Dynamics of bottom currents in a small lake¹

U. Lemmin

Laboratoire d'hydraulique, École Polytechnique Fédérale de Lausanne,
CH-1015 Lausanne, Switzerland

D. M. Imboden

Institute of Aquatic Sciences (EAWAG), Swiss Federal Institute of Technology,
8600 Dübendorf, Switzerland

Abstract

The dynamics of bottom currents in Baldeggersee, Switzerland, were investigated with a specially designed recording current meter sensitive to current velocities of $0.3\text{--}2.5\text{ cm s}^{-1}$. Supporting information was obtained from thermistor-chain temperature recordings and from records of atmospheric boundary-layer parameters measured in the center of the lake. During 1980–1981 bottom currents recorded for 1-week periods on the central bottom plateau of the lake (65-m water depth) were highly variable. The mean speed was slightly $> 1\text{ cm s}^{-1}$ with no seasonal trend. Speeds $> 2.5\text{ cm s}^{-1}$ occurred after periods of high wind; quiescent periods were rare and seldom lasted more than 1 h. Spectral analysis shows that the primary mechanism generating bottom currents during stratification is internal gravity waves in the thermocline. During winter mixing when chemical stratification is observed below 30 m, the wind stress distribution is directly reflected in the bottom current pattern. In both periods wind-induced disturbances were felt in the bottom layer with little time delay, indicating the event-dominated structure of bottom current dynamics. Bursts of particle transport in the bottom layer are observed during periods of high wind, suggesting episodic particle resuspension. Such events may be important for the control of mass exchange at the sediment–water interface.

Lake eutrophication has become a major problem worldwide. Initially it was believed that a reduction of external loading would be sufficient to curb eutrophication and return a lake to mesotrophic or even oligotrophic state. In many lakes, however, the decay of deposits accumulated during eutrophication produces internal loading. This mineralization of nutrients from the sediments and the subsequent transport upward through the hypolimnion may play a decisive role in the development of the trophic state of a lake. Both remineralization and upward transport are linked to horizontal water movement in the bottom layer of the lake.

Understanding of hypolimnetic currents has depended on the availability of sensitive instrumentation. For larger lakes with sufficient fetch, progress was made soon after the first reliable current meters were produced. Current measurements in Lake Geneva (medium sized) during winter showed

clearly that hypolimnetic currents resulted from predominant wind patterns (Bétant and Perrenoud 1932). Long time series of data obtained more recently with self-contained recording instruments made it possible to develop a coherent picture of the hydrodynamics in large lakes (Csanady 1984). This knowledge allowed accurate mathematical modeling of circulation in these lakes (Simons 1980).

In small lakes which may have horizontal dimensions of only a few kilometers, current patterns seem simpler since it is generally assumed that the modifying influence of the earth's rotation can be neglected. In addition, because horizontal dimensions are small and slopes are generally steep, many details of slope-induced cross-sectional current structure such as subsurface jets (predicted by Bennett 1974) will not be detectable. Therefore wind setup and internal gravity waves remain the principal driving forces for hypolimnetic currents. It is evident however from Bennett's work that the hypolimnetic currents are usually small. Attempts to study them in small lakes with standard oceanographic instrumentation have failed because the currents remain

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mostly below the threshold of the instrumentation. No direct current measurements near the bottom have been reported even though Nansen (1906) had already produced a recording current meter sensitive to currents as low as 0.5 cm s^{-1} .

It is generally assumed that mixing in the hypolimnion is a slow, quasi-steady process. However, the large scatter found in mixing coefficients calculated from tracer measurements in the hypolimnion (de Bruijn et al. 1980) indicates the influence of advective processes due to horizontal currents. Mortimer (1941, 1942) used measurements of temperature and chemical parameters to argue that below the thermocline, horizontal turbulent motions generated by internal waves are dominant during stratification. More recently, Lathbury et al. (1960) reported drogue measurements in the hypolimnion of Lake Mendota. During stratification they found steady motion at about 7 cm s^{-1} with an indication of seiche-induced oscillations. Current speeds increased toward the lake bottom. From sedimentation rates, Serruya (1977) deduced intermittent resuspension of sediments in Lake Kinneret as a result of strong currents generated by diurnal winds (Serruya et al. 1974).

This paper reports a study of the deep water currents in Baldeggersee. Bottom currents, which were found to exist at all times of year, were highly variable. The dynamics of the bottom currents and the manner in which they may cause sediment transport and affect deep water mixing are discussed with supplementary information from temperature recordings.

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Experimental equipment

During 1980 and 1981, bottom currents were measured on several occasions for 1-week periods with a specially designed, bottom-resting current meter (Lemmin et al. 1985). As an indicator of velocity the instrument uses an inverse pendulum consisting of a slightly buoyant sphere on a very

Fig. 1. Depth chart of Baldeggersee. Positions of moorings are: 102—meteorological buoy; 151–153—basinwide current study; 204—thermistor chain (position of thermistor-chain station 205 is identical with station 102); 301—bottom current. Inset: location of Baldeggersee (B) and Sempachersee (S).

thin, light thread. The deviation of the sphere from a reference point is a measure of the current vector. The position of the sphere is recorded photographically at predetermined intervals. The sampling interval was set at 3 min, which allowed continuous recording for up to 1 week with one roll of film. For Baldeggersee the instrument was tuned for a current speed range from 0.3 to 2.5 cm s^{-1} . For higher current speeds the sphere was outside the field of view of the camera. However the direction of the flow could still be determined, because the thread to which the sphere was tied remained visible.

Currents were measured about 80 cm above the sediment surface. For the velocities found in Baldeggersee, this level may be in the upper portion of the logarithmic layer. The interest in this study was in the characteristics of the free-stream flow and its correlation with driving forces. Therefore the data will not be analyzed in terms

Fig. 2. Typical sample trace of the longitudinal current component at station 301 (midlake).

of boundary-layer parameters. The recording technique also allows a view of the sediment surface and shows the passage of suspended materials between the bottom and the camera. In all cases the instrument was deployed at mooring station 301 (Fig. 1) on the central bottom plateau of the lake.

The temperature distribution throughout the water column was measured with permanently moored thermistor chains and recorded automatically every 20 min. The vertical distance between thermistors was 2 m. They were individually calibrated and had a resolution of 0.02°C . Meteorological boundary-layer data were simultaneously taken on a stabilized buoy in the center of the lake. Wind speed was measured at a height of 8 m (automatic instrumentation by Aanderaa). During fall and winter 1978–1979, Aanderaa current meters were moored at stations 151, 152, and 153. The sampling interval was set at 15 min. All mooring locations are indicated in Fig. 1.

The Baldeggersee environment

With a surface area of 5.2 km^2 and a maximum depth of 66 m, Baldeggersee is a small, deep lake (Fig. 1). River-induced, basinwide flow is negligible, since the lake has a mean water residence time of 4–8 years. The lake is sheltered by low mountains running parallel to its axis. Recorded winds are predominantly oriented close to the lake axis with an annual average range $<3.0 \text{ m s}^{-1}$ about 80% of the time. Standing internal gravity waves which are only slightly damped can be observed during most of the stratification period. A well-mixed epilimnion hardly ever develops. The study of deep

water movement in Baldeggersee was undertaken within the framework of a larger investigation of the mechanisms controlling vertical diffusive transport (Imboden et al. 1983).

The following analysis is mainly based on Baldeggersee data. Additional data from Sempachersee (about 10 km west of Baldeggersee; see Fig. 1) are included in the discussion of sediment transport. Data were analyzed for the effects of winds and internal waves on bottom currents. For the purpose of the analysis we split the annual cycle into two periods which we call “stratification” and “mixing” to depict their dominant properties.

The stratification period can be defined as the time during which the vertical temperature structure is favorable to the generation of internal waves and less favorable to vertical mixing. In this sense Baldeggersee typically remains stratified from April or May into December. The extent of vertical water exchange during the mixing period, which is characterized by a weak, non-existent, or inverse stratification in the upper 25 m of the water column, strongly depends on meteorological conditions: In some years the lake reaches one or more brief homothermal situations in late December or January and in February or March. In other years, because of the absence of strong winds mixing never penetrates to the lake bottom. Thus there remains a chemically induced, deep water stratification.

Bottom currents

General pattern—At the lake bottom, there are currents throughout the year. Dur-

ing 26 observations lasting up to 1 week, quiescent periods were rarely found and never lasted for >1 h. In contrast, speeds >2.5 cm s $^{-1}$, the maximum value the instrument was tuned for in Baldeggersee, were observed more often. Typically such speeds occurred in bursts of variable duration which we will show to be related to periods of high energy input into the lake.

When assembled in histograms, the bottom currents show a log-normal distribution centered around 1 cm s $^{-1}$. The speeds beyond the range of the instrument account for $<20\%$ of the total length in most records. There is no systematic difference between records from different seasons, except that in a few winter observations (omitted from the present analysis) current speeds >2.5 cm s $^{-1}$ may total $>50\%$ of the record.

Figure 2 typifies the strong variability of bottom currents. The high-frequency oscillations visible in the record do not necessarily represent small-scale current fluctuations; vortex shedding at the sphere induces slow cross-current oscillations of the pendulum (Lemmin et al. 1985). In the following analysis the data were averaged over at least three observations; spectral analysis was limited to a cutoff period of 1 h. For part of the analysis, the current data were split into two components: one along the lake axis (longitudinal) and one perpendicular to it (lateral). For the spectral analysis carried out on these records with the fast Fourier technique, the data were averaged over 3–10 current samples. The records were then segmented, transformed, and ensemble averaged.

Stratification period—Results from the spectral analysis of the bottom current component along the main axis of the lake are presented in Fig. 3. The most prominent feature in all of the curves is a statistically significant peak around 9 h. This period represents the first-mode standing internal wave in Baldeggersee. Depending on the structure of the stratification, the period varies slightly. It is obvious from this diagram that bottom currents are correlated with internal waves during stratification. The second mode remains below the level of significance in these spectra.

The structure of standing internal gravity

Fig. 3. Spectra of horizontal bottom-current component along the main axis of the lake during stratification. Starting date for each record shown on the curve. Records span 4–7 d. Shaded areas cover typical ranges of the first and second modes of the internal gravity wave during stratification.

waves in Baldeggersee can be modeled by the modified Defant method (Mortimer 1979). This model is based on actual basin topography with two layers of homogeneous temperature. The wave periods, the wave contour, the volume transport, and the depth-averaged current speeds in each layer are predicted. An example is given in Fig. 4 and is used for reference in explaining the data below. Dynamics during stratification (October 1980) are presented in more detail. The 8°C and the 11°C isotherms were calculated from the thermistor-chain data at station 204 (Fig. 1).

Fig. 4. Defant model calculation for the first and second internal seiche mode in a two-layer model of Baldeggersee. Situation for 5 and 6 October 1980 with interface depth, 10 m; epilimnion temperature, 12°C; hypolimnion temperature, 4.8°C. Arrows indicate position of the measuring stations along the lake axis. The calculated periods are 9.4 h for the first mode and 4.3 for the second.

Isotherms and the longitudinal bottom-current component are given in Fig. 5 together with the wind data. The oscillatory current reversals of the bottom currents reflect undulations of the thermocline. Due to the distance between the measuring stations, there is a phase lag between oscillations in the thermocline and near the lake bottom. In the afternoon of 7 October, a wind pulse destroyed the internal wave oscillations, and almost immediately oscillations ceased in the bottom currents. High-frequency motion set in. Another wind pulse occurred in the evening of the same day. After the winds died, new, large-amplitude

internal waves were set up in the thermocline. The amplitudes of the corresponding pattern in the bottom currents exceeded the range of the instrument. It is apparent that during stratification bottom currents are controlled by thermocline dynamics and that winds affect the bottom currents only indirectly through their action on the thermocline. Bottom currents respond with little time lag to dynamics of the thermocline. In Baldeggersee fetch is short and does not produce large-scale circulation. Consequently, long-lasting unidirectional currents are not likely in the bottom layer of the baroclinic lake.

Fig. 5. Case study of internal wave dynamics. Top—wind data, station 102; middle—isotherm pattern for the 11° and 8°C isotherms, station 204; bottom—longitudinal component of bottom current, station 301. A 16-h mean has been subtracted from the original current data.

The spectral curves for the 11°C isotherm-depth fluctuations (Fig. 6) are dominated by a peak at 8.4 h for the first-mode internal wave. There are also peaks corresponding to the second mode at 4.1 h and to the fourth mode at 2.0 h. The spectral curves for the two bottom-current components show the first mode and an indication of higher modes at 4.1, 2.8, and 2.0 h. This wave pattern is also imprinted on the lateral component, indicating that the internal wave does not necessarily travel straight up and down the long axis of the lake basin.

Coherence between the isotherm depths and the longitudinal current component (Fig. 7) is high for the first and second mode. Low coherence at other frequencies indicates that the standing internal waves dominate the internal dynamics during stratification. Sta-

Fig. 6. Spectra for the 11°C isotherm-depth fluctuations at station 204 and the two bottom-current components at station 301, 4–8 October 1980. Periods of the first and the second internal wave modes are indicated by vertical dashed lines. Units for energy density are $^{\circ}\text{C}(\text{cph})^{-1}$ for isotherms and $\text{mm s}^{-1}(\text{cph})^{-1}$ for currents.

tion 301 is near the node of the first mode (Fig. 4) where currents reach a maximum, whereas station 204 is near the southern antinode (where displacements are largest). Since the sign of the longitudinal current is chosen positive to the north, we expect the displacement at station 204 to lead the current by a phase angle of 90°. This prediction is confirmed by measurements at the frequency of the first mode (Fig. 7).

For the second mode, the situation is more complicated since the two nodes and three antinodes subdivide the lake axis into four regions with different phases between displacement and current. It appears (Fig. 4) that station 204 is south of the southern node and station 301 is slightly north of the central antinode. From these positions we expect and find that the currents at station 301 lead the displacement at station 204 by a phase angle of about 270° (Fig. 7).

Fig. 7. Phase and coherence between the 11°C isotherm at station 204 and the longitudinal bottom-current component at station 301, 4-8 October 1980. The phase is given for the displacement relative to the current. Periods of the first and second internal wave modes are indicated by vertical dashed lines. Horizontal dashed line shows confidence limit.

The Defant model predicts the correct standing internal wave periods for the measured temperature profile in October 1980. The depth-averaged maximum hypolimnetic currents for the measured thermocline amplitudes reach 1.0 cm s^{-1} on 5 and 6 October (Fig. 4). They become 1.9 cm s^{-1} on 8 October. Calculated values are smaller than observed ones, in accord with a more detailed two-dimensional model (Mortimer pers. comm.). If we consider the relatively small discrepancy between the observed and

the predicted values, however, the water masses in the hypolimnion seem to be moved predominantly by currents produced by standing internal waves.

Wind events were rare during stratification, and they influence bottom currents only through the filter of the thermocline (Fig. 5). Due to the relatively short record lengths of the bottom current measurements, it is not possible to establish a reliable statistical correlation between wind and bottom currents during stratification. However, some insight into the relation between wind stress and bottom currents can be gained from comparing the distribution of the wind stress and the path length of the bottom current transport over the total length of one data set. For this purpose a histogram of the squares of the hourly mean wind vector partitioned into eight sectors and five speed classes was established (Fig. 8a). Sector 1 dominates the histogram because of the contribution from several events with speeds $> 5 \text{ m s}^{-1}$. Wind speeds $> 5 \text{ m s}^{-1}$ are less frequent in the remaining sectors and wind energy input from these sectors is more evenly distributed.

Corresponding bottom currents were analyzed in the same manner (Fig. 8b). The transport path length was calculated with a running mean over at least three data points and the assumption that the current velocity remained constant over the time interval between two consecutive observations. As currents $> 2.5 \text{ cm s}^{-1}$ were not measured, they were replaced by the value of 2.6 cm s^{-1} . The real currents were certainly higher, producing a conservative estimate. The principal features of the current rose are not greatly affected by this approximation.

In sector 1, most of the bottom water transport occurred at speeds beyond the range of the instrument and resulted from the initial strong thermocline tilt in each wind event (Fig. 5). More than two-thirds of the total transport is balanced in the opposing sectors 1 and 5 along the lake axis. Thus the directionally biased wind field produces an almost balanced pattern of bidirectional bottom transport. The high wind events in sectors 6 and 7 do not penetrate the thermocline and thus have no noticeable influence on bottom currents. This lack of

Fig. 8. Sector histogram for (a) the squares of the hourly mean wind speeds and (b) the bottom-current transport path length, 4–8 October 1980. The path length was calculated from the mean over three current readings on the assumption that the current remained constant. (Winds from the direction, currents toward the direction.)

an effect is due to the relatively short cross-lake fetch, further reduced by the mountains on the western side of the lake.

Turning of the bottom current vectors was observed in the records as long as some thermal stratification remained in the water column. When plotted as progressive vector diagrams, the currents formed closed loops that were clockwise most of the time. Typically not more than two full circles occurred in sequence, but up to four consecutive turns were observed in May and in December. In most cases bottom currents formed these loops when the current speed was slow. It is unlikely that they are artifacts of the measuring system, as each cycle consists of more than 50 vectors.

Rotary spectral analysis was carried out for all runs. For the period range in which internal standing waves can be expected, most of the energy is concentrated in the clockwise component, but statistical significance is not always reached. As demonstrated in the set from July 1980 (Fig. 9), the peak in the clockwise component is always at the period corresponding to the first internal wave mode.

Such wave patterns may be set up as a

result of uneven basin topography and wind forcing of the thermocline, which is not aligned with the lake axis. Alternatively, the effect of the earth's rotation cannot be ruled out completely. The internal wave period is $>60\%$ of the inertial period. Bäuerle (1985) has shown that for frequencies higher than the inertial one, clockwise rotation can be expected.

Mixing period—During this period effects from stratification of near-surface layers on the bottom current pattern can be neglected. Bottom current records from the mixing period were spectrally analyzed. The spectral curves of the longitudinal and the lateral components (Fig. 10) are fairly smooth and do not show any significant features. The slope of the curves is close to -3 in most cases, an indication of stratified flow (Turner 1973). Wiegand and Carmack (1981) observed a temperature inversion and stabilization of the stratification of the lower water body due to salinity in Kootenay Lake during one winter. Conductivity measurements over several years (Joller 1985) indicate that in Baldeggersee the density profile below 35 m is stabilized by chemical stratification and that the temperature in-

Fig. 9. Rotary spectra of bottom currents, 2-7 July 1980.

version is a common feature which—similar to Kootenay Lake—lasts from late December into March (Imboden et al. 1983).

In Baldeggersee convective cooling and wind mixing penetrated down to about 35 m by late December 1980. At this time cooling was also observed in the bottom layer, leaving a layer of warmer temperature be-

Fig. 10. Spectra of the longitudinal current component during circulation. Starting date for each record shown on the curve. Records span 4-8 d. Dashed lines indicate a slope of -3.

Fig. 11. Pattern of isotherms (°C) at station 205.

tween. During the remainder of the mixing period, the whole lake cooled, maintaining the inversion (Fig. 11). This unstable temperature profile cannot result from vertical convective mixing. Instead, cool, dense water must be advected horizontally below the inversion layer by the river entering the lake from the south. Conductivity of the river water is about four times greater than that in the lake bottom layer and the temperature is comparable to or below that of the lake surface layer. During this time of the year the river water is always heavier

Fig. 12. a. Lagged cross-covariance between the longitudinal components of wind stress and bottom currents, 12–20 January 1981. b. Observed (solid) and computed (dashed) bottom currents for the same period.

than the lake water and will form a sinking plume reaching the lake bottom layer in the manner described by Wiegand and Carmack (1981). From a mass balance, current speeds $< 1 \text{ cm s}^{-1}$ are estimated. It was not possible to resolve this flow in the current data since winter winds come predominantly from the north, producing comparable transport in the same direction.

The relationship between the wind and bottom currents was studied for the period between 12 and 20 January 1981. Winds blew predominantly along the lake axis. Bottom currents were oriented similarly. The cross-covariance between the longitudinal components of wind stress and bottom current (Fig. 12a) had a peak around 15 h and a reversal for lags > 25 h. Thus for lags < 25 h, bottom currents can be assumed to act as a return flow to the wind-induced surface currents. (Wind direction is that from which it blows; current direction is that toward which it flows.)

For the same data set the impulse response function was calculated. In this method of analysis (Schwab 1979; Simons 1984), the response of the lake to the general wind distribution in time and space is represented by the integrated effects of sequences of wind impulses to a point on the

surface of the lake. For simplicity the wind stress field is taken as homogeneous above the lake. From the time series of the longitudinal components of the wind stress and the bottom current, 3-h averages were formed. Simons pointed out that for this analysis the current record should be much longer than the wind record. In order to find the optimum length for the response function, varying lengths of the wind stress record were used in the calculation. Additionally the current vector was lagged with respect to the wind stress vector. The error between observed and calculated currents did not decrease significantly if the response function was extended beyond 26 h. The error was always smallest for lags of 6–9 h. The result of the calculation with these limits (Fig. 12b) shows that the general trends of the currents, especially the current reversals can be described by this model. However there remains some discrepancy, particularly at the peak values. The assumptions of linearity and a homogeneous wind field may not be correct. For oscillatory currents, Kundu (1984) has shown that a variable wind field may lead to an augmentation of the current speeds.

Basinwide study—From 25 November 1978 to 2 February 1979, Aanderaa record-

Fig. 13. Basinwide current study. Top—wind data, station 102; others—current data from stations 151, 152, and 153. The sensor depth is indicated for each station. (Winds from the direction, currents toward the direction.)

ing current meters were moored at stations 151, 152, and 153 at 5-m depth in the wind-driven layer and at 37-m depth (about 6 m above the lake bottom; Fig. 1). Most of the time current speeds remained below the threshold of the instruments ($2\text{--}3\text{ cm s}^{-1}$). Occasionally, current spikes lasting $<1\text{ h}$ were found in the records. Stronger currents of longer duration were measured only three times. In each case, strong winds blew for several hours.

The most detailed of these three cases is presented in Fig. 13. From the end of December 1978 to early January 1979, winds ranged up to 10 m s^{-1} . These winds were oriented mostly along the lake axis from northerly directions. The resulting current pattern at the three mooring stations shows strong differences between the stations. Station 151, closest to the northeastern end of the lake, has the shortest fetch. Currents in the upper layer (5-m depth) reach up to 8 cm s^{-1} and vary proportionally to the wind speeds with short time lags. Typical of non-steady state situations, the current direction fluctuates widely. On 1 January 1979 when hourly mean wind speeds exceeded 7 m s^{-1} current directions in the lower layer (37 m) indicate a return current with speeds up to about 8 cm s^{-1} .

Station 152, toward the southwestern end of the lake, has the longest wind fetch. In the upper layer the currents respond most frequently to winds $>5\text{ m s}^{-1}$ and are oriented along the axis of the lake. However, current speeds remain well below the maximum speeds observed simultaneously at station 151. In the lower layer, current speeds are also much lower than at station 151 but give an indication of a return current. Station 153 is in the northwestern part of the basin. Currents here are significantly slower than at the other two stations and do not permit a systematic interpretation.

The setup time for currents appears to be of the order of 1–2 h. Because of the influence of local topography on the wind field, the wind-generated currents are horizontally inhomogeneous. The difference in current speeds at stations 151 and 153 indicates an uneven wind field at the northern end of the lake. From the current direction at station 151, we can infer that the wind there has a

noticeable westerly component that has disappeared when it reaches the midlake meteorological buoy. The nearby mountains on the western side of the lake seem to shelter the western half of the lake so that currents at station 153 are generally weak. This effect is reduced by the time the wind field reaches station 152.

It was seen that the setup from a 7 m s^{-1} wind results in a lakewide current pattern with drift currents in the upper layer and adjustment currents below, with current speeds well above the instrument threshold of 3 cm s^{-1} . However, as winds of that strength do not often occur for a sufficiently long duration, basinwide circulation with speeds above the threshold of the rotor current meters is a rare event in Baldegersee. When it does occur, it dies out very rapidly after the winds have dropped, because of internal friction. Therefore water particle displacements calculated from the current-meter speeds usually range around 200–500 m during a wind event. Unfortunately no bottom current measurements were carried out simultaneously.

Interaction of particles and bottom currents

Sediment transport was not actually observed in Baldegersee. During winter 1983, the current meter was deployed several times in Sempachersee, another deep but slightly larger lake near Baldegersee (see Fig. 1), but more exposed to wind. Bottom currents were measured in the center of that lake with a more buoyant pendulum. Bottom current speeds ranged up to 6 cm s^{-1} .

In several instances the pictures in Sempachersee were clouded by the passage of fine materials between the camera and the lake bottom. The observation shown in Fig. 14 was made when wind speeds were $> 7 \text{ m s}^{-1}$. The first picture was taken just before particle transport was observed. In the following pictures the cloudiness increased. The maximum was reached 20 min later. From the position of the sphere, we can see that the current velocity did not change during this sequence. Typically such situations last for about 30 min.

These findings indicate the possibility of

episodic resuspension events elsewhere, perhaps at higher levels where currents are stronger. Bottom currents in Sempachersee remain at least strong enough to advect the material to the measuring site. These observations are evidence for the hypothesis of Serruya (1977) that sediment traps near the lake bottom may contain more materials than those further up in the same water column because of resuspension.

Although currents of comparable strength were not measured at station 301 in Baldegersee, current speeds $> 10 \text{ cm s}^{-1}$ had been recorded for short periods 6 m above the sediment surface in 43 m of water at station 151 during the basinwide study (see Fig. 13). Episodes of resuspension similar to those seen in Sempachersee may therefore also occur along the upper slopes of Baldegersee. Because of the generally lower wind input and the shorter duration of high wind energy input in Baldegersee, bottom currents in the deep part of the lake are weaker and thus unable to advect these materials to the bottom-current measuring site.

Conclusions

In Baldegersee bottom currents exist year-round. Currents were highly variable and speeds seldom remained constant for more than a few hours. Current reversals were frequent. Even though currents typically ranged around $1\text{--}1.5 \text{ cm s}^{-1}$, they exceeded 2.5 cm s^{-1} during individual events associated with bursts of high wind energy input. The wind field above the lake is rather variable; Kundu (1984) has pointed out that a succession of wind pulses of relatively small intensity may be better able to excite inertial oscillation than one strong pulse. With a relatively short setup time, bottom currents in this lake may be generated in a similar way.

As long as the lake is stratified, the hypolimnion remains shielded from the direct influence of the wind and the structure of the bottom currents is controlled by the dynamics of the thermocline. The response of bottom currents to bursts of high winds is transmitted through the thermocline almost instantaneously if the wind fetch is oriented along the lake axis. Strong winds with short fetch however, do not seem to influence the

Fig. 14. Sediment transport in Sempachersee near the center of the lake. Left—just before sediment transport started; right—21 min later.

bottom currents at this time of year. The peak in the current spectra at the internal wave frequency and the agreement between the measured current speeds and those predicted for internal waves by a simple two-layer model both indicate that internal waves dominate the bottom currents.

During the mixing period the lake responds more strongly and more directly to wind energy than it does during stratification. The lakewide current pattern is inhomogeneous as a result of a topographically altered wind stress field. Therefore simple linear models cannot fully describe the structure of the bottom currents. The deep layers of the lake remain stratified, producing a temperature inversion at mid-depth. Thus two different processes act simultaneously in the upper and the lower part of the water column to produce the water transport.

Above the inversion layer, convective cooling and wind mixing proceed vertically

downward. Below the inversion layer, the horizontal advective flow of dense riverine water is a rather continuous process of deep water renewal in comparison to the upper layer dynamics. However, the wind-induced variable horizontal bottom currents may serve to mix this riverine water within the bottom layers. Thus, similar to the observations in Kootenay Lake (Wiegand and Carmack 1981), the classical pattern of a lake overturn produced by vertical mixing over the whole water column does not apply to Baldeggersee.

Bursts of particle transport were observed during the mixing period in Sempachersee. In Baldeggersee the location of station 301 near the center of the lake is not well suited for the study of sediment resuspension and sediment transport. However, the magnitudes of the current velocities measured in shallower water during the basinwide study were high enough to produce resuspension in that area of the lake.

Bottom currents and events of particle resuspension also have an effect on the magnitude of the sediment flux—the mass exchange between sediment and water. At present this flux is mostly deduced by methods that neglect the effect of variable water movement and bottom stress. Therefore sediment fluxes determined so far can be taken only as mean values giving little information about the exchange dynamics. From our measurements it appears that throughout the year the event-dominated structure of the bottom currents will be reflected in the mixing and transport pattern in the hypolimnion, which explains some of the scatter typically found in tracer measurements. Tracer measurements are usually taken over fixed time intervals of several weeks and both the number and the strength of events during such a period are variable.

This study has shown the general correlations between bottom currents and their driving forces, the order of magnitude of the currents, and some of the effects that they may have. Other aspects of the bottom currents, such as maximum velocity, turbulence scales, bottom boundary-layer structure, and magnitude of bottom friction, upon which progress is being made in the oceans (Grant and Williams 1984; Chriss and Caldwell 1984) have yet to be studied in lakes.

References

- BÄUERLE, E. 1985. Internal oscillations in the Lake of Geneva. *Ann. Geophys.* 3: 199–206.
- BENNETT, J. R. 1974. On the dynamics of wind-driven lake currents. *J. Phys. Oceanogr.* 4: 400–414.
- BÉTANT, A., AND G. PERRENOUD. 1932. Etudes sur la part occidentale du lac de Genève. Courants and température. *Mem. Soc. Sci. Phys. Hist. Nat. Genève Fasc. 2*, p. 225–293.
- DE BRUIN, P. J., L. LIJLEMA, AND G. VAN STRATEN. 1980. Transport of heat and nutrients across a thermocline. *Prog. Water Technol.* (Toronto) 12, p. 751–765.
- CHRISS, T. M., AND D. R. CALDWELL. 1984. Universal similarity and the thickness of the viscous sublayer at the ocean floor. *J. Geophys. Res.* 89: 6403–6414.
- CSANADY, G. T. 1984. Milestones of research on the physical limnology of the Great Lakes. *J. Great Lakes Res.* 10: 114–125.
- GRANT, W. D., AND A. J. WILLIAMS III. 1984. Bottom stress estimates and their prediction on the northern Californian continental shelf during code 1: The importance of wave-current interaction. *J. Phys. Oceanogr.* 14: 506–527.
- IMBODEN, D., U. LEMMIN, T. JOLLER, AND M. SCHURTER. 1983. Mixing processes in lakes: Mechanisms and ecological relevance. *Schweiz. Z. Hydrol.* 45: 11–44.
- JOLLER, T. 1985. Untersuchungen verticaler Mischungsprozesse mit chemisch-physikalischen Tracern im eutrophen Hypolimnion des Baldeggersees. Ph.D. thesis, ETH No. 7830.
- KUNDU, P. K. 1984. Generation of coastal inertial oscillations by time-varying wind. *J. Phys. Oceanogr.* 14: 1901–1913.
- LATHBURY, A., R. BRYSON, AND B. LETTAU. 1960. Some observations of currents in the hypolimnion of Lake Mendota. *Limnol. Oceanogr.* 5: 409–413.
- LEMMIN, U., T. JOLLER, M. SCHURTER, D. IMBODEN, AND H. ABEGGLEN. 1985. An instrument for measuring bottom currents. *Limnol. Oceanogr.* 30: 1116–1122.
- MORTIMER, C. H. 1941, 1942. The exchange of dissolved substances between mud and water in lakes. 1. The distribution of some physical variables and concentrations of dissolved substances in Esthwaite Water, April 1939–February 1940. 4. General discussion. *J. Ecol.* 29: 280–312, 30: 168–201.
- . 1979. Strategies for coupling data collection and analysis with dynamic modelling of lake motion, p. 183–277. *In* Lake hydrodynamics. Proc. Symp. Elsevier.
- NANSEN, F. 1906. Methods for measuring direction and velocity of currents in the sea. *Publ. Circ.* 34. Copenhagen [with appendix: V. W. Ekman, Current measurements by means of buoy and releasing clock work]. 42 p.
- SCHWAB, D. J. 1979. Analytical and empirical response functions for storm surges on Lake Erie. *Can. Manuscr. Rep. Fish. Aquat. Sci.* 53, p. 140–144.
- SERRUYA, C. 1977. Rates of sedimentation and resuspension in Lake Kinneret, p. 48–56. *In* Interaction between sediments and freshwater. Junk.
- , M. EDELSTEIN, U. POLLINGER, AND S. SERRUYA. 1974. Lake Kinneret sediments: Nutrient composition of the pore water and mud water exchanges. *Limnol. Oceanogr.* 19: 489–508.
- SIMONS, T. J. 1980. Circulation models of lakes and inland seas. *Can. Bull. Fish. Aquat. Sci.* 203.
- . 1984. Topographic response of nearshore currents to wind: An empirical model. *J. Phys. Oceanogr.* 14: 1393–1398.
- TURNER, J. S. 1973. Buoyancy effects in fluids. Cambridge.
- WIEGAND, R. C., AND E. C. CARMACK. 1981. A wintertime temperature inversion in Kootenay Lake, British Columbia. *J. Geophys. Res.* 86: 2024–2034.

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