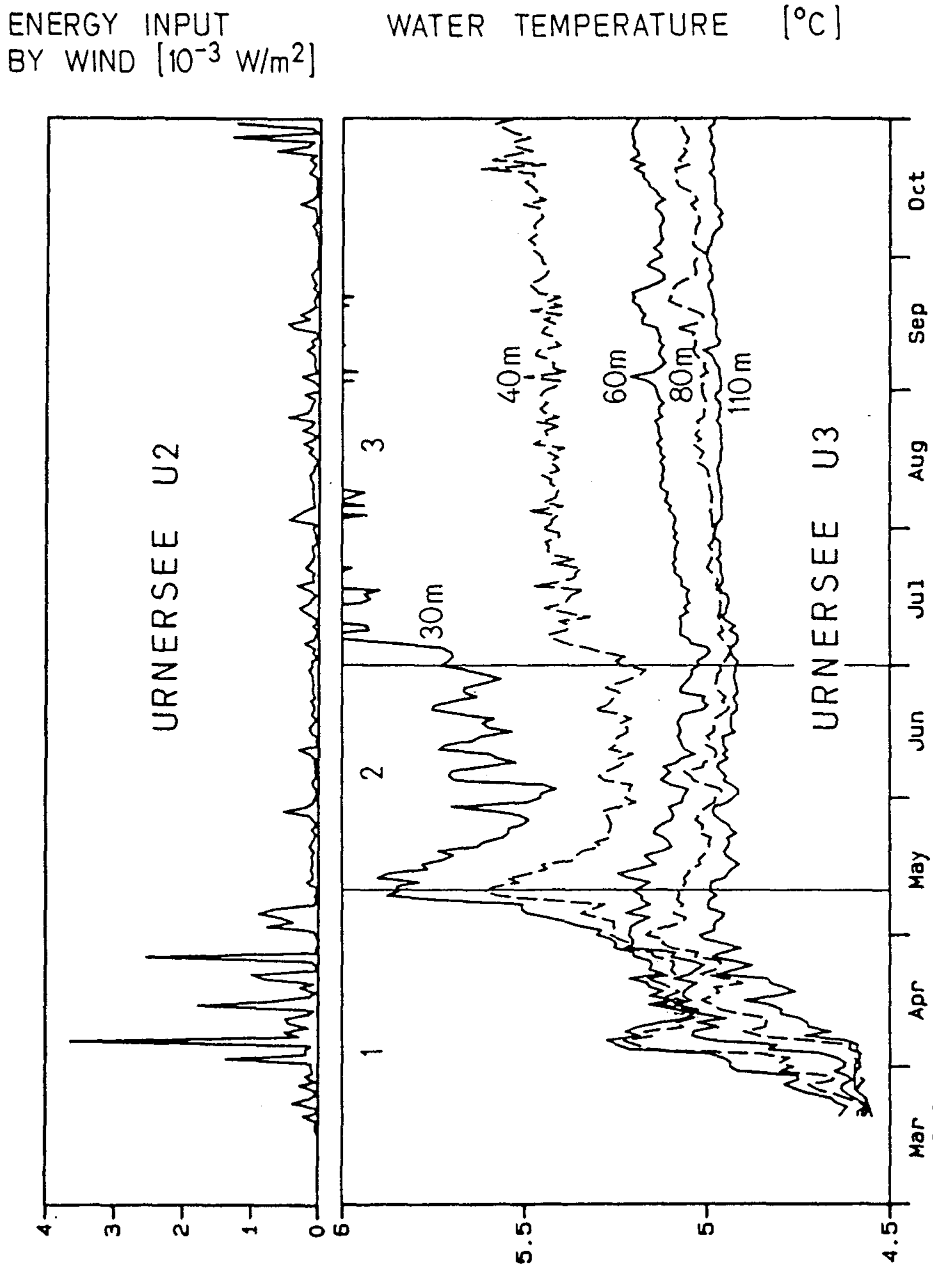


Figure 2. Input of turbulent kinetic energy E_{kin} by the wind at the lake surface and water temperatures in the hypolimnion of Urnersee during the investigation period (March to October 1986). E_{kin} is calculated from the third power of the wind speed measured 4 m above the water surface (see Marti and Imboden (1986) for details). High wind speeds occur in spring (seven storms between April 3 and May 6) and in fall (end of October). As discussed in the text three time periods can be distinguished to characterize the changes of the hypolimnic water temperature.

the upper hypolimnion (30 to 40 m) the temperature changes reflect the different meteorological conditions, at 60 m and below the weather is felt less directly. Neglecting the short-term fluctuations (they are caused by vertical oscillations of the isotherms) three phases can be distinguished regarding the temperature variations of the deeper layers:

(1) Period of rapid temperature increase (mid March to May 7)
(2) Period of slight but consistent temperature decrease (May 7 to end of June)
(3) Period of low but continuous temperature increase (July to end of experiments in October)

Since the vertical temperature gradient remained negative during the whole period (temperature decreasing with depth), the development during the second phase cannot be explained by diffusive mixing. It must be caused by advective flow of water to the hypolimnion. In the absence of any major subsurface water input to Urnersee, the only explanation for the observed temperature changes are density currents flowing into the hypolimnion. As can be seen from the upper curve of Fig. 2, the first heating period coincides with a period of several major storms. In contrast, during the cooling phase no extreme wind velocities were observed. The rest of this chapter is devoted to the different processes leading to the observed changes. Since water density plays an important role, the factors controlling it shall be discussed first.

3.2 *Water density and stability of water column*

The density of water (ϱ) at constant pressure depends on temperature (T), dissolved (D) and particulate (S) compounds:

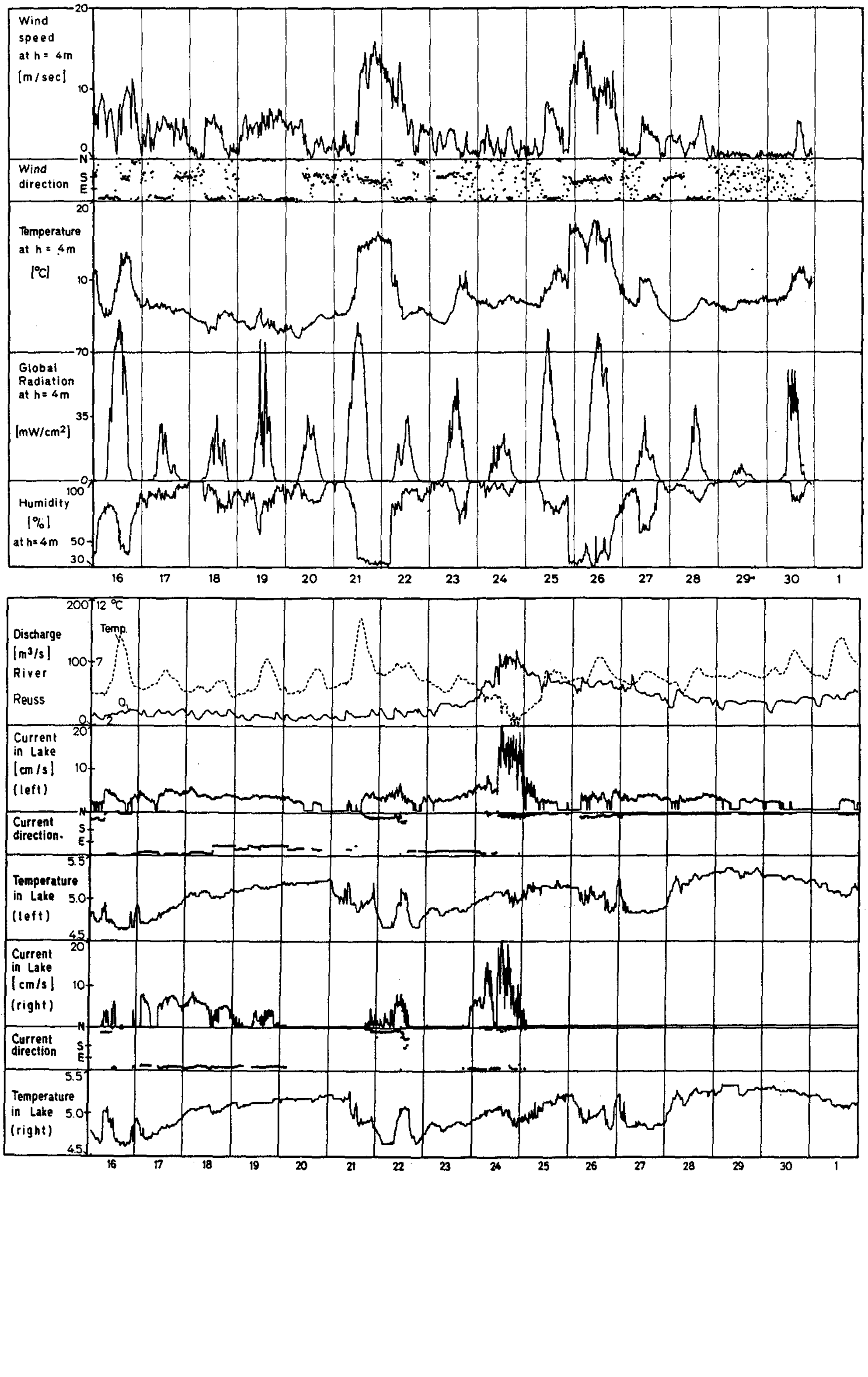
$$\varrho(T,D,S) = \varrho_0(T) + \Delta\varrho(D) + \Delta\varrho(S) \qquad (2)$$

where ϱ_0 (T) is density of pure water at temperature T and $\Delta\varrho(D)$, $\Delta\varrho(S)$ are the corrections due to the water chemistry. The local stability of the water column depends on the change of ϱ with depth; the column is stable, neutrally stable, or unstable if ϱ, measured at an arbitrary standard pressure, increases, remains constant, or decreases with depth, respectivelly. Since in lakes the absolute value of the vertical temperature gradient is usually much larger than the adiabatic temperature gradient (which is about $10^{-5} K\,m^{-1}$, see e. g. Neumann and Pierson, 1966), no correction for the adiabatic temperature change caused by the transition to the standard pressure is necessary for calculating water stability in lakes.

In the thermocline vertical density gradients are controlled by temperature. In the hypolimnion, however, temperature has little effect on ϱ since temperatures are between 4 and 5°C and the coefficient of thermal expansion $\alpha = (-1/\varrho)(\partial\varrho/\partial T)$ is close to zero. Thus, in the hypolimnion ϱ ist primarily controlled by water chemistry. The contribution of dissolved gases to $\Delta\varrho(D)$ is usually negligible (Joller, 1985); suspended solids are only relevant close to the river mouths or during flood events when turbid water may be spread along the bottom of the whole lake basin.

Once the chemical influence on ϱ is reduced to dissolved ions, $\Delta\varrho(D)$ can be approximated by the electric conductivity $\varkappa_{20}$ (calculated at the reference temperature of 20°C). In fact, in most Swiss lakes $\varkappa_{20}$ is mainly determined by the concentration of

URNERSEE METEOROLOGICAL BUOY (MIDLAKE STATION) Data for the month of April 86



calcium carbonate. Thus, $\Delta\varrho(D)$ can be calculated by the molar volumes of these ions (Duedall and Weyl, 1967) and their specific conductivities (Bührer and Ambühl, 1975). Täsch (1987) has tested this approximation for the specific composition of water from Urnersee. She found that the error in $\Delta\varrho(D)$ introduced by neglecting the difference between the calcium carbonate and the real ion composition (at the same $\varkappa_{20}$) is less than 10%. By a careful choice of published molar volumes and conductivities she arrived at the following expression relating $\Delta\varrho(D)$ and $\varkappa_{20}$:

$$\Delta\varrho(D) = \Delta\varrho(\varkappa_{20}) = \gamma\varkappa_{20},$$

$$\gamma = 0.68 \times 10^{-3}\,(\mathrm{kgm^{-3}})\,(\mu\mathrm{Scm^{-1}})^{-1} \qquad (3)$$

Her γ-value is slightly smaller than the value introduced by Bührer and Ambühl (1975) of 0.8×10^{-3} $(\mathrm{kgm^{-3}})$ $(\mu\mathrm{Scm^{-1}})^{-1}$. Equation (3) was used to calculate density from the temperature and conductivity profiles measured with the CTD probe.

3.3 *Mixing due to wind*

In April, stratification in Urnersee was still weak; the maximal vertical temperature variation was only about 1K. Between April and May 7, 1986, seven storm events with wind speeds larger than $10\,\mathrm{ms^{-1}}$ were observed; six of them were Föhn storms (winds from the south), one storm blew from the north. Two Föhn storms (April 21/22, April 26) are shown in Fig. 3. The wind from the south caused the cold water from the deep hypolimnion to rise at the south end of the lake. This is manifested by the temperature drop at station U4. On April 22, T dropped by about 0.6 K indicating that water from below 100 m rose to the instrument moored at 65 m depth. Water currents reached a speed of about $0.07\,\mathrm{ms^{-1}}$ to the north-west indicating that the instruments were under the direct influence of the surface currents driven by the wind and not of the subsurface counter-current. In contrast, the much higher currents measured two days later (April 24) were linked to a discharge peak in the river Reuss.

During the wind storms, a large-scale circulation is induced in the lake causing a rapid temperature increase below 80 m depth. For instance, between April 10 and 29, the temperature increased by about 0.2 K (Fig. 4); this amounts to a heat input of 1000 MJ to the layers below 110 m and to a total water replacement of about 50 percent. No corresponding heat input was found in Gersauersee during this period. Since the flow of river water will later be identified as another important hypolimnic mixing mechanism, at this point we want to stress the fact that for the discussed

Figure 3. Recordings from stations U2, U3, U4 and from the hydrology station H at the river Reuss for second half of April 1986. During the first 8 days, the water currents at U4 (moorings "left" and "right", both at 65 m depth) are due to wind forcing, especially during the Föhn storm of April 21/22. The strong temperature oscillation at U4 recorded on April 21 and 22 are due to water transport to the north by the Föhn and subsequent transport back due to strong northerly winds during the night. On April 24, a high discharge of the Reuss causes current speeds up to $20\,\mathrm{cms^{-1}}$.

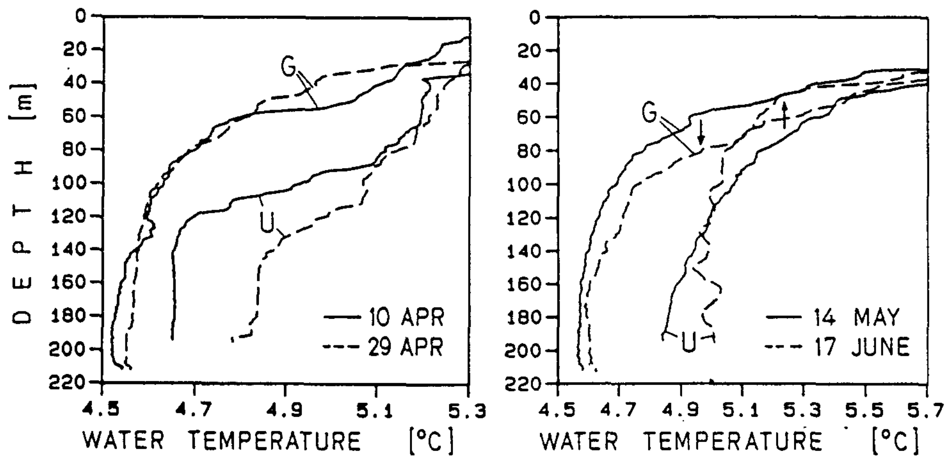


Figure 4. Comparison of vertical temperature profiles measured with the CTD probe in Urnersee (U = station U3) and Gersauersee (G). In April, vertical transport of heat by wind mixing is larger in Urnersee than in Gersauersee. In May and June, lateral water exchange from Gersauersee into the deep hypolimnion of Urnersee causes the U-profile between 40 and 110 m to move upwards by 30 to 40 m. In contrast, the G-profile drops by about 25 m. Warming at the bottom of U is due to river-induced density currents. The structure in the profile around 170 m depth probably originates from the peak discharge of the Muota on June 11 (see Tab. 4).

period (April 86) rivers could not have been important for deep water renewal. Even if all the water from the rivers Reuss and Muota had flowed to the deep hypolimnion of Urnersee, it could only have accounted for about one third of the measured heat input. We conclude that wind mixing is the majors cause of hypolimnic water exchange during this early and weak phase of the annual stratification cycle.
Although later in the year, the influence on hypolimnic mixing from the wind becomes smaller, it is more predictable, does not depend as strongly on single storm events and can be quantified by a vertical eddy diffusion coefficient K_z using the turbulent flux equation (1). As discussed in greater detail by Wüest (1987), K_z for different Swiss lakes can be expressed as a function of vertical stability of the water column, of turbulent kinetic energy input from the wind and of depth.

3.4 *Mixing by river-induced intrusion and density currents*

The level at which river water intrudes into a stratified lake is determined by the fluxes of mass, momentum and buoyancy, by the entrainment of ambient lake water into the river plume (or jet), by the distribution of currents and stratification in the lake, and by the geometry of the river mouth (Fischer et al., 1979). The seasonal variations of temperature and turbidity of the river water as well as the annual stratification cycle of the lake continuously change the input conditions. If the river water is lighter than the epilimnic water, the river water spreads at the lake surface. This situation usually occurs when the river is warm and contains little suspended

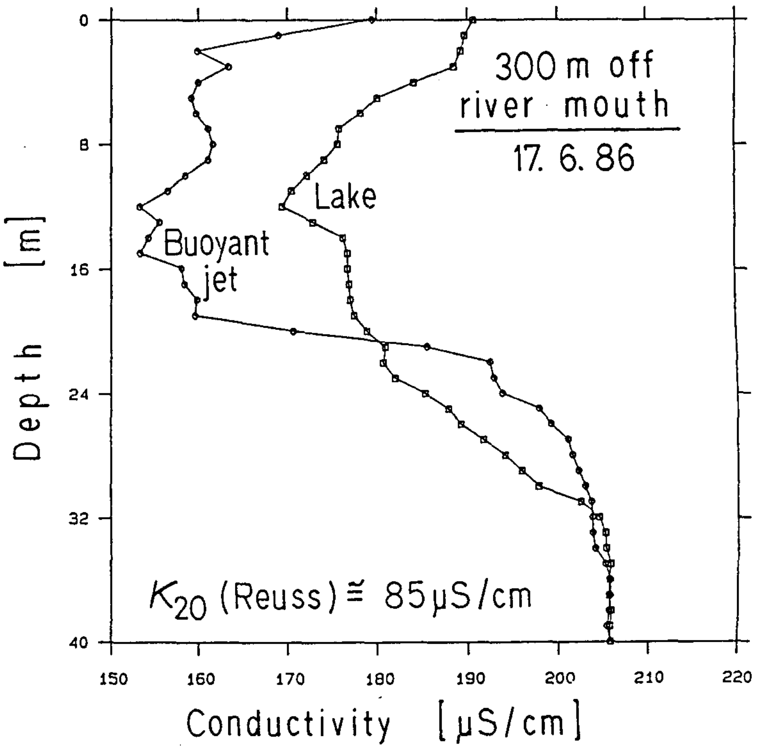


Figure 5. Electric conductivity of lake water $\varkappa_{20}$ measured at mouth of river Reuss (station U4), June 17, 1986. The spreading of the river water in the top 20 m can be traced by a drop in $\varkappa_{20}$ in the lake. Note that the river water has a significantly lower $\varkappa_{20}$. This situation is typical for late spring and early summer.

material. The conditions on June 17, 1986 illustrate this case for the river Reuss (Fig. 5). More frequently however, the river water plunges to the thermocline where the densitiy of the lake water changes significantly within a small vertical distance thus providing a large range of "suitable" densities for the river water to find its level of neutral buoyancy (Fig. 6).

In spring, the intrusion level of river water is more variable since the density differences are usually quite small. Fig. 7 shows temperature and electric conductivity recorded at the Muota river mouth (station U1) on April 10. The intruding river water is clearly visible between 44 and 58 m. The water in the Muota was only a few tenths of a degree warmer than the nearly homogeneous lake water. The relative density difference, $\Delta\varrho/\varrho$, between the depth of intrusion and the lake bottom was only about 5×10^{-6}, so that the intrusion level may not have been very stable, at this time. Indeed, variable current speeds between 0 and 0.1 ms^{-1} were recorded at station U1 during that day.

Although during most of the year the discharge rates of the inlets are close to the corresponding annual mean values (Tab. 2), the few events of extremely large discharge are probably more significant to lake mixing than all the normal days. This is

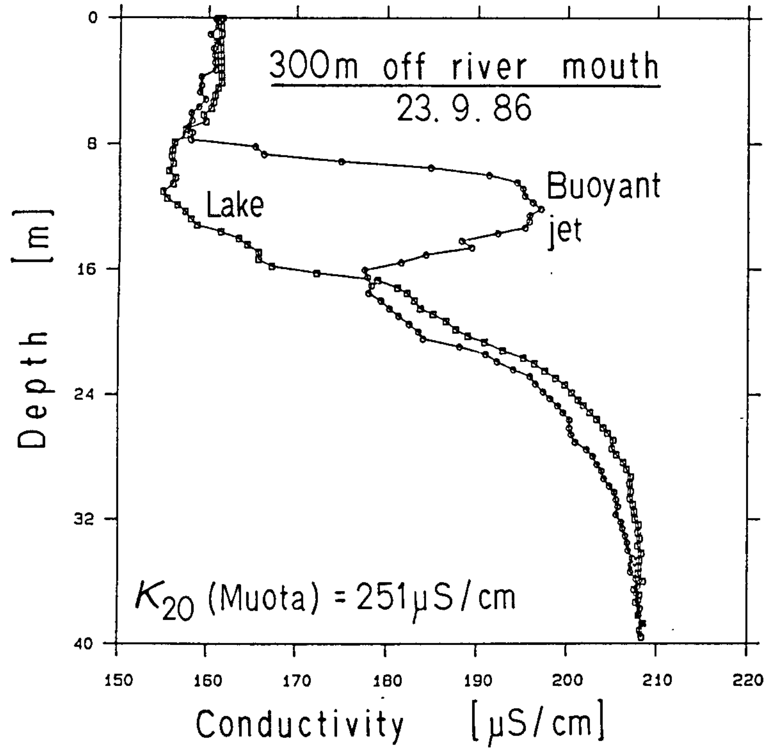


Figure 6. Electric conductivity of lake water $\varkappa_{20}$ measured at mouth of river Muota, September 23, 1986. Note that, in contrast to the Reuss, the Muota has a higher $\varkappa_{20}$ than the lake. Due to its lower temperature, the river water plunges to the thermocline. The situation is typical for summer and fall.

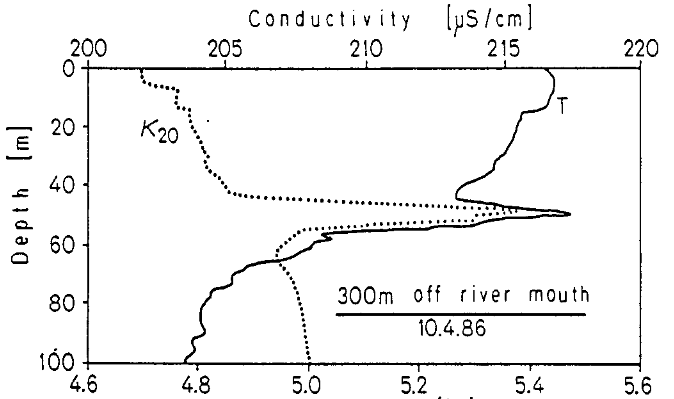


Figure 7. In April, temperature differencies between river and (nearly homogeneous) lake water are still small. Therefore, small changes in the river water temperature can significantly alter the intrusion depth. On April 10, 1986, the plume from the river Muota was clearly visible at about 50 m depth. The fine structure of the temperature profile may show relicts of preceding intrusions at other depths.

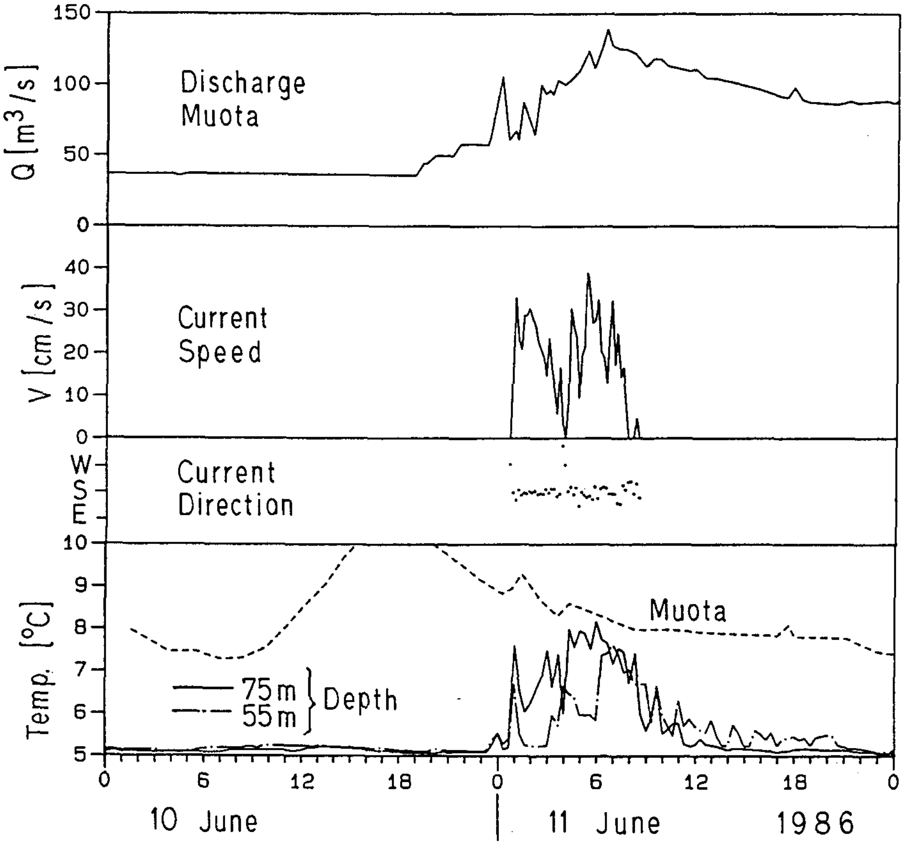


Figure 8. Density current 300 m off the mouth of river Muota on June 11, 1986, one typical example out of 9 similar events produced by heavy rainfall or thunderstorms in the drainage area (Tab. 4). Current speeds and water temperature were measured by moorings at station U1. Currents and temperature suddenly increased to maximum values of 40 cm/s and 8°C, once the river discharge exceeded about 60 m^3s^{-1}. Currents point southwards into Urnersee. Fluctuation in water temperature during the event indicate changing depth of river intrusion, possibly due to changing load of suspended solids.

not only due to the large quantities of water added to the lake by floods but also because large concentrations of suspended solids which are typical for flood conditions (especially during the initial phase) increase the density of the river water to such an extent that even during the summer the warm river water can plunge to the cold lake bottom as a turbidity current. Two examples shall illustrate this:

During the night of June 10/11 the discharge of the river Muota increased from 35 to 140 m^3s^{-1} within a few hours (Fig. 8). Shorthly after midnight, the heavy river water (temperature 8.8°C) flowed along the sloping lake bottom causing a sudden increase of the current speed at 75 m to peak values of 0.37 m/s and a warming of the water at the same depth of about 2 K. The temperature at 55 m was also influenced, but not as strongly. This indicates that the river water was primarily flowing along the lake

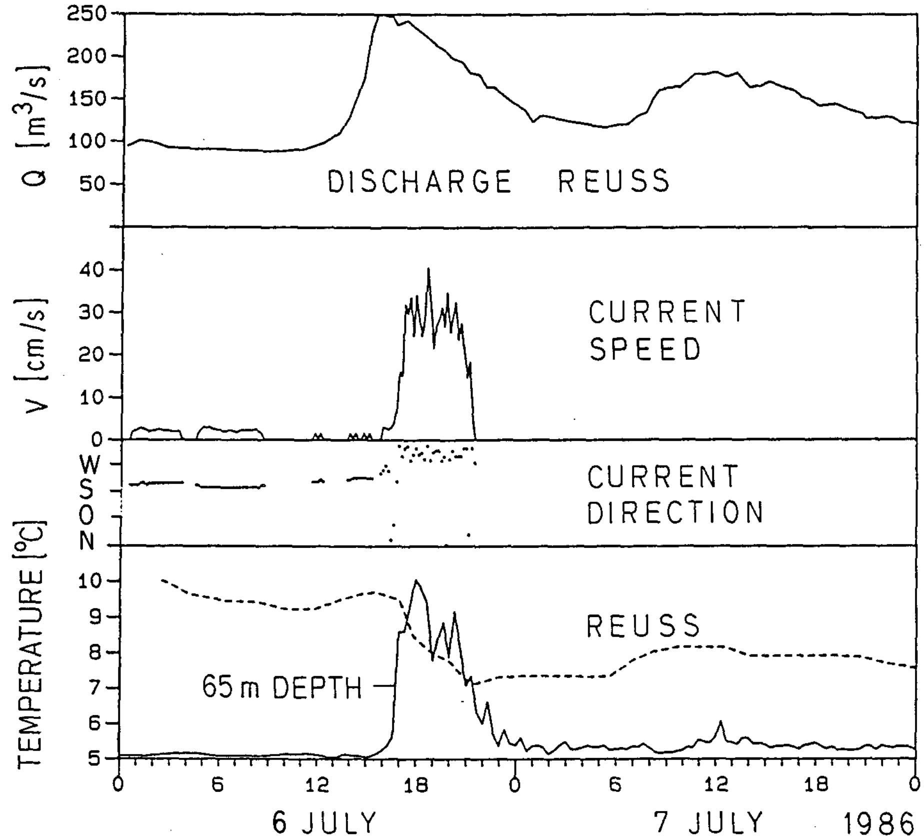


Figure 9. One out of 8 density currents (Tab. 4) recorded at station U4 350 m off the mouth of the river Reuss on July 6, 1986. As for the Muota, there is an immediate response of current speed and water temperature above a certain discharge threshold value. The temperature measured in the lake at the depth of the current meter (65 m) temporarely exceeds the temperature of the river water. This is due to entrainment of water from the warm lake surface into the river plume.

bottom. The fluctuations of current speed and water temperature which were also found during other turbidity currents (Lambert, 1979) may be caused by a fluctuating plunging depth due to changes of plume relative to ambient water density caused by varying concentration of suspended solids or by internal waves at the thermocline. Lateral oscillations of the plume may add to the fluctuations. A second example is shown for the river Reuss (Fig. 9). On July 6, the discharge reached 250 m^3s^{-1}. (This value is still well below the estimated discharge of 700 m^3s^{-1} during the disastrous flood on August 25, 1987.) The bottom currents showed peak values of 0.4 m/s, the temperature increased by 3 K to a value clearly above the temperature of the river water. This demonstrates the effect of entrainment of warm water from the lake surface into the plunging plume.

A detailed analysis of all recordings from the four moorings in Urnersee allows to

Table 4: Summary of plunging river inflows recorded between April and October 1986

Date	Maximum and mean discharge of river [m^3s^{-1}]	Duration of event[1)] [hours]	Max. and mean temperature change[1)] [K]	Max. current velocity[1)] [ms^{-1}]
At river Reuss				
April 10	76/60	1.5	−0.2/−0.1	0.15
April 24	115/100	12	–	0.21
May 8/9	90/70	40	0.9/0.6	0.09
May 19/20	181/140	8.3	2.4/1.0	0.12
June 23/24	214/190	8.5	4.6/2.0	0.41
July 6	253/205	4.8	5.0/3.5	0.41
August 12	149/138	3.2	2.2/0.4	–
October 20/21	38/26	11	3.5/0.6	0.16
At river Muota				
May 19	96/87	2.2	2.5/1.7	0.34
May 21	73/73	1.0	3.1/3.0	0.22
June 2/3	110/98	3.0	2.4/0.5	0.04
June 11	138/112	6.4	3.1/2.2	0.37
June 17	90/60	2.0	2.4/1.2	0.09
June 23/24	174/150	1.6	3.1/2.5	0.46
July 7	127/119	2.1	3.4/1.7	0.21
August 18	86/49	3.2	4.0/2.0	0.22
October 23	126/60	2.1	5.0/2.5	0.15

1) Measured by mooring at river mouth, i. e. station U4 (depth 65 m) for Reuss, station U1 (depth 75 m) for Muota.

estimate the integrated effect of all the plunging events on the exchange of hypolimnic water. Four phases can be distinguished:

(1) April: Intrusion of river water into the whole water column; little effect on hypolimnic heat balance since temperature differences between river and lake water are small.
(2) May: Intrusion of river water between 50 m depth and the thermocline with rising tendency.
(3) June to October – during average discharge: Intrusion at the surface or in the thermocline.
(4) May to October – during peak discharge: Appearance of density currents, primarily in May; in June and later, density currents occur only in combination with large concentration of suspended solids.

A summary of all plunging events for the two rivers, Reuss and Muota, is given in Table 4. The electric conductivity measured at station U2 (Fig. 10) shows that the temporal evolution of the undercurrents is also felt far away from the river mouths. From the information put together in Table 4 it is not directly possible to calculate the total flux of water and heat to the deep hypolimnion because the total amount of entrainment of lake water into the plunging plume is not known. Täsch (1987) has

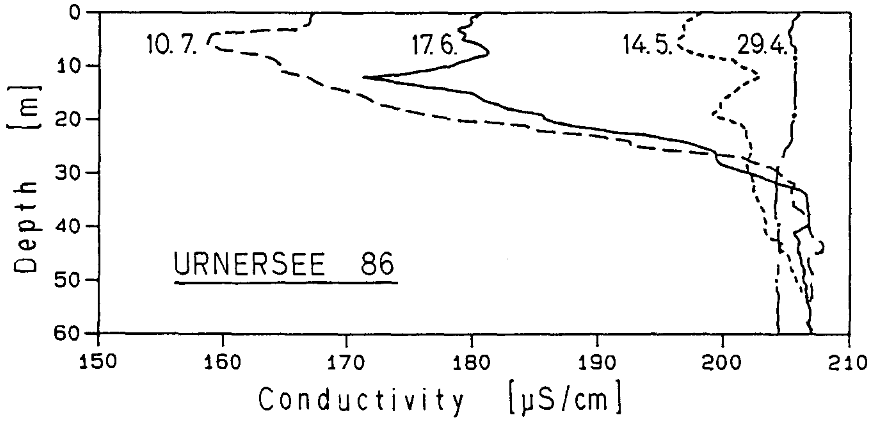


Figure 10. Electric conductivity $\varkappa_{20}$ measured at mid-lake station U3 summarizes the intrusion of water from the rivers Reuss between April and July 1986. Since less water is brought into Urnersee from the river Muota, its signal (positive $\varkappa_{20}$-peak) is covered by the signal from the Reuss. In April and May, intrusion depth is still variable leading to a irregular $\varkappa_{20}$-profile. The clearly visible intrusion depth of the river water increases slightly from June to July due to rising temperatures in the river.

estimated the entrainment rate E for the intrusion of Reuss water by two methods, by direct measurement of the three-dimensional geometry of the jet at the river mouth (traced by its characteristic electric conductivity), and by a mathematical model (Fischer et al., 1979). E is defined by the equation

$$\partial Q/\partial x = 2\pi E R u \qquad (4)$$

where Q is volume flux of water, x distance from the river mouth, R plume radius and u mean plume flow velocity. She found an entrainment rate E for the buoyant plume between 0.02 and 0.1 and observed a decrease of E with increasing distance from the river mouth.

Wüest (1987) developped a simple jet model which bases on the conservation of horizontal momentum and uses a constant entrainment factor E (Morton et al., 1956). Although E is only constant within some range from the river mouth (Hauenstein, 1983), it can be assumed that during high discharge the observation stations U1 and U4 are still within this range. This is confirmed by the measurements by Täsch (1987). Wüest varied the entrainment rate in the model and calculated the corresponding theoretical plume dilution factor μ at the level of the current meters. The factor μ is defined as the ratio between plume flow at the current meters and water discharge at the river mouth. The transport of heat, ΔH, into the deep hypolimnion can then be calculated by the following equation:

$$\Delta H = \mu c\varrho \, \Delta T \, Q_0 \, \Delta t \qquad (5)$$

where Q_0 is discharge rate at river mouth, $c\varrho$ is specific heat of water per volume ($4.18 \times 10^6 Jm^{-3}K^{-1}$), ΔT is temperature difference between plume water at current meters and deep hypolimnic water, Δt is duration of plunging event. Note that entrainment below the current meters does not alter the transport of heat, ΔH, since the additionally entrained water has about the same temperatures as the deep hypolimnion. By comparing the calculated ΔH for different dilution factors μ with measured temperature changes Wüest found an average value for μ of 3.4 corresponding to an entrainment rate E in the jet model of about 0.015. Wüest concludes that his result does not contradict the result by Täsch since the latter was found for average discharge, whereas the former applies to turbidity currents during which large density differences between plume and lake water suppress entrainment (Ellison and Turner, 1959).

The heat fluxes, calculated from eq. (5) with a constant dilution factor of 3.4, for all

Table 5: Input of water and heat into the hypolimnion of Urnersee due to plunging river plumes

Date	Water input [10^6 m^3] At river mouth	At mooring[1]	Below 110 m[2]	Heat input below 110 m [10^{12}J]
At river Reuss				
April 10	0.3	1	3	−0.4
April 24	4.3	15	39	
May 8/9	10.1	34	91	87
May 19/20	4.2	14	38	60
June 23/24	5.8	20	52	164
May/June (total)	20	70	180	310
July 6	3.5	12	32	172
August 12	1.6	5	14	18
October 20/21	1.0	3	9	8
July/October (total)	6	20	55	200
At river Muota				
May 19	0.7	2.4	4.2	17
May 21	0.3	0.9	1.6	11
June 2/3	1.1	3.7	6.6	8
June 11	2.6	8.8	16	81
June 17	0.4	1.5	2.6	8
June 23/24	0.9	2.9	5.2	32
May/June (total)	6	20	36	160
July 7	0.8	3	5.0	20
August 18	0.5	1.5	2.8	13
October 23	0.5	1.5	2.7	16
July/October (total)	2	6	10	50

1) At 65 m for river Reuss, at 75 m for river Muota, calculated with dilution $\mu = 3.4$ for both rivers
2) Calculated for river Reuss with $\mu = 9$, for river Muota with $\mu = 6$. However, in contrast to the situation at the depth of the moorings where the passing of the turbidity current was actually measured, it is not clear whether all currents reach the layers below 110 m depth.

measured river-induced density currents (Table 4) are listed in Table 5. During May and June, the combined effect from the two rivers results in a total heat input below 110 m of about 600×10^{12} J, provided that all the water measured at the mooring off the river mouth eventually plunges below the 110 m level.

Whereas entrainment into the plume below the current meter level does not alter the ΔH-value, this is not true for the total water input into the deep hypolimnion. The plume dilution μ can be extrapolated to 110 m depth by assuming the same entrainment rate as in the upper layers; the values are 9 for the Reuss plume and 6 for the Muota. In May and June, the total water input at the 65 m level ist about $90 \times 10^6 m^3$ (Table 5). This is 5 percent of the volume of Urnersee below this depth ($V(z > 65\ m) = 1850 \times 10^6 m^3$). At the 110 m-level the input reaches a maximum value of about $210 \times 10^6 m^3$, i. e. about 20 percent of the volume below this depth. Yet, since it is not known whether plume entrainment does actually continue at the same rate, a more realistic value would probably lie somewhere between the 65 and 110 m estimation.

3.5 *Origin of other density currents*

Density currents transport significant quantities of water to the deep hypolimnion of Urnersee (Table 5) leading to a slow upward movement of the whole water column. Since water temperature decreases with depth, at a fixed depth the upwelling should result in a temperature drop because cooler water is pushed towards the surface. The continuous temperature recording at station U3 as well as the CTD profiles confirm the expected behavior. As shown in Fig. 4, between May 14 and June 17 the temperature in Urnersee decreased above 120 m depth and increased below. These changes are consistent with a flow of warmer water into the deep hypolimnion. The corresponding volume fluxes can be calculated from the heat balance equation at depth z

$$\Delta t\,(\partial T/\partial t) = \Delta T = -\,h(z)\,(\partial T/\partial z) = -\,(\Delta V/A_z)\,(\partial T/\partial z) \qquad (6)$$

where Δt = time period between measurements, $\partial T/\partial t$ the temporal temperature gradient (measured from linear regression of the continuous recordings or from consecutive profiles), h(z) is vertical displacement of the water column at depth z ($h > 0$ for downward movement), $\partial T/\partial z$ is the vertical temperature gradient at depth z, A_z is lake area at depth z, and ΔV the transported volume of water during time Δt ($\Delta V > 0$ for downward transport).

The observed temperature gradient $(\partial T/\partial t)_{obs}$ has to be corrected for the effect of vertical eddy diffusion which mainly originates from the input of wind energy (see section 3.3). As a rough estimation it is assumed that the contribution to the gradient from diffusion is equal to the temporal temperature gradient observed during the summer (July to October), when turbulent mixing is the only mechanism which influences the hypolimnic water temperature:

$$(\partial T/\partial t)_{corr} = (\partial T/\partial t)_{obs} - (\partial T/\partial t)_{eddy\ diffusion} \qquad (7)$$

Vertical displacement volumes ΔV are calculated for the period May/June 1986

Table 6: Vertical flux of water in Urnersee and Gersauersee in May and June 1986, calculated from temperature changes in the water column

Depth	Area A_z	Temperature change ΔT measured	corrected[1]	$\partial T/\partial z$	Displacement Δh[2]	Volume flux ΔV[3]
	[km^2]	[K]	[K]	[$10^{-3} Km^{-1}$]	[m]	[$10^6 m^3$]
Urnersee						
60	18.8	−0.19	−0.26	−8.6	−30	560 ± 40
70	18.3	−0.16	−0.23	−6.8	−34	620 ± 50
80	17.8	−0.14	−0.20	−5.8	−35	620 ± 60
90	17.4	−0.11	−0.16	−3.3	−47	810 ± 80
100	16.8	−0.08	−0.13	−2.7	−46	770 ± 100
110	16.1	−0.06	−0.10	−2.9	−35	560 ± 100
Gersauersee[4]						
50	26.5	0.52	0.44	−16.7	26	−700
60	25.9	0.38	0.31	−10.8	28	−740
70	25.1	0.32	0.24	−9.8	25	−620
80	24.3	0.28	0.22	−8.0	27	−650
Mean						−670 ± 50

1) In situ temperature changes are corrected for effect of eddy diffusion using eq. (7)
2) From eq. (6)
3) From eq. (6)
4) Including the small basin between sill S2 und S3 (see Fig. 1)

(Table 6). In Urnersee a water volume of 600 to $800 \times 10^6 m^3$ is desplaced upwards from about 100 m depth or even from below. This quantity is significantly larger than the total flux induced by turbidity currents from the two major rivers during the same period which, according to Table 5, is about $90 \times 10^6 m^3$ at the mooring depths and may reach about $200 \times 10^6 m^3$ at 110 m provided that all turbidity currents reach this depth. Thus, we conclude that an additional quantity of water (between 500 and $700 \times 10^6 m^3$) of still unknown origin flowed into the hypolimnion of Urnersee, in May and June.

In addition to river-induced density currents, water from the upper hypolimnion of Gersauersee is the source of deep water replacement in Urnersee. Water density in the two basins was calculated with eqs. (2) and (3). As shown in Fig. 11, at sill depth of 85 m the horizontal density difference was about 8×10^{-6} g/cm^3, on May 14. In fact, the water in Gersauersee at the sill is heavier than any water in Urnersee because it is generally cooler and has a larger electric conductivity $\varkappa_{20}$ than water in Urnersee ($\Delta\varkappa_{20} \sim 6 \mu S/cm$) due to the calcareous drainage area of Gersauersee. Temperature profiles taken with the CTD probe near Brunnen (Fig. 12) often show mixing structures in both, $\varkappa_{20}$ and T, which probably result from intrusion of Gersauersee water and confirm that the change in water density occurs within a small zone between the two basins. Indeed, STD casts illustrated the horizontal homogeneity of the water

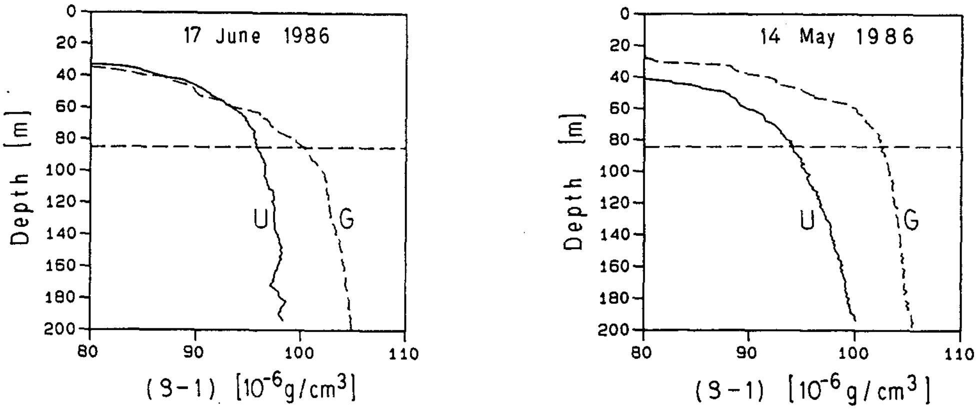


Figure 11. Density profile in Urnersee (U) and Gersauersee (G), calculated from water temperature and electric conductivity $\varkappa_{20}$ using eq. (2). On May 14, the density in G at sill depth (85 m: broken line) was larger than density at any depth in U. On June 17, the densities were equalized in most of the water column above the sill.

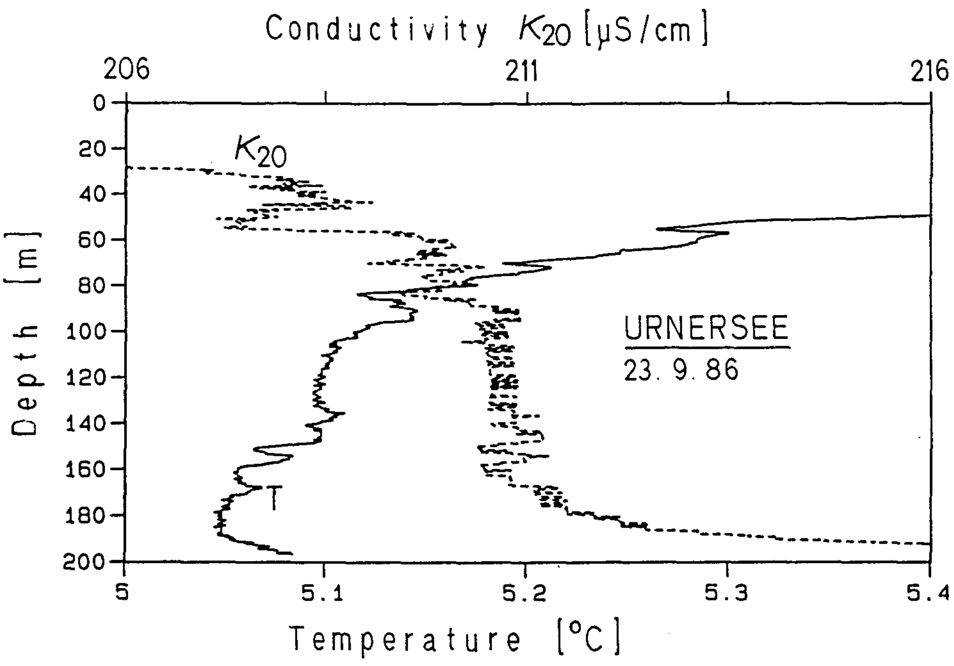


Figure 12. Temperature T and electric conductivity $\varkappa_{20}$ in Urnersee north of Brunnen (near station U1) measured on September 23, 1986. The vertical fine structure measured for both parameters below about 30 m probably indicate lateral intrusion of water from Gersauersee which has different-physical-chemical properties at this depth.

within each of the basins. Yet, more detailed measurements are needed in order to understand the actual physics involved in the overflow, especially the speed and shape of the flow. From the CTD measurements we can only conclude that the flow took place somewhen between mid May and mid June, since the major part of the density gradient had disappeared on June 17 (Fig. 11). The observations in Gersauersee are consistent with a downward flux of about $670 \times 10^6 m^3$, roughly the same volume as the Urnersee upwards flux (Table 6).

There is enough evidence to conclude that density induced currents from intermediate depths of Gersauersee into Urnersee must be responsible for the observed temperature and conductivity changes. Turbulent diffusion could not have created such changes; it had decreased the horizontal gradients of *all* parameters. In fact, during the postulated density flow the temperature in Gersauersee between 30 and 70 m became even larger than the temperature in Urnersee at the same depth; the difference remained visible until August. It should also be noted that river-induced density currents alone would have reduced $\varkappa_{20}$ at the bottom of Urnersee since the water of the river Reuss (the major source of intruding water) has smaller $\varkappa_{20}$-values; yet measurements showed that $\varkappa_{20}$ increased by about $0.8 \mu S/cm$ during this time.

Table 7: Input of water and heat into the deep hypolimnion[1)] of Urnersee: Summary of all processes

Process/Period	Input of water		Input of thermal energy	
	Total [$10^6 m^3$]	% of volume[1)] replacement	Total [$10^{12} J$]	Heat flux per area[2)] [Wm^{-2}]
WIND-INDUCED				
April 10 to 30[3)]	550	50	1000	36
INFLOW FROM GERSAUERSEE				
May/June	500 to 700	55 to 75	?	?
RIVER-INDUCED				
May/June (2 months)				
Reuss	180	17	310	3.7
Muota	36	3	160	1.9
TOTAL	216	20	470	5.6
July/October (4 months)				
Reuss	55	5	200	1.2
Muota	36	3	50	0.3
TOTAL	91	8	250	1.5
During single flood event[4)]	32	3	172	600
VERTICAL EDDY DIFFUSION				
permanent				0.5

1) Deep hypolimnion of Urnersee defined as lake volume below 110 m depth ($V = 1070 \times 10^6 m^3$)
2) Average heat flux during indicated period per unit time and per lake area at 110 m depth ($A_{110} = 16.2 \times 10^6 m^2$)
3) Three Föhn storms during 20 days. Note that in the same period heat flux into to deep hypolimnion of Gersauersee is only 2.4 Wm^2c^2
4) Flood in river Reuss on July 6, duration 4.8 hours (see Table 4)

4. Synergetic effects of hypolimnic exchange mechanisms

In this section, an attempt is made to compare and combine the various processes responsible for the interaction between the hypolimnion of Urnersee and the rest of the lake. The following parameters will be discussed: Water, heat, suspended solids, and dissolved oxygen.

4.1. *Water transport*

Renewal of hypolimnic water in Urnersee is dominated by three processes which vary on a seasonal basis (Table 7):

(1) In April, weak stratification and strong episodic storms allow wind stirring to penetrate into the deep layers of the lake causing transport of surface water to the hypolimnion. Based on the warming of the hypolimnion, we estimated a water renewal of about 50% of the deep hypolimnion for this month alone (see section 3.3). Though we do not yet have measurements of the winter period we can speculate that such exchanges took place also before April, once the density stratification from the preceding year was eroded by cooling and wind mixing. A subtle effect of the large wind mixing during April is that below about 20 m depth the waters of the exposed Urnersee become lighter than in the adjacent sheltered Gersauersee.

(2) In May and June, as the stratification in the surface layers got stronger and winds became relatively calm, the horizontal density gradient causes renewal of Urnersee

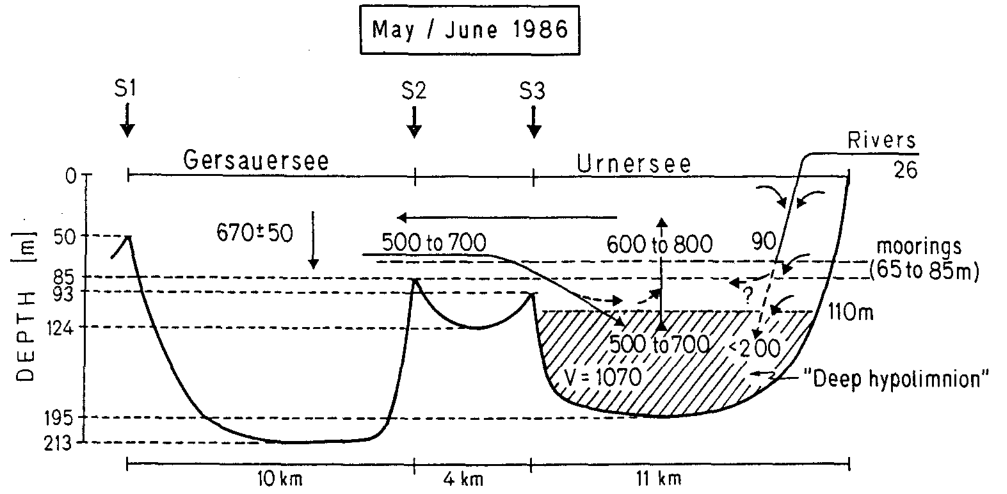


Figure 13. Total water fluxes in May and June 1986 into and from the deep hypolimnion of Urnersee. Numbers are in units of 10^6 m^3. The input of river water (Reuss and Muota) of 26 units increases to 90 units at mooring depth due to entrainment of lake water and reaches 200 units at most at the 110 m boundary. A density current from Gersauersee of 500 to 700 units adds to the river-induced flux to a total of 600 to 800 units. During the two months, the relative water exchange in the deep hypolimnion reaches 55 to 75 %. Note that position of inlet and the shape of the water body are schematized.

bottom water by the heavier Gersauersee intermediate water. The total flow is estimated to lie between 500 and $700\times10^6m^3$ (Fig. 13).
(3) Simultaneously with these processes are the episodic floods which may also transport water into the hypolimnion depending on the relative density difference between the river inflow and the lake. The effect of the two major rivers, Reuss and Muota, at the level of the moorings (65 to 85 m) amounts to a total flux of about $90\times10^6m^3$ (Table 5). Provided that entrainment of ambient river water into the plume continues at the same rate as in the upper hypolimnion, these density currents could be responsible for a total mass flux into the deep hypolimnion of as much as $200\times10^6m^3$ (Fig. 13).
The volume of Urnersee below 110 m depth is $1070\times10^6m^3$ (Table 1). Although the exact size of the river-induced transport to this volume is not known, the total imput of water (overflow and density currents) can be calculated from the temperature changes in the two basins to lie between 600 and $800\times10^6m^3$ (Table 6). This is between 55 and 75 % of the water volume. The relative contribution from Gersauersee to the flux is about 80 %.
During the rest of the summer and fall, the effect of turbidity currents on hypolimnic water exchange decreases to a total volume of $65\times10^6m^3$, at most, about 85 % of it induced by the river Reuss. Yet, a single flood event can still cause a significant flux per unit time: For instance, on July 6 within about 5 hours the flood of the river Reuss may have brought up to $30\times10^6m^3$ water to the bottom of Urnersee (Tables 4 and 5). Therefore, extreme meteorological conditions during the summer (such as the floods of the year 1987) may cause much more water exchange than during the average year.

4.2 *Heat fluxes*

The flux of heat into the deep hypolimnion depends on both, on the water volume transported to the hypolimnion and on the temperature difference between the inflowing water and the replaced hypolimnic water. The different processes which add to the heat content of Urnersee are listed in Table 7. In April, three major Föhn storms increased the deep hypolimnic temperatures by about 0.2 K. This corresponds to an average vertical heat flux of 36 Wm^{-2} during three weeks. Even if all the river water had flowed to the hypolimnion it could not have produced such a large heat input.
In May and June, about two thirds of the water exchange is caused by lateral overflow from Gersauersee. Since the temperature of the intruding water is very close to the temperature in the hypolimnion of Urnersee (Fig. 4), it is not possible to estimate the corresponding heat flux. Due to their relatively high temperatures river-induced density currents are probably more important for the transport of heat to the deep hypolimnion. The values in Table 7 were calculated from Table 4 based on equation (5). The mean vertical heat flux in May and June is 5.6 Wm^{-2} and then drops to 1.5 Wm^{-2} between July and October. However, during the single flood event in river Reuss of July 6, during about 5 hours the heat flux reaches the extreme value of 600 Wm^{-2}. In contrast, the contribution from vertical eddy diffusion is only about

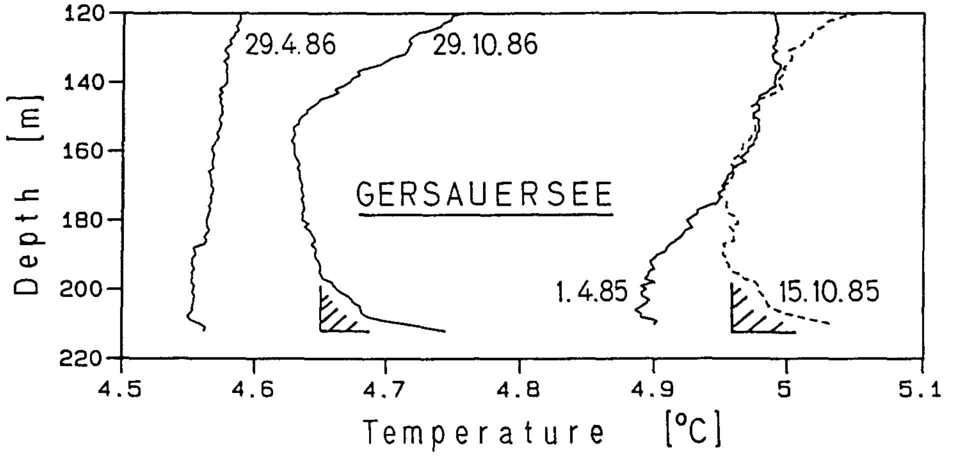


Figure 14. Change of vertical temperature distribution in Gersauersee in the summer of 1985 and 1986. The hatched triangles represent the possible temperature increase due to geothermal heat flux (0.1 Wm^{-2}). The origin of the additional heat is unknown.

0.5 Wm^{-2}. This should warn all those who calculate eddy diffusivity from temperature changes. The method is applicable in between flood events only; for other periods the resulting (pseudo-)values of K_z would greatly overestimate the effect of turbulence.

4.3 *Input and distribution of suspended solids*

Based on the weekly measurements of suspended solids in the river Reuss by the Swiss Hydrological Service, the annual input of solids to Urnersee is estimated as 60 000 t. As an example we use the flood event of July 6/7, 1986, observed in the river Reuss (Fig. 9). If the mean density of the solids is assumed to be 2.65 g cm^{-3} (quarz), from eq. (2), we calculate that the concentration of suspended solids must have been at least 1300 g m^{-3} to overcome the buoyancy of the warm river water in the cold water of Urnersee. (This value is not unrealistic since samples taken at random in 1985 twice gave values above 1000 g m^{-3}). Thus, the total input of suspended solids during this particular flood event amounted to 5000 t, at least, or to 8 % of the annual input. Investigations on the river Rhine in Lake Constance (Waibel, 1962) and on the river Linth in Walensee (Lambert et al., 1976) confirm the fact, that the largest fraction of the annual load of particles is brought into alpine lakes during a few flood events.

Results from sediment trap experiments in Urnersee (station U3) by M. Sturm (private communication) yield a mean sedimentation rate of about 5 g $m^{-2}d^{-1}$, most of it allochthonous material. The flux shows a clear maximum in June to August, the time of high discharge. For the whole surface area of the lake, the *in situ* measurements yield an annual flux of solids of 40 000 t which is in rough agreement with the value estimated before. It can be concluded that the major part of the particle load brought to the lake is distributed by turbidity currents within the whole lake basin. Sedimentation in the delta area is important for the coarse material only (sand, gravel); it represents only about one tenth of the total input of solid material.

4.4 *Dissolved oxygen*

Density currents can be efficient mechanisms for the transport of dissolved oxygen into the hypolimnion of lakes (e. g. Lake Mendota, Bryson and Suomi, 1951). If we assume that the river water underflow, after its mixing with surface water, contains about 10 g m^{-3} of dissolved oxygen, the density currents would transport a maximum of about 3000 t of oxygen to the deep hypolimnion of Urnersee (about $300 \times 10^6 m^3$ of water with 10 mg/l of O_2). This corresponds to a mean input per deep hypolimnion volume of about 3 g m^{-3} or about 10 g m^{-3} for the volume below 160 m depth. Since the water is replacing hypolimnic water which has a relatively high O_2-concentration already, the net input is of course much smaller. The calculated quantity rather expresses a maximum potential of oxygen transport for the worst case that, because of lake eutrophication, the hypolimnic O_2-concentration would drop to zero.
In the early seventies, typical oxygen consumption rates in the bottom layer of Urnersee during the stagnation period have been 1 to 2 g m^{-3} (Bossard and Ambühl, 1984). Due to improving conditions in the lake, the oxygen consumption rate has a decreasing trend. We conclude that river-induced density currents have an oxygen transport capacity to the Urnersee hypolimnion which is able to compensate for the O_2-consumption by biomass degradation even if the productivity of the lake were significantly larger than today.

5. Conclusions

Lake Lucerne with its different basins appears as a very interesting and instructive object to the physical limnologist. The two neighboring basins, Gersauersee and Urnersee, both of similar size and depth, located in the same macroclimate, and yet very different in their physical characteristics, demonstrate the effects of external physical "forces". The three main differences are: (1) the wind exposure, (2) the direct discharge of water from inlets, and (3) the water chemistry (total concentration of dissolved chemicals approximated by the electric conductivity of the river water). All three factors seem to act in favor of a large renewal rate of hypolimnic water in Urnersee, because of wind forcing in winter and spring, and because of density currents induced by the inflows and by lateral exchange of heavier water from Gersauersee in summer.
The oxygen concentrations in the deep water of Urnersee have always been much higher than those in Gersauersee (Bossard and Ambühl, 1984). While this difference has been linked to the wind (the most obvious distinction between the basins), we were able to demonstrate the additional influence of density currents from river

inflows and the flow of Gersauersee intermediate water. Compared to these density flows the small-scale turbulent diffusion seems to be much less important for vertical mixing in summer. It is hypothesized that also in other lakes at least part of the changes observed in the hypolimnion are rather by advective processes than by turbulence.

Several questions remained open, new questions evolved. It is still not known how diapycnal mixing occurs during storms, especially in spring when the water column is still weakly stratified. Is turbulent diffusion concentrated at the boundaries (breaking internal waves?) or rather concentrated in the center of the lake where large shear may cause mixing by Kelvin-Helmholtz instabilities? What happens at the boundary between Gersauersee and Urnersee where large horizontal density changes are concentrated on a relatively small distance? Furthermore, in order to understand their physics it is important to measure directly the lateral density currents which, till now, are only postulated based on indirekt evidence. Finally, mixing in Gersauersee seems to be complicated as well. One question concerns the mechanism leading to an increase of the bottom water temperature which we found during two summers and which cannot be explained by geothermal heat flux alone (Fig. 14). New kinds of experiments are planned in Lake Lucerne such as the use of artificial chemical tracers and of a new generation of current meters capable to trace bottom currents in the periods between the more spectacular events. Lake Lucerne still keeps a lot of secrets and will certainly continue to do so for other generations of curious observers.

ZUSAMMENFASSUNG

Urner- und Gersauersee, zwei benachbarte Becken des in der Zentralschweiz gelegenen Vierwaldstättersees, sind durch eine 85 m tiefe Unterwasserschwelle getrennt. Sie besitzen sehr ähnliche Topographie (maximale Tiefen 195 bzw. 213 m), sind aber «äußeren Kräften» (Wind, Zuflüsse) sehr verschieden ausgesetzt. Der Urnersee wird sowohl durch ausgeprägte Hang/Tal-Winde als durch gelegentliche starke Föhnstürme beeinflußt, im Gersauersee hingegen sind die Winde meist schwach. Zwei relativ große Zuflüsse, in denen starke Hochwasser auftreten können, erneuern das Wasser des Urnersees in etwa 1,4 Jahren; in den Gersauersee direkt mündet kein großer Fluß. Vom März bis Oktober 1986 wurden meteorologische Parameter, Wassertemperaturen und Strömungen quasi-kontinuierlich gemessen mit dem Ziel, Wasseraustausch und Mischung im Urnersee sowie die relative Wichtigkeit der Wind- bzw. Zufluß-induzierten Mischung zu quantifizieren. Drei Perioden konnten identifiziert werden: (1) Im April führen bei noch schwacher Schichtung starke Winde zu einer Wassererneuerung im tiefen Hypolimnion (definiert durch das Volumen unterhalb 110 m) von 50 % und zu einem vertikalen Wärmefluß von 36 Wm^2. Als Folge dieser Mischung wird etwa unterhalb 20 m Tiefe das Wasser im Urnersee wärmer als dasjenige im Gersauersee. (2) Im Mai und Juni führt der horizontale Dichtegradient zu einem Austausch von ca. 65 % des Wassers im tiefen Hypolimnions des Urnersees durch das schwerere Wasser aus den mittleren Tiefen des Gersauersees. (3) Gleichzeitig mit diesen Vorgängen führen die gelegentlichen Hochwasser in den Zuflüssen zu einem weiteren Wasseraustausch von ca. 20% und einem Wärmefluß von etwa 6 Wm^2. Während des restlichen Sommers bleibt die Wassererneuerung kleiner als 10%; sie kommt fast ausschließlich durch Hochwasser-induzierte Dichteströmungen zustande, der Einfluß des Windes bleibt schwach. Während der Hochwasser können aber immer noch große Wassermengen pro Zeit ins Hypolimnion transportiert werden, und der Wärmefluß kann 600 Wm^2 und mehr ausmachen. Der Einfluß der lateralen Dichteströme auf Mischung und Wasseraustausch zwischen den beiden Seebecken ist ökologisch sehr wichtig; er erklärt, wieso die Sauerstoffsättigung im Hypolimnion des Urnersees meistens sehr viel größer ist als im Hypolimnion des Gersauersees.

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