Enhanced mixing in narrows: A case study at the Mainau sill (Lake Constance)

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ABSTRACT

Previous work has identified bottom currents as a significant source of turbulence in stratified lakes. Sills may therefore be a major factor determining overall turbulent diapycnal (vertical) exchange in lakes with multi-basin hypolimnia.

In order to investigate the contribution of the Mainau sill (separating Upper Lake Constance from Lake Überlingen) to the overall diapycnal mixing in Lake Constance, a series of temperature microstructure profiles was taken at Mainau Island in October 1993. From these profiles, using Batchelor's method, the rate of dissipation of turbulent kinetic energy was determined and related in an energy balance to the turbulent kinetic energy input from the wind, the energy content of internal seiches and the energy dissipation of bottom currents at the sill. Further, the vertical diffusivities were calculated using the dissipation method.

The analysis shows that $\approx 5.5\%$ of the wind energy flux was found in to the water column (below 2 m depth) and that energy dissipation was 8 times higher in the shear zone of the thermocline ($\approx 8.4 \cdot 10^{-3} \text{ W m}^{-2}$) than in the bottom boundary layer ($\approx 1.1 \cdot 10^{-3} \text{ W m}^{-2}$). Dissipation above the Mainau sill ($\approx 9.5 \cdot 10^{-3} \text{ W m}^{-2}$) exceeded the basin-wide average dissipation of internal seiche energy ($\approx 0.3 \cdot 10^{-3} \text{ W m}^{-2}$) by a factor of 34. However, since the areal extent of the sill is small ($\approx 1\%$ of the lake area), the sill contributes only about 40% to the basin-wide dissipation. Also vertical diffusivities within the thermocline were consistently enhanced by approximately the same amount over the sill. The synthesis of the observations implies that the sill plays a disproportionately large, but not dominant, role for small-scale diapycnal mixing in the hypolimnion of Lake Constance.

Introduction

Many natural aquatic systems are topographically subdivided into different basins. The structure of the narrows connecting such basins has several implications for water exchange and mixing. One prominent phenomenon associated with narrows is locally-enhanced turbulence resulting from intensified currents and shear forces

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(e.g. due to tides). A classical example of this is the Strait of Gibraltar (Wesson and Gregg, 1994), where shear forces exceed oceanic background values by orders of magnitude, and where the production of turbulent kinetic energy (TKE) is several orders of magnitude higher than in the open ocean. Other examples are the Strait of Denmark (Oakey and Elliott, 1980), the Strait of Aqaba, the Bosphorus, entries to sounds (Seim and Gregg, 1994), fjords (Stigebrandt, 1989) and estuaries (Peters, 1997).

Sills play a dominant role in enhancing vertical exchange in multi-basin lakes. The most obvious case is that of baroclinic gradients between basins, driving “heavier” water into a basin of “lighter” water. In Lake Lucerne, for example, river input and differential wind forcing have been found to be responsible for inter-basin baroclinic gradients over several sills (Aeschbach-Hertig et al., 1996), leading to significant vertical water exchange between the respective deep hypolimnia (Wüest et al., 1988; Schlatter et al., 1997). In addition, internal seiche pumping (Van Senden and Imboden, 1989) and differential heating (Horsch and Stefan, 1988; Imberger and Patterson, 1989) have been identified as driving mechanisms for vertical exchange. All these processes are moderated by the structure of the sills.

Besides these large-scale displacements of water masses, narrows intensify diapycnal mixing (i.e. mixing perpendicular to density surfaces) locally due to increased internal shear (Peters et al., 1988) and bottom friction (Goudsmit et al., 1997). Sills and narrows are therefore potential sources of diapycnal mixing in stratified natural waters.

Such a situation is found in Lake Constance, at the point where the Mainau sill separates the two main basins, Upper Lake Constance and Lake Überlingen (Fig. 1 and Fig. 1 in Güting and Hutter; this issue). Diapycnal diffusivity in Lake Überlingen, determined during summer stratification at the level of maximum sill depth (≈ 100 m), indeed shows high values of K_z ($= 0.3$ to $1 \text{ cm}^2 \text{ s}^{-1}$; Heinz, 1990; Heinz et al., 1990; Maiss et al., 1994). We therefore initiated a case study in order to test the hypothesis that the Mainau sill is 1) the major source of diapycnal exchange and 2) the major sink of kinetic energy. Specifically, we looked for answers to the following questions:

- What is the level of turbulence within the bottom boundary layer at the Mainau sill and how does it compare to the level of turbulence in the thermocline?
- Is the rate of dissipation of TKE within the bottom boundary layer at the sill related to the current speed, and what is the average dissipation during stratification?
- Is the sill responsible for the large background diffusivity which has been observed in the past in the lower thermocline of Lake Überlingen?

In order to answer these questions, we measured 96 temperature microstructure profiles at the sill during a period of five days in October 1993. Based on these data, we inferred TKE dissipation rates and vertical diffusivities, and analyzed wind forcing and bottom currents. After a brief summary of the dynamics at the sill and of the experiment (Section 2), the results are shown in Section 3. The locally measured dissipation is then compared to the rate of decay of the internal seiche energy and to the average annual forcing (Section 4). Finally, conclusions are drawn about the role played by the Mainau sill on the magnitude of the turbulent energy budget and vertical mixing in Lake Constance (Section 5).

Experiment

Dynamics at the Mainau sill

Lake Constance (Fig. 1 a), located in Germany, Austria and Switzerland, is the source of drinking water for about 4 million people. The lake, which has a surface area of 535 km² and a volume of 47.6 km³ (water renewal time: 4.1 a), is subdivided into three basins. Whereas Lower Lake Constance is completely separated from the main water body, the sidearm Lake Überlingen (surface area ≈ 65 km²) is connected to the main basin of Upper Lake Constance (surface area ≈ 407 km²) above the glacial moraine of the Mainau sill (Fig. 1 b). The saddle of the sill is 101 m below the lake surface. From this point, the water depth increases to a maximum depth of 147 m in Lake Überlingen and 253 m in Upper Lake Constance (Fig. 1 in Güting and Hutter, this issue).

The seasonal dynamics of the stratification shows features typical of temperate lakes. Convective mixing during the winter period reaches the deepest parts of the lake only sporadically every few years (IGKB, 1989–96). During the period of thermal (and chemical) stratification in summer (April to October), the internal dynamics of the hypolimnion is driven by wind-induced internal seiching, and diapycnal mixing is reduced to weak, small-scale turbulence.

Strong winds, blowing for several hours from one direction, and sporadic storms (occurring typically about once a month and lasting about a day) excite broad-band internal seiches with periods of 3.5 to 5.5 d (Bäuerle, 1981; Schimmele, 1993). Consistent with the first vertical first horizontal mode structure (Bäuerle, 1981 and 1994), and in agreement with the Merian Formula (Lemmin and Mortimer, 1986),

Figure 1. a Map of Lake Constance showing the locations of the moorings BM (thermistor string and wind), MM (current meter) and T6 (wind). A more detailed map is given in IGKB (1990). b The region of the Mainau sill showing the locations of mooring MM and of the microstructure profiles (marked by different symbols each day)

observed seiche periods have been found to be generally shorter during summer and longer in fall (Maiss et al., 1994). Since the wind excitation is irregular, seiching is usually forced and not free oscillations (Schimmele, 1993). Applying a linear model with stratification-dependent eigenfrequencies, Schimmele (1993) was able to reproduce the seiching motion which occurs under irregular wind forcing. The results of his study are representative insofar as the typical wind forcing was close to average (annual average $\approx 2.5 \text{ m s}^{-1}$ at mooring BM, Fig. 1).

In terms of internal seiching, the separation by the Mainau sill is not very distinct, as the sill is much deeper than the thermocline (Fig. 1 in Güting and Hutter, this issue). Consequently, the internal seiches excited in the lake as a whole (Bäuerle, 1981; Zenger, 1989) lead to horizontal currents and high exchange rates between the two basins. Tracer experiments reveal the water residence time-constant to be short; viz. only $80 \pm 10 \text{ d}$ for the entire Lake Überlingen basin (Heinz et al., 1990; Maiss et al., 1994). Due to intensification by the narrowing cross-sectional area of the sill, currents at 80 m depth (20 m above the saddle point) have been observed to show sporadic (approximately monthly) peak values of up to $\approx 20 \text{ cm s}^{-1}$ (Schimmele, 1993; Maiss et al., 1994; Hollan and Simons, 1978). In addition, non-linear internal surges with high current speeds ($> 30 \text{ cm s}^{-1}$) and abrupt changes of direction (Heinz, 1995; Schimmele, 1993) and a low damping time-constant of only $3.1 \pm 0.8 \text{ d}$ (amplitude damping: 6.25 d; Schimmele, 1993) support the working hypothesis of intense mixing at the sill.

Instrumentation

An experiment involving several research institutes was conducted to investigate the internal dynamics in the western part of Lake Constance. The experimental set-up, consisting of several thermistor strings and current meters, has been described by Heinz (1995). In this contribution we focus only on the role of the Mainau sill as a sink of internal seiche energy and as a source of diapycnal mixing. In addition to temperature microstructure profiles (locations in Fig. 1b), the investigation is based on the following mooring data, all sampled at 20 minute intervals:

- Wind speed and direction, measured 4.4 m above the lake surface using an anemometer (Aanderaa Instruments, Bergen, Norway) at moorings BM (Lake Überlingen) and T6 (Upper Lake Constance; Fig. 1a).
- Current speed and direction, measured at 80 m depth above the sill at position MM (Fig. 1a).
- Temperature profiles from 3.4 to 140.5 m depth, continuously measured by two thermistor strings (21 thermistors) moored at BM (Fig. 1a).

Temperature microstructure method

The temperature microstructure method allows profiles of the dissipation of TKE to be determined from well-resolved temperature profiles and also allows vertical diffusivity to be estimated. The method is based on the fact that small-scale temperature fluctuations are always present in natural waters. At the Mainau sill the tem-

perature fluctuations are generated by turbulence due to 1) bottom friction and 2) interior shear of the horizontal velocity of the seiching strata.

The quantitative relationship between the temperature fluctuations on the smallest length scales (mm) – where temperature differences are smoothed by thermal diffusivity κ_T – and the intensity of turbulent mixing is described by Batchelor's (1959) theory. Under isotropic and stationary conditions, the spectrum of one-dimensional temperature fluctuations is described by:

$$\phi_T(k_z) = \frac{\pi \chi \kappa_T^{1/2} q^{3/2} \nu^{3/4}}{\varepsilon^{3/4}} \left(\frac{\exp(-x^2)}{x} - \sqrt{\pi} (1 - \operatorname{erf}(x)) \right) \quad [\text{K}^2 (\text{cpm})^{-1}] \quad (1)$$

where k_z [cpm] denotes the vertical wavenumber, $x = k_z \kappa_T^{1/2} \nu^{1/4} q^{1/2} \varepsilon^{-1/4}$ is the non-dimensional vertical wavenumber, ν the kinematic viscosity of water ($1.0 \cdot 10^{-6}$ to $1.5 \cdot 10^{-6} \text{ m}^2 \text{ s}^{-1}$), and $q = 3.4$ the experimentally determined turbulence constant (Dillon and Caldwell, 1980). The rate of dissipation of TKE, ε [W kg^{-1}], and temperature variance χ [$\text{K}^2 \text{ s}^{-1}$] were determined by fitting spectra of the measured temperature profiles to Batchelor's (1959) model spectrum (eq. 1). In other studies, these dissipation estimates have been compared to estimates obtained from the shear dissipation method (Oakey, 1982; Kocsis et al. 1998) and the diffusivity estimates have been compared to diffusivity estimates obtained from tracer studies (Ledwell et al., 1993; Wüest et al., 1996). In both cases agreement was to within a factor of 2.

Temperature microstructure data were measured at 96 Hz using a pair of FP07 fast-response thermistors (response time = $7 \cdot 10^{-3} \text{ s}$; relative resolution 10^{-4} K) mounted on an adapted SBE-9 profiler (SeaBird, Bellevue, Washington, USA; Fig. 2), sinking freely at about 0.1 m s^{-1} down to the lake bottom (as close as $\approx 0.1 \text{ m}$). To reduce the quantization noise of the small temperature fluctuations at small scales, preemphasis (Mudge and Lueck, 1994) was applied by linearly enhancing the microstructure signal as a function of frequency before A/D conversion (details in Gloor et al., 1995). With this arrangement it is possible to resolve dissipation values ranging from 10^{-11} to $10^{-6} \text{ W kg}^{-1}$ within a factor of 2 (see Kocsis et al., 1998 for a detailed analysis of noise levels). The spectra $\phi_T(k_z)$ were calculated from profile segments 1 m in length. Details of the data analysis have been given by Gloor (1995).

In order to obtain statistically robust and easily comparable average estimates, the dissipation profiles $\varepsilon(z)$ were subdivided into an epilimnion layer (the uppermost 20 m), a thermocline layer (20 m below the lake surface to 20 m above the lake bottom) and a bottom layer (0 to 20 m above the lake bottom). The choice of these compartments was guided by the question of the role played by bottom and internal friction in determining overall dissipation in the hypolimnion. Finally, vertical diffusivities were calculated according to the dissipation method using the following expression (Osborn, 1980):

$$K_z = \gamma_{\text{mix}} \varepsilon \text{ N}^{-2} \quad [\text{m}^2 \text{ s}^{-1}] \quad (2)$$

The stability N^2 was calculated from the temperature profiles. The value $\gamma_{\text{mix}} = 0.12$ was used for the mixing efficiency (Peters and Gregg, 1987) due to the lack of a more appropriate parameterization.

Figure 2. The adapted SeaBird Electronics microstructure profiler used in this study. The sinking speed is adjusted to 10 cm s^{-1} by the buoyancy of the profiler (see Gloor et al., 1995 for technical details)

Observations

Wind and seiching at the Mainau sill

The major overall driving force for vertical mixing during the summer stratification period is wind. Figure 3a shows the wind speed, measured 4.4 m above the lake surface at mooring BM (Fig. 1), during 12 days at the end of October 1993. Since the wind data measured at BM and T6 (Fig. 1) are highly correlated, we consider the record at BM to be representative of the lake as a whole, and calculations of the wind stress exerted on the lake surface are based on this record. At station BM, the average wind speed during the sampling period (Oct. 25 – 29) was $\langle w_{4.4\text{m}} \rangle = 2.95 \pm 0.06 \text{ m s}^{-1}$, while along the axis of the lake it diminished to $\langle w_{4.4\text{m}}(330^\circ) \rangle = 1.30 \pm 0.03 \text{ m s}^{-1}$ ($\langle \rangle$ indicates an average taken over the sampling period). The downward kinetic energy flux E_{10} from the atmosphere 10 m above the lake surface due to a wind speed $w_{10} [\text{m s}^{-1}]$ is given by:

$$E_{10} = \rho_{\text{air}} C_{10} w_{10}^3, \quad [\text{W m}^{-2}] \quad (3)$$

where $\rho_{\text{air}} [\text{kg m}^{-3}]$ denotes the density of air and $C_{10} \approx 10^{-3}$ (Amorocho and de Vries, 1980) the wind drag coefficient. During the experiment, energy input (Fig. 3b) occurred predominantly on two occasions (October 22 and 26/27) from NE winds. Since such winds blow almost perpendicular to the axis of the lake, their efficiency

Figure 3. **a** Wind speed 4.4 m above water level at station BM (Fig. 1). The strong winds on October 22 and October 26–27 were from the NE. Microstructure measurements were conducted during the periods shaded. **b** Downward kinetic wind energy flux E_{10} 10 m above the lake surface (eq. 3). **c** Longitudinal (black) and transverse (grey) current velocities at 80 m depth at station MM with 4.6 d seiche period. Positive transverse currents flow towards the NE (60°). **d** Time series of 5°C (lowest line), 5.5°C , 7°C and 10°C (uppermost line) isotherms measured at station BM (Fig. 1)

in exciting internal seiches is likely to have been less than that of the much weaker NW winds on October 24, which blew along the axis of the lake (330°).

The wind-induced currents in 80 m depth, registered at mooring MM (with a lower detection limit of 1 cm s^{-1}), are plotted in Figure 3c. This record reveals the presence of a longitudinal deep-water current with a periodicity of about 4.6 d, in good agreement with the periodicity of the first vertical first horizontal seiche mode (see Section 2a). Two details are worth mentioning here: 1) Such currents lead to typical longitudinal pathways at the sill on the order of $\approx 5 \text{ km}$. The water masses, experiencing potentially intense mixing at the sill, are pushed back and forth over the sill for several cycles before they eventually intrude into one of the two basins. 2) Abrupt changes in the current, such as that observed during the second part of October 23, might be linked to non-linear internal surges, as reported by Heinz (1995).

The isotherm dynamics (Fig. 3d), monitored by the thermistor string at position BM (Fig. 1), supports the interpretation that the observed currents are due to a seiche of the first vertical first horizontal mode. The first mode structure in the vertical is revealed by the in-phase displacements of up to 12 m of the 5°C , 5.5°C , 7°C and 10°C isotherms shown in Figure 3d. However, as winds occur irregularly on the time scale of the seiche periods, seiching is forced (Schimmele, 1993). The lowest isotherm record (5°C), which is closest to the saddle of the sill, contains high-frequency variations, indicating sources of eddies either due to lateral oscillations or to an interaction with the bottom topography (Heinz, 1995; Hollan and Simons, 1978).

Two examples of microstructure profiles

With a view to quantifying mixing at the Mainau sill, we measured 96 microstructure profiles (Mathis, 1996) scattered over the cross-section of the narrows (Fig. 1b) from October 25 to October 29, 1993 (shaded periods in Fig. 3). Most of the data originate from the hypolimnion, especially from the bottom boundary layer, which was expected to be the most turbulent zone. In Figure 4, two examples of microstructure profiles show the characteristics of the stratification and the small-scale variability. The “active” profile was measured on October 26, 1993 during windy conditions ($w_{4.4\text{m}} = 7.7 \text{ m s}^{-1}$), while the “inactive” one was taken during quiet conditions on October 29 ($w_{4.4\text{m}} = 0.8 \text{ m s}^{-1}$). The four panels of Figure 4, showing the profiles of temperature, temperature gradient, dissipation of TKE and dissipation of temperature variance, will be discussed in the following.

The temperature profiles (Fig. 4a) are characteristic for fall, revealing a $\approx 20 \text{ m}$ thick, convectively-mixed surface layer, and a sharp transition between the epilimnion and the thermocline. The lower thermocline, reaching a minimum temperature of 4.6°C , was weakly stratified.

Profiles of the vertical microstructure temperature gradient (Fig. 4b), show strong fluctuations (exceeding 10 K m^{-1}) with a patchy structure due to the intermittent nature of the turbulence. Double-sided fluctuations in the temperature gradient, indicating active turbulence, are weaker on October 29 (low wind) than on October 26 (high wind), especially below 45 m depth. In the upper thermocline, where turbulence is an indirect effect of the wind via seiching, strong temperature fluctuations persist.

Figure 4. Two examples of microstructure profiles at the Mainau sill, measured during windy conditions (October 26, $w_{4.4m} = 7.7 \text{ m s}^{-1}$; dark) and calm conditions (October 29, $w_{4.4m} = 0.8 \text{ m s}^{-1}$; grey): Temperature **a**, temperature gradient (both profiles offset by 5°C m^{-1}) **b**, dissipation ϵ of TKE **c** and dissipation χ of temperature variance **d**. Double-sided temperature gradients indicate active turbulence. In zones of strong turbulence, ϵ and χ are correlated

The two profiles of the dissipation ϵ (Fig. 4c), determined in vertical bins of 1 m, support this observation quantitatively. During windy conditions, ϵ is high throughout the entire water column (dark shading) and sporadically reaches values of up to $\epsilon = 10^{-6} \text{ W kg}^{-1}$. The October 29 profile (light shading) differs distinctly from this, with high dissipation only within the surface layer (the top 13 m) and within two patches of the upper thermocline, whereas the restratifying mixed layer (Brainerd and Gregg, 1995) and the rest of the thermocline are quiet. Neither of the two profiles shows a distinct increase in dissipation towards the bottom.

The profiles of the dissipation of temperature variance χ (Fig. 4d) show the same structure as those of ϵ : high values of χ throughout the profile on October 26 and the same three major turbulent zones on October 29. The fact that χ is generally decreasing with depth is not only due to the limited invasion of turbulence, but also due to decreasing background temperature gradients (eq. 1) at greater depth.

Due to the characteristic variability of turbulence, both ϵ and χ are distributed over several orders of magnitude with probability distributions similar to lognormal distributions, when forcing conditions are steady and homogeneous (Baker and

Gibson, 1987; Davis, 1996). Therefore, a large number of estimates is necessary in order to achieve robust ensemble averages. If dissipation follows a lognormal distribution exactly, the maximum likelihood estimate $\langle \epsilon \rangle_{\text{ML}}$ provides the correct average (Baker and Gibson, 1987), where $\langle \epsilon \rangle_{\text{ML}} = \epsilon_0 \exp(\langle \ln(\epsilon/\epsilon_0) \rangle + \sigma^2/2)$ [W kg^{-1}], with the intermittency factor σ^2 (a measure of the degree of intermittency) being given by $\sigma^2 = \langle (\ln(\epsilon/\epsilon_0) - \langle \ln(\epsilon/\epsilon_0) \rangle)^2 \rangle$ [–], and with the scaling factor $\epsilon_0 = 1 \text{ W kg}^{-1}$. Especially for small ensembles, this type of average is often more robust than the arithmetic mean.

Compared to oceanic intermittency factors σ^2 , which typically range between 1 and 7 (Baker and Gibson, 1987; Shay and Gregg, 1986; Gregg and Sanford, 1988), in Lake Constance the intermittency in the epilimnion ($\sigma^2 = 4.2$) and in the thermocline ($\sigma^2 = 7.7$) was large. This finding underlines the huge spatial and temporal variability of mixing over the sill.

Energy balance and vertical mixing

To infer the role of the Mainau sill for mixing in Lake Constance we compare the measured dissipation at the sill with the dissipation in the entire lake. In a first step we relate the dissipation of the stratified water column at the sill to the energy input from the wind, to identify the main sinks of energy. In a second step, we compare dissipation at the sill with the basin-wide dissipation inferred from the decay of internal seiches.

TKE fluxes and sinks at the Mainau sill

Based on the dissipation profiles discussed in Section 3, we determined the sink of TKE in the water column at the sill by calculating the energy dissipation per unit area for the three compartments epilimnion, thermocline and bottom layer, by integrating vertically as follows:

$$P_{\text{Comp}}([a,b]) = \int_a^b \rho(z) \langle \epsilon \rangle_{\text{ML}}(z) dz \approx \rho \int_a^b \langle \epsilon \rangle_{\text{ML}}(z) dz, \quad [\text{W m}^{-2}] \quad (4)$$

where a, b are the lower and upper bounds of the three compartments and $\langle \epsilon \rangle_{\text{ML}}(z)$ stands for the daily maximum likelihood estimates over the 1 m bins. While the scatter of the individual dissipation values ϵ is dominated by intermittency, the uncertainties in P_{Comp} are due rather to systematic errors (calibration, model assumptions, etc.) of a factor of ≈ 2 (Kocsis et al., 1998).

The integrated dissipation estimates P_{Comp} are plotted together with the wind energy flux E_{10} in Figure 5. From the daily mean P_{Comp} we determine the averages for the entire sampling period October 25 to 29 (again indicated by $\langle \rangle$). The averaged vertical wind energy flux was $\langle E_{10} \rangle = 0.22 (\pm 0.13) \text{ W m}^{-2}$. The large standard deviation (in parentheses) is the result of the high degree of variability prevailing during the sampling period and is not due to measurement errors ($< 5\%$). Dissipation in the epilimnion $\langle P_{\text{epi}} \rangle = 2.6 \cdot 10^{-3} (\pm 1.3 \cdot 10^{-3}) \text{ W m}^{-2}$, induced directly by the wind, is strongly correlated to wind and subsequently has a similar variability.

Figure 6. Comparison of the dissipation of TKE in the bottom layer P_{bot}^{ϵ} (0.1 to 20 m above bottom, eq. 4) based on microstructure data, and P_{bot}^u (0 to 20 m above bottom) calculated from current measurements (according to the law of the wall, eq. 5). About half the bottom dissipation is caused by smooth-flow bottom friction

technique (Fig. 6) shows that only about 10% of the turbulent dissipation in the bottom boundary layer was caused by smooth-flow bottom friction ($\langle P_{bot}^u / P_{bot}^{\epsilon} \rangle = 15 (\pm 10)\%$), while – other processes contribute to the production of TKE, for instance instabilities due to non-linearities in internal seiches, the breaking of internal waves (Gargett and Holloway, 1984) and the generation of eddies at topographic features. These additional sources might hide the typical $1/z$ dependence of dissipation as expected for a classical boundary layer. The comparison of P_{bot}^u with P_{bot}^{ϵ} indicates that dissipation within the 10 cm above the lake bottom which were not measured by the microstructure profiler contributes less than 5% to P_{bot}^{ϵ} (assuming a viscous sublayer 1 cm thick).

We conclude that even if dissipation within the bottom boundary layer was larger than expected by smooth-flow bottom friction alone, the bottom boundary layer at the Mainau sill was not the major sink of the local TKE. The comparison of the dissipation in the three compartments shows that the major part of the energy input of the wind into the water column was transferred to the seiching motion.

Relevance of the Mainau sill for dissipation in Lake Constance

To assess the relevance of the Mainau sill as a sink of energy for the whole lake, we relate the dissipation at the sill to the average rate of decay of energy contained in the seiching motions. Here we do not consider the epilimnion, which is directly forced by the wind and which is not significantly influenced by the underwater sill. Consequently we use $\langle \epsilon_{sill} \rangle = \langle P_{tc} \rangle + \langle P_{bot}^{\epsilon} \rangle = 9.5 \cdot 10^{-3} W m^{-2}$ as an estimate for the dissipation caused by seiching in the hypolimnion at the sill. The average rate of

decay of the seiche energy $\langle \epsilon_{IS} \rangle$ is assessed from the internal energy of the seiches, estimated as $2 \cdot \langle E_{Pot} \rangle$, i.e. twice the average potential energy of the seiche, and from the decay time scale of the internal seiches, $\tau_{IS} = 3.1 \pm 0.8$ d, as given by Schimmele (1993). The expected basin-wide dissipation due to internal seiching is then given by $\langle \epsilon_{IS} \rangle = 2 \langle E_{Pot} \rangle / \tau_{IS}$. The potential energy $\langle E_{Pot} \rangle$ is calculated from the local potential energy $E_{Pot}(BM)$ by using the temperature profiles measured at mooring BM:

$$E_{Pot}(BM, t) = g \int_{\text{bottom}}^{\text{surface}} dz [\rho(z, t) - \bar{\rho}(z, t)] \delta z(z, t), \quad [J \text{ m}^{-2}] \quad (6)$$

where $\delta z(z, t) = \frac{T(z, t) - \bar{T}(z, t)}{\partial T / \partial z}$ is the vertical displacement of the water parcel from its equilibrium position and $\bar{T}(z, t)$ and $\bar{\rho}(z, t)$ are the water temperature and density (calculated from temperature), respectively, averaged over 6 d. The average potential energy at BM was $\langle E_{Pot}(BM) \rangle = 142 \pm 8 \text{ J m}^{-2}$. From this local value at BM, the basin-wide potential energy $\langle E_{Pot} \rangle$ was extrapolated by integrating over the volume V of the lake with the amplitude of the internal seiche $\delta z_{\max}(x)$ and the cross section $A(x)$ along the thalweg x (Zenger et al., 1990):

$$\langle E_{Pot} \rangle = \langle E_{Pot}(BM) \rangle \frac{1}{V} \int_{\text{thalweg}} dx \left(\frac{\delta z_{\max}(x)}{\delta z_{\max}(BM)} \right)^2 A(x) = 37 \text{ J m}^{-2} \quad (7)$$

This value for the basin-wide potential energy $\langle E_{Pot} \rangle$, combined with the decay time scale of the internal seiches τ_{IS} , implies a rate of decay of seiche energy $\langle \epsilon_{IS} \rangle = 2 \langle E_{Pot} \rangle / \tau_{IS} = 0.28 \cdot 10^{-3} \text{ W m}^{-2}$ which is 34 times less than the dissipation $\langle \epsilon_{sill} \rangle$ over the sill. To infer the overall role of the Mainau sill, we compare the dissipation over its area ($A_{sill} \approx 6 \text{ km}^2$) to the internal seiche dissipation over the entire area of Lake Constance ($A_{Lake} = 472 \text{ km}^2$):

$$\frac{\langle \epsilon_{sill} \rangle \cdot A_{sill}}{\langle \epsilon_{IS} \rangle \cdot A_{Lake}} \approx 0.43 \quad [-] \quad (8)$$

This ratio has an uncertainty factor of ≈ 3 due to the dissipation rate at the sill (factor ≈ 2), the estimate of the potential energy $\langle E_{Pot} \rangle$ (factor ≈ 1.5) and the surface area of the sill A_{sill} (factor ≈ 1.5). In order to reduce this uncertainty, the average dissipation rate $\langle \epsilon_{IS} \rangle$ and the extent of the sill, especially with respect to jets (Hollan and Simons, 1978; Heinz, 1995) and hydraulic jumps, should be determined experimentally.

Vertical diffusivity

Using the temperature profiles, the stability N^2 was calculated. Combined with the dissipation profiles, the vertical diffusivity K_z was estimated by applying eq. (2) and using a mixing efficiency of $\gamma_{\text{mix}} = 0.12$. The daily averages of vertical diffusivity in the thermocline, calculated over the 20 m to 60 m depth range, were $K_z = 1.4, 49$,

2.8, 5.2 and $4.9 \text{ cm}^2 \text{ s}^{-1}$ for each of the 5 days from October 25 to October 29. Average thermocline K_z over the measurement period was $\langle K_z \rangle = 13 \text{ cm}^2 \text{ s}^{-1}$.

Considering turbulence within the bottom boundary layer, we can expect a comparable contribution to vertical diffusivity. Taking into account the residual stratification within the well-mixed bottom boundary layer, typically a chemical stratification with $N^2 = 7 \cdot 10^{-7} \text{ s}^{-2}$ (Maiss, pers. comm.), and using the reduced effectiveness of well-mixed layers ($\gamma_{\text{mix}} \approx 0.01$; Wüest and Gloor, 1998), a value of $\langle K_z \rangle = 7.5 \text{ cm}^2 \text{ s}^{-1}$ would result.

Using SF_6 as a tracer in Lake Überlingen in fall 1990, Maiss et al. (1994) found vertical diffusivities in the same depth range (20 to 60 m) of $K_z = 0.38 \text{ cm}^2 \text{ s}^{-1}$ at station BM (Fig. 1) and $K_z = 0.55 \text{ cm}^2 \text{ s}^{-1}$ 2.5 km NW of the position of the micro-structure profiles. Even though the increase towards the sill (by a factor of 1.4) is not very significant, these estimates are consistent with the conclusion that both dissipation and vertical diffusivity at the sill are enhanced coherently by one order of magnitude relative to open-water estimates.

Long-term mixing

To scale our observations to basin-wide diapycnal mixing representative of the entire stratification period in Lake Constance, we compared wind and current measured at the sill to their respective averages over the entire stratification period. During the sampling period, the average wind speed $\langle w_{4.4\text{m}} \rangle = 2.95 \text{ m s}^{-1}$ was only slightly higher than the annual average ($\langle w_{4.4\text{m}} \rangle_{\text{annual}} \approx 2.5 \text{ m s}^{-1}$) and blew most of the time from the NE. Only 1/3 of the annual winds ($> 3 \text{ m s}^{-1}$) blow from $60^\circ \pm 20^\circ$ (NE) and 2/3 from WSW ($260^\circ \pm 40^\circ$), perpendicular to the axis of the lake (330° ; Schimmele, 1993). Although observed winds during the sampling period were mainly transverse, and therefore inefficient for exciting internal seiches (E. Bäuerle, pers. comm.), seiche amplitudes (Fig. 3) were of typical size ($\approx 10 \text{ m}$; Schimmele, 1993). In addition, the observed bottom currents at the sill ($\langle |u_{20}| \rangle = 3.6 \text{ cm s}^{-1}$) were slightly stronger than the mean value during the entire stratification period ($\langle |u_{20}| \rangle = 2.6 \text{ cm s}^{-1}$ (11.4–24.10.1993) and the annual average over 5 a ($\langle |u_{20}| \rangle = 2.3 \text{ cm s}^{-1}$ (J. Ilmberger, pers. comm.).

Summarizing this comparison, we can conclude that the sampling period of October 25–29, 1993, can be considered typical for the entire stratification period in terms of wind input and internal seiche excitation. Wind, internal seiche amplitudes and currents at the sill were only slightly, but coherently, enhanced during the five days of observation. Since the effect of the sill increases with the degree of internal seiche excitation, we can conclude that the contribution of the sill to the basin-wide vertical mixing rate, expressed by eq. (8), while representative for the entire stratification period, is rather an upper limit. However the role of non-linear internal surges has not been specifically considered.

Concluding summary

The effect of the Mainau sill on the diapycnal component of vertical mixing in Lake Constance was investigated during the stratification period. Based on 96 tempera-

ture microstructure profiles measured during five days in October 1993, vertical profiles of TKE dissipation were calculated by applying the Batchelor method. Long-term observations of wind, internal seiche displacements (determined from thermistor strings) and bottom currents at the sill allowed TKE budgets to be calculated for the entire hypolimnion and for the stratified part at the sill.

Of the total wind energy flux E_{10} (10 m above the lake surface), 5.5% was dissipated below 2 m depth at the sill. This rudimentary comparison indicates that turbulence at the Mainau sill was not drastically higher than that found in other natural water bodies. Dissipation was highly correlated with E_{10} in the epilimnion ($\approx 0.014 \cdot E_{10}$) and in the bottom boundary layer ($\approx 0.003 \cdot E_{10}$), but dissipation in the thermocline was not directly correlated with the wind input, reflecting rather the background excitation of the internal seiches.

The major energy sink was the thermocline ($8.4 \cdot 10^{-3} \text{ W m}^{-2}$). Dissipation there was 8 times as much as in the bottom boundary layer, which is consistent with the analysis of Zenger (1989) based on the assumptions of Spigel and Imberger (1980). The thermocline is thus a large energy sink, comparable to the ocean thermocline: Gregg and Sanford (1989), for instance, found dissipation between 10 m and 1 km depth in the North Pacific to be $4.8 \cdot 10^{-3} \text{ W m}^{-2}$.

Extrapolation of this energy balance at the Mainau sill to the entire lake reveals that damping of the internal seiche over the sill ($9.5 \cdot 10^{-3} \text{ W m}^{-2}$) was 34 times stronger than the basin-wide average ($0.28 \cdot 10^{-3} \text{ W m}^{-2}$). Diapycnal diffusivity in the thermocline above the sill was enhanced by a similar factor. Since the sill occupies less than 1.5% of the area of the lake, the sill contributed about 43% to both the dissipation of the internal seiche and to the basin-wide vertical diffusivity. The sill therefore plays a disproportionately large role for small-scale diapycnal mixing in the hypolimnion of Lake Constance.

Compared to turbulence at the sill, turbulence within the bottom boundary layer made only a minor contribution to the overall dissipation. Since the mixing effectiveness of already well-mixed water is low, we conclude that bottom boundary mixing at the sill is not responsible for the high diapycnal diffusivity found in Lake Constance. The most plausible new hypothesis – based on this analysis – is that turbulence and mixing in the entire hypolimnion of Lake Überlingen, rather than only at the Mainau sill, is responsible for the intense diapycnal mixing in Lake Constance.

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