Research Plan for the Dissertation of Claudia Lorrai, Environmental Sciences Department, ETH Zürich

Turbulence and Fluxes in the Bottom Boundary Layer of Stratified Natural Waters

Ph.D Committee

Examiner:	Prof. Alfred Wüest (EAWAG)	....
Co-Examiner:	Prof. Bernhard Wehrli (ETH, EAWAG)	....
Co-Examiner:	Dr. Andreas Lorke (University of Constance)	....
External Examiner:	To be decided later	....
Supervisor:	Dr. Daniel F. McGinnis (EAWAG)	....
Ph.D. Student:	Claudia Lorrai	....

Abstract

Vertical exchange driven by turbulent mixing is a key process in lakes. In recent years the ability to measure small scale processes, which is linked to the enormous development of instruments, has led to advances in our understanding of these processes. Estimating, measuring and modelling vertical flux mechanisms are a key subject of this Ph.D. project.

The study site will be mainly Lake Alpnach. A basic lake monitoring program will begin in spring 2007 and last through the stratification season to obtain background data and to know the boundary conditions. The collected data will be used for the investigation of several processes such as bottom convective mixing, turbulent fluxes and other processes related to mixing in natural waters.

The project consists of three different work programs. The first work program aims to explore the applicability of the eddy correlation method. The second program will focus on investigating the role of shear-induced convection above slopes. With the results from these two work programs and the collected data sets a 3-D model will be developed. The goal will be finally to compare observations with the model and quantify the water exchange between the bottom boundary layer and the interior as well as the density balance and the buoyancy flux.

Index

1 Introduction and present state of knowledge

Turbulent fluxes of heat, solutes and particles are important to the ecology of stratified natural waters. A prime question in lakes concerns the flux paths between the stratified interior, through both the bottom boundary layer (BBL) and the sediment surface. The overall aim of this project, which is funded by the Swiss National Science Foundation (Grant: 200020-111763), is to measure directly temperature and oxygen fluxes from the lake interior through the BBL into the sediment and to investigate interactions between the interior and the (partly well-mixed) boundary layers above the tilted sediment.

The characteristic of the turbulent mixing and fluxes are different for (Lerman, Imboden et al. 1995):

- Surface Boundary Layer (SBL)
- Interior of the density-stratified sub-surface water
- Bottom Boundary Layer (BBL)

The main source of mixing in natural waters is wind, which transfers part of its energy into baroclinic motions of different frequencies (Saggio and Imberger 1998). The energy stored in the internal wave field (Thorpe 1996) provides the basis for irreversible mixing, leading to vertical transport of mass, momentum and energy (Imberger 1998).

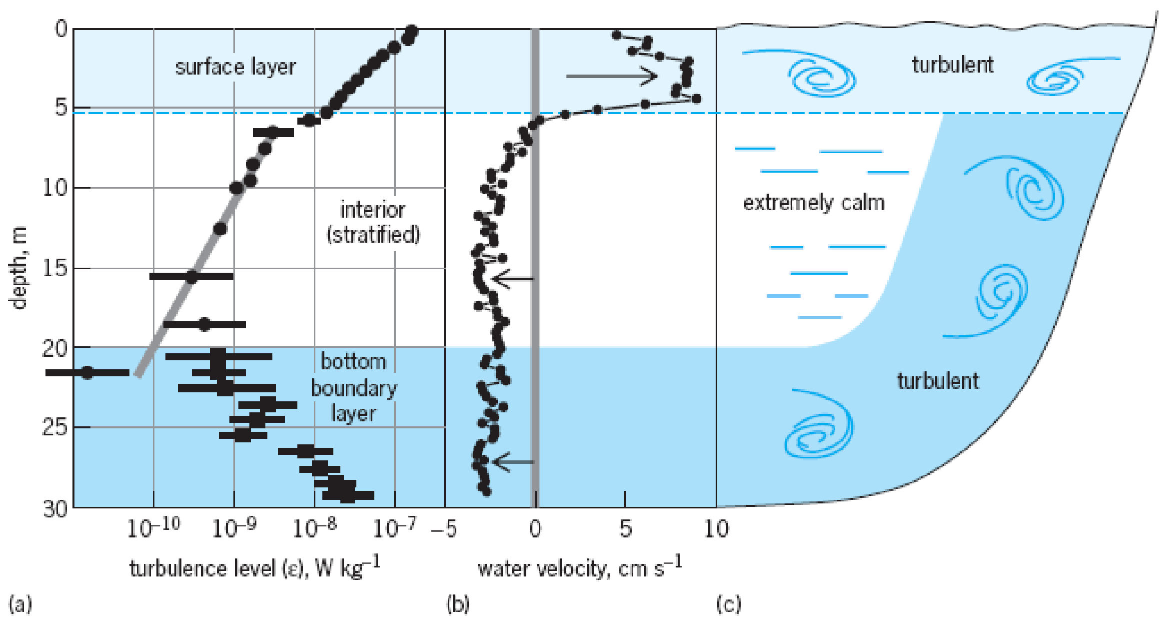


Figure 1: Vertical profiles in lakes. (a) Turbulence profile in Lake Alpnach, Switzerland, demonstrating the high turbulence levels in the surface layer due to wind mixing and in the bottom boundary layer due to bottom (seiche) currents at the sediment-water interface. (b) Typical velocity profile for two-layer seiching. Measurements were obtained in Lake Hallwil, Switzerland, which has similar geometry and wind forcing. (c) Schematic of resulting turbulent zones in a lake enclosing the low-turbulence, quiescent zone in the interior. (McGinnis and Wüest 2005)

Vertical exchange in stratified lakes and reservoirs occurs mainly in two shear zones (Fricker and Nepf 2000):

1. Turbulence generated in the BBL as a result of friction at the sediment and due to breaking of internal waves above sloping boundaries (Thorpe and Jiang 1998).
2. At the interface between the SBL and the pelagic interior as a result of vertical shear origination form the modal structure of the large scale baroclinic motion.

In the ocean (Ledwell, Watson et al. 1998) as well as in lakes or reservoirs (Goudsmit, Peeters et al. 1997), BBL turbulence levels have been found orders of magnitude higher than in the interior.

This research, which will mainly focus on Lake Alpnach, addresses the above mixing mechanisms by

1. Measuring *in situ* turbulent fluxes,
2. using different data analysis methods for inferring turbulence levels and turbulent fluxes,
3. and modelling the mixing processes to quantify the overall balance of the buoyancy in the stratified water body.

The following paragraph summarizes the state of research in this field and the recent contributions of studies at Eawag as it relates to this proposed Ph.D.

1.1 Eddy correlation method

The development of new technologies allows *in situ* investigations of small scale processes in natural waters. With an Acoustic Doppler Velocity (ADV) meter (Nortek) coupled to a Clark-type oxygen sensor (Unisense) turbulent fluxes of oxygen can be determined using the eddy correlation method, as first proposed and implemented by Berg et al. (2003). The technique has been tested under various field conditions; Measurements were conducted in the Wümme River near Bremen (Germany), in Aarhus Bay (Denmark) and in Limfjorden sound (Denmark) by Berg et al. (2003) and resulted in successful determination of vertical turbulent O_2-fluxes toward the sediment.

Eawag applied the method on Lake Alpnach (dynamic system) and Lake Wohlen (steady system, Figure 2). The results were compared to both the calculated theoretical eddy sizes and timescales, as well as dissolved oxygen fluxes obtained using the LISA (Lander for ion selective analysis) oxygen microprofiles through the sediment-water interface.

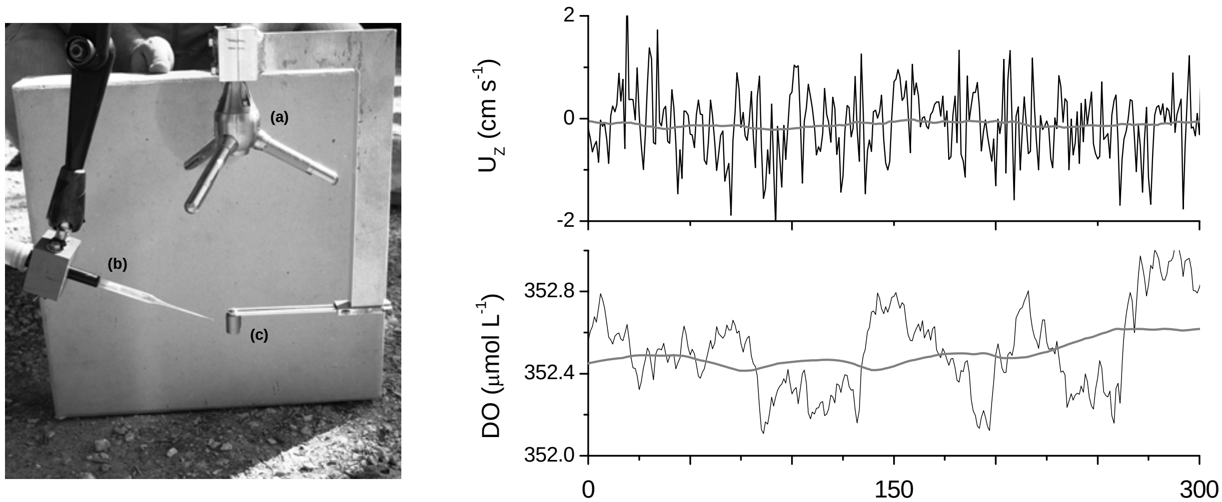


Figure 2: Left panel: Eddy correlation instrument. (a) Three-beam Nortek Vector with (b) Unisense oxygen sensor and (c) artificial measurement volume for positioning the oxygen sensor. Right panel: sample data series collected at Lake Wohlen for vertical velocity (UZ; top) and dissolve oxygen (DO; bottom). Grey, smooth line indicates running average of a sampling time of 240 seconds. (McGinnis et al. in preparation)

The results proved to be encouraging for both cases; however the technique is in the early stages of application to dynamic lake systems. More data need to be collected, as longer time series are required to enhance understanding and reveal the full capability of this new technique.

1.2 Bottom convective mixing

Observations performed in Lake Alpnach during previous experiments revealed the surprising result that the BBL is often unstably stratified even though the background water column shows strong stratification. These instabilities result from forcing of the BBL (such as by seiches) which leads to differential shear-dispersion and so, cooler (and therefore heavier) water is forced on top of lighter, warmer water (Figure 3). When the flow direction changes, with flow towards higher densities, the opposite takes place: warmer (lighter) water is stratified over cooler (heavier) water, thereby suppressing turbulence. The measurements in Lake Alpnach reveal convincing evidence that this is an important BBL mixing process in lakes (Lorke, Peeters et al. 2005).

Slinn and Levine (2003), presented numerical simulations which validate the occurrence of convectively driven mixing in the BBL as a result of tidal oscillating flow over the tilted sea bottom.

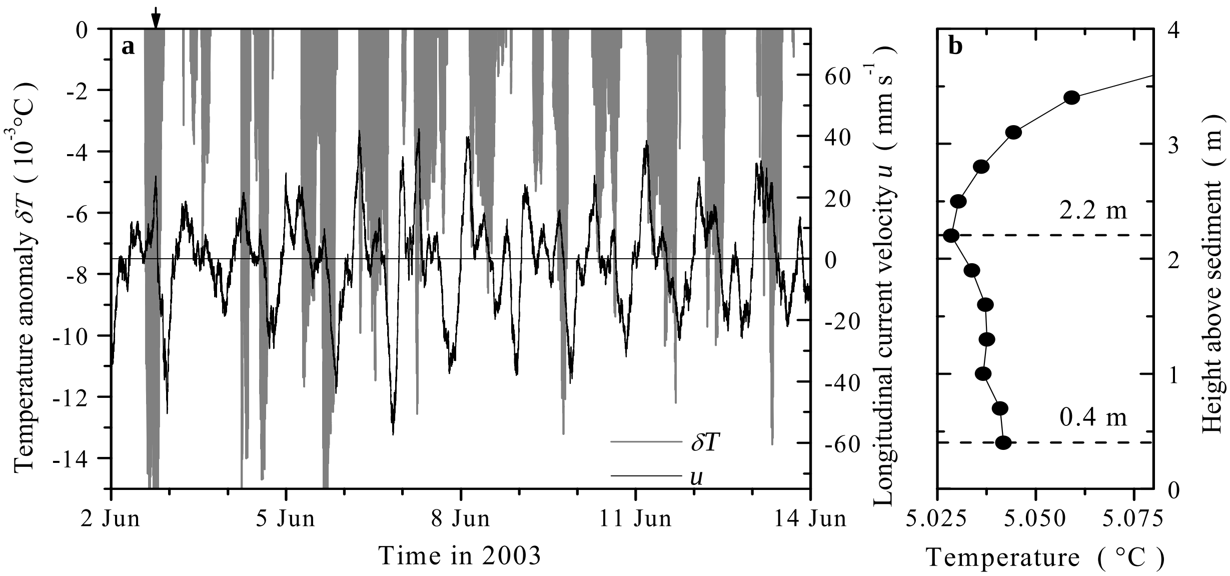


Figure 3: (a) Time series of the along-lake current velocity u_{long} and the temperature anomaly δT, estimated as the difference between the temperatures measured at 2.2 and 0.4 m above the sediment. Note that only negative values of δT, representing unstable stratification, are shown. Positive current velocities were associated with up-slope currents at the mooring site. For clarity of presentation, only a representative part of the entire observations is shown. (b) A temperature profile measured during unstable stratification (the sampling time is indicated by the arrow at the upper axis). The two dashed lines encompass the depth range used for calculating δT (Lorke, Peeters et al. 2005).

The study by Lorke et al. (2005) produced two significant conclusions:

1. It was not possible to make a clear distinction between shear-induced and buoyancy-driven turbulence in the BBL on slopes. Since the maximum dissipation rate increased by only a factor of two during convective mixing, it can be concluded that bottom shear production and buoyancy-driven (convective) production contributed by similar amounts to the turbulent kinetic energy (TKE), and hence their presence or absence could not be reliably detected.
2. Equal contribution of shear-induced and buoyancy-driven turbulence emphasizes the importance of shear-induced convection on sloping boundaries. Attempts to make a budget of the TKE production and the coupled mixing processes in lakes (Imberger 1998a) and in the ocean (Garrett 2003) revealed the importance of BBL turbulence for basin-scale diapycnal mixing, but the only processes they considered are breaking of internal waves and shear production.

Further numerical and observational research should concentrate on the parameterization in terms of stratification and bottom slope current velocities.

1.3 Interaction between the interior and the boundary

The strong stratification in the interior of lakes suppresses turbulence and is therefore characterized by internal wave dynamics. Imberger (1998b) and Wuest, Piepke et al. (2000b) showed that most of momentum and energy which passes through the SBL and enters the interior is transferred into basin-scale internal wave motion. The weak turbulence in the interior of lakes has been confirmed using microstructure and tracer methods by Wüest, Senden et al. (1996); Goudsmit, Peeters et al. (1997); MacIntyre, Flynn et al. (1999) and Etemad-Shahidi and Imberger (2001).

By contrast, the BBL of lakes is usually actively turbulent and is almost as dynamic as the surface layer. The key processes are exchange of momentum, heat and solutes with the sediment, the turbulent dissipation of energy from currents and waves and strong vertical mixing. In contrast to the SBL the current velocity vanishes at the sediment – water interface according to the Law of the Wall (LOW).

$$\frac{\partial u}{\partial h} = u_* \frac{1}{kh} \qquad [s^{-1}]$$

with $\frac{\partial u}{\partial h}$ = functional dependence of the horizontal velocity u on height h above bottom (positive upward), $u_* = \sqrt{\frac{\tau_{BBL}}{\rho}}$ denotes the friction velocity and k = 0.41 represents the von Kàrmàn constant. The integration of this equation gives the logarithmic profile for the horizontal velocity in the BBL.

In the deep part of the lake energy is mainly transferred by low-frequency seiching, whereas in the metalimnion other sources (such as breaking of high-frequency waves) are needed to explain the observed typical basin-wide mixing.

Further research should investigate the communication of buoyancy between the interior and the boundary by using the vast amount of observational and analytical studies and try to resolve the phenomena by 3-D model computations.

1.4 Turbulence models

A 1-D water column model and a 3-D transport model, *General Ocean Turbulence Model* (GOTM) and *General Estuarine Transport Model* (GETM), respectively, will be used in this study for modelling turbulence in Lake Alpnach. Both models are written in FORTRAN90/95 code. An interface is implemented between GOTM and GETM.

Key features and assumptions of the models are listed below:

GOTM

- Solutions for the 1-D versions of the transport equations of momentum, salt and heat.
- Well-tested turbulence models that have been implemented in the code are related to scientific publications
- One member of every relevant model family
- Modular concept
- Different types and levels of closure models to compute the vertical turbulent fluxes
- Platform for all researchers interested in the application and development of turbulence models.
- Website: http://www.gotm.net/

GETM

- 3-D transport model
- Uses hydrostatic pressure assumption
- GETM reproduce non-linear waves; can resolve hydraulic jumps
- Missing non-hydrostatic effects as dispersion of steep internal waves
- Coordinate system follows the topography.
- Website: http://www.bolding-burchard.com/html/GETM.htm

2 Study sites

We have selected two study sites for our work, Lake Alpnach and Lake Wohlen. Lake Alpnach is excellent for modelling and investigating turbulent fluxes coupled with lake dynamics because of its simple shape, its shallowness of about 34 m and it is exposed to regular wind forcing. It is a well studied lake, with several publications emphasizing the structure and dynamics of internal seiching (Münnich, Wüest et al. 1992; Wuest, Piepke et al. 2000b), the seiche-induced BBL (Gloor, Wüest et al. 1994; Lorke, Umlauf et al. 2002) and the control of sediment water exchange by BBL turbulence (Lorke, Müller et al. 2003).

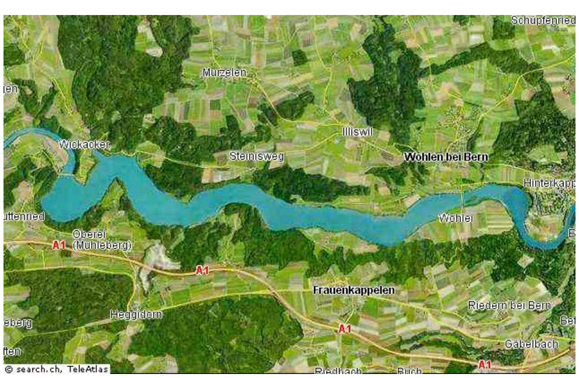
To test the applicability of the EC method, we discovered that Alpnach hydrodynamically complex and not ideal for testing the application of the eddy correlation device, so we went to Lake Wohlen which provides more steady conditions.

2.1 Lake Alpnach

Lake Alpnach is 1.5 km wide and 5 km long and is connected to Lake Lucerne by a 3 m deep shelf. The interior dynamics are characterized by wind driven seiching of the first and second vertical mode (Münnich, Wüest et al. 1992) with a period of about 24 hours and a maximum velocity of 3 cm/s (Lorke, Müller et al. 2003).

2.2 Lake Wohlen

Lake Wohlen is a eutrophic run-of-the-river reservoir with a high sediment oxygen demand, just downstream of the City of Bern (Switzerland). With construction of the dam completed in 1920, Lake Wohlen has a surface area of 3.65 km² and a maximum depth of 20 m. This lake has a riverine character with a steady flow and hence not affected by internal waves.



3 Measurement techniques

During the measurement campaign starting in early spring 2007 the following experimental observations will be implemented. These measurements are performed to better understand the eddy correlation technique, to get the boundary conditions for the model, to investigate the processes as bottom convective mixing and resolve the interchange of the boundary and the interior of the lake. The data will be analysed with spectral and time series analysis for the turbulent energetics and the turbulent fluxes. The overall dataset and knowledge derived from the data will give the basics for the turbulence model of Lake Alpnach.

3.1 Eddy correlation device

3.1.1 Acoustic Doppler Velocity meter (ADV)

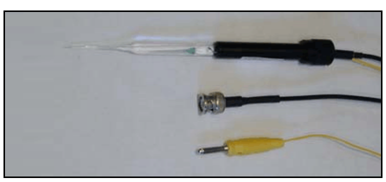
The ADV from Nortek measures velocity in three dimensions (u, v, z) in a small cylindrical volume. This instrument can record velocities with a maximum frequency of 64 Hz. It allows measurements under true in situ conditions without disturbance of the sediment. The advantages of the ADV are excellent precision, no calibration requirements, and the enormous measurement range (as low as 1 mm/s).

We have performed several modifications to the standard ADV. These modifications are listed below and are necessary to get the data we need.

- External 1GB Memory and extra battery → longer time series up to one week
- Oxygen sensor attached at the ADV → application of the EC method to derive turbulent oxygen fluxes
- Fast temperature sensor (FP07) attached at the ADV → turbulent heat fluxes.

3.1.2 Oxygen sensor

Attached at the ADV will be a Clark-type O_2 microelectrode (fast Ox-10 from Unisense) with a response time of < 0.3 s as reported by the manufacturer.



3.1.3 Temperature sensor

PME will provide us with a FP07 fast temperature sensor with a response time of approximately 7 ms to add to the ADV. The fast temperature sensor is capable of measuring rapid temperature fluctuations with the frequency of 96 Hz, but coupled to the ADV it is only possible to measure with a maximum frequency of 64 Hz.

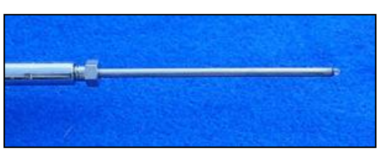


Figure 4: *left: RBR thermistor (white) configuration mounted on ADV tripod. right: ADV with electronics housing,* O_2 *sensor and arm. Sensor tip positioning with artificial sampling volume.*

3.2 Acoustic Doppler Current Profilers (ADCP)

The table shows the ADCPs that will be used for measurements in Lake Alpnach:

	RDI **Workhorse ADCP Sentinel**	**RDI** **Workhorse ADCP Sentinel**	**NORTEK** **Aquadopp Profiler**
Resolution	1.2 MHz	600 kHz	2 MHz
Beams	4-beam	4-beam	3-beam
Profiling Range	Up to 12 m	Up to 50 m	5-12 m
Profiling Range: Hig resoution mode	0.6 - 4 m	0.9 - 8 m	4 - 10 m

3.3 Thermistors

High-resolution thermistor string with TR1050 temperature loggers (RBR Ltd.). Response time < 3 s with a resolution of $\pm 2 \times 10^{-3}$ °C and 5×10^{-5} °C.

3.4 CTD

We use a SBE 9plus, Sea-Bird Electronics, Inc., Washington, USA. Samples at 24 Hz. DO sensor is the SBE 43 and was factory-calibrated July 2005. Range and accuracy of DO sensor is 0 to 120 and 2 % of saturation, respectively.

4 Methods

4.1 Eddy correlation method

The eddy correlation method for oxygen in natural waters, allows to identify turbulent fluxes at the sediment-water interface. The idea is to measure the concentration of dissolved oxygen simultaneously with vertical velocity near the sediment. An ADV coupled with an oxygen microsensor is suitable for this purpose.

The recorded data, namely concentration of oxygen (C) and the vertical velocity (u_z), will be split up with Reynolds decomposition into the average and the correspondent fluctuation.

$$u_z = \overline{u_z} + u_z'$$

$$C = \overline{C} + C'$$

The perturbations u_z' and C' are defined such that their time average equals zero. The equation to describe the vertical oxygen flux driven by advection is

$$Flux = u_z C$$

where u_z = vertical velocity, C = oxygen concentration and u_z' and C' become equal to zero, if they are averaged over a time period longer than the turbulent fluctuations. The vertical velocity $\overline{u_z}$ should be zero so we can calculate the turbulent flux with the following equation:

$$\overline{Flux} = \overline{u_z' C'}$$

4.2 Microstructure method

This method is used for deriving the mixing intensity in natural stratified waters. The basic idea is that in natural waters the temperature is never homogeneous because of the heat exchange. That means that there is always some temperature gradient between two adjacent water parcels. Mixing of water with different temperature causes temperature fluctuations of the magnitude.

$$T' \approx L' \times \frac{\partial T}{\partial z}$$

L' = vertical displacement of the water parcel from its rest position. The spectral analysis of these turbulent fluctuations T' can give information about the mixing intensity. Two methods can be applied:

- Cox number method
- Dissipation method.

4.3 Inertial dissipation method

Determination of turbulent kinetic energy (TKE) dissipation from pulse-coherent ADCP measurements using the inertial dissipation method has been developed and applied on Lake Alpnach (Lorke and Wüest 2005). While this inertial dissipation technique is widely accepted and applied in oceanographic and atmospheric research its application to ADCP data is limited by the loss of directional information for high-wavenumber current fluctuations. Measurements in the BBL of a lake, however, revealed astonishing agreement between dissipation rates estimated from temperature microstructure profiles and those estimated from two different brands of ADCPs.

This method is based on the existence of an inertial subrange in the wavenumber spectrum of velocity fluctuations $E(k)$.

$$E(k) = \alpha \varepsilon^{2/3} k^{-5/3} \qquad [m^3 s^{-2}]$$

Experimental evidence yields α = 1.56 for the non-dimensional constant (Wyngaard and Coté 1971).

The spectra shows the $k^{-5/3}$ slope (k is the wavenumber). Scalar properties like temperature and oxygen follow this characteristic slope. The dissipation of TKE ε will be estimated by spectral fitting.

5 Objectives

This project aims to achieve the following objectives:

1. Get more insight when and where to apply the eddy correlation method.

2. Investigate the driving force for turbulent O_2 transport through the BBL and the sediment

3. Investigate spatial and temporal structure of the turbulence level (dissipation) of the BBL processes such as bottom convective mixing and shear-induced convection above slopes

4. Investigate interaction and communication of buoyancy between interior and BBL water masses (where buoyancy flux is predominant).

In order to achieve these goals the following tasks are planned:

- Applying the fluxes eddy correlation method with the ADV coupled to an oxygen sensor and a fast temperature sensor. To measure simultaneously oxygen, temperature and velocity fluctuations in the same water volume.

- Quantify turbulent heat and oxygen fluxes with the eddy-correlation method

- Understand the mechanisms which trigger bottom convective mixing. Quantify shear-induced convective turbulence (thermal instabilities) in the BBL above slopes by measuring turbulent fluxes during the convection-restratification cycling.

- Characterize the communication respectively turbulent fluxes from the stratified interior through the BBL and into the uppermost sediment. Understand how BBL water is exchanged and how density differences, occurring as a result of the homogenized BBL is equilibrated in concern of time scale and dynamics by modelling the processes.

6 Work programs

To achieve the objectives the tasks will be organized within three work programs. The first will be methodical and starts with a measurement campaign. The recorded data will also be used for the work programs 2 and 3. For work program 2 and 3 additional specific measurements will be performed. We can use the records for all of the three processes because they are interrelated in respect of data that is needed for the analysis.

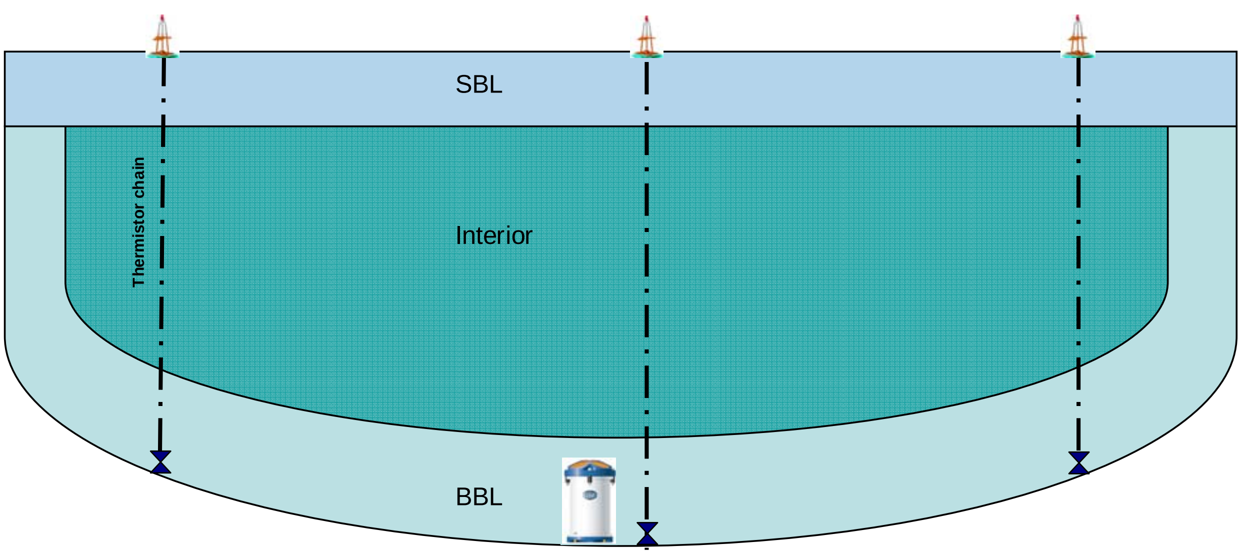
6.1 Work program 1: Method Study – Eddy correlation

6.1.1 Basic monitoring campaign

A basic monitoring program will begin in spring 2007 and last through the stratification season to obtain background data and to know the boundary conditions.

The following equipment is used:

- 2 or 3 temperature moorings (at two or three points in the lake)
- weather station near the lake
- ADCP (600 kHZ, fixed at the bottom looking upwards in the center of the lake)
- CTD transects every couple of weeks



6.1.2 Application of the eddy correlation method

As previously described, EC measurements with the oxygen sensor attached at the ADV were performed in 2005 and 2006, with promising preliminary results obtained in both Lake Alpnach and Lake Wohlen (McGinnis et al. in preparation). While the preliminary data is good, the time series are short, and should be increased in future studies to gain better insight into the applicability of the method.

To investigate the relevant driving forces for turbulent O_2 transport and to understand when the technique can be successfully applied, the following steps are required:

- Measure turbulent fluxes of oxygen with the ADV: For oxygen concentration measurements the ADV will be coupled with an oxygen sensor with a fast response time. To estimate oxygen fluxes from the collected data the EC method will be applied.
- The next challenge is to measure heat fluxes near the sampling volume of the ADV. This novel approach reveals turbulent transport of heat in the BBL. Microstructure measurements have been previously performed in Lake Alpnach, but this method (ADV with temperature sensor) measures at one point the change in temperature and velocity so one can correlate the two parameters and calculate turbulent fluxes through the BBL. Temperature is a good choice because it is conservative, good tracer for turbulence and easy to measure.
- If the two separate techniques provide positive output, then the oxygen sensor and the temperature sensor will be simultaneously connected to the ADV to obtain three correlated data sets recorded at the same time and in the same volume.
- Recording time series of one week with the eddy correlation device to understand and resolve the processes in the BBL.

6.2 Work program 2: Process Study – Characterisation of BBL convection above slopes: the role of shear-induced convection

The goal of this task will be to estimate the additional production of turbulence by shear-induced convection in the BBL. This will allow quantifying the build-up of well-mixed BBLs as a result of both Reynolds production and shear-induced convection and their respective role in the BBL formation in enclosed basins.

The following steps are required:

- Up- and downward looking profilers will measure the detailed vertical velocity structure and variance over time scales of days for different seasonal periods. High frequency ADV records will provide currents and turbulence levels with high temporal and vertical resolution. Closely-spaced (vertically) thermistors will resolve the dynamics of the turbulence within the destratification-stratification cycle (see chapter 6.1.1). This will provide a temporal and vertical scheme of turbulence production and decay.
- Deploying high spatial resolution CTDs over short distances (magnitude approx. 10 m) along the slope to resolve a 2-D map of the BBL structure.
- The equivalent arrangement (ADCPs looking downward and upward) will be used to characterize the convective turbulence simultaneously along the sloping bottom at three levels of stratification.
- O_2 and temperature eddy-flux measurements will allow connecting turbulence levels and turbulent fluxes throughout convection-restratification cycling.
- This data set will allow a unique comparison between measured and modelled turbulence for the combined BBL friction-induced and (shear-induced) convective mixing. This comparison will allow identifying the contributions and the dynamics of the BBL formation at the sloped bottom of natural stratified waters.

Dr. A. Lorke (University of Constance) is working on a similar project on Lake Constance. The hydrodynamics of this system are more complex than our system. This gives the opportunity for exchange of experience, information and even instruments.

6.3 Work program 3: Synthesis Study – Communication between BBL and interior

In work program 3 a numerical model of the lake-internal processes will be established. The goal is to understand how the well-mixed BBL water is exchanged with the interior water body and how the density differences, occurring as a result of the homogenized BBL is equilibrated. To achieve this goal we try to quantify the water exchange value between the BBL and the interior, the buoyancy flux and the density balance over time scales of a month or more by comparison of observations with the 3-D modelling.

6.3.1 Specific measurements in Lake Alpnach

To investigate the turbulent exchange between the relatively quiet interior and the energetic boundary, specific measurements with ADV (oxygen and temperature sensor) in the BBL of the lake and two ADCPs (1.2 MHz looking upward and 2 MHz looking downward) will be done.

We will develop a digitized bathymetry of Lake Alpnach. This dataset is needed for modelling the processes in the lake with the 3-D transport model "GETM".

6.3.2 Modelling Lake Alpnach

The modelling work will be carried out in collaboration with Dr. L. Umlauf (IOW Warnemünde).

With the digitized bathymetry, lake temperature profiles and wind data, we will set up a basic 3-D model. The output of the model will then be used to better plan the specific measurements to capture the relevant processes (as described in chapter 6.3.1). The overall recorded data will then be needed to compute a model which aims to show the communication (water exchange, time scale and dynamics) of the BBL with the interior and related processes like BBL turbulence and internal waves.

Secondary we try some examples with prescribed pressure gradients in GOTM (1-D water column model).

7 Organization

7.1 Involved Eawag staff

Michael Schurter technical support

Dr. Daniel F. McGinnis as supervisor, support in the fieldwork

Maybe: Andreas Brand support in the fieldwork.

7.2 Additional manpower

Dr. Andreas Lorke (University of Constance) has experience on working with ADCPs in Lake Alpnach, and is now working on a similar project at Lake Constance.

- Analysis of the ADCP measurements.
- Exchange of experiences concerning eddy-correlation measurements.

Dr. Lars Umlauf (Baltic Sea Research Institute Warnemünde) will mainly compute the model of Lake Alpnach

8 Time schedule

Date	General activities	Work Program1	Work Program 2	Work Program 3
October 2006	• Literature reading (ongoing) • Lab tests with oxygen sensor • Research plan			
November 2006				
December 2006				
Januray 2007				
February 2007		Open an order for ADV with temperature sensor		Make digitized bathymetry of Lake Alpnach
March 2007	Basic monitoring program Lake Alpnach			Learn to use read GETM data and put bathymetry into the model
April 2007		Test measurements with ADV with oxygen sensor and temperature sensor	Test measurements with ADV and ADCPs	
May 2007				GETM model output from Lars Umlauf
June 2007				Read the GETM output data
July 2007		Specific measurements with ADV with oxygen sensor and temperature sensor	Specific measurements with ADV and ADCPs	
August 2007				
September 2007		Arrange recorded data		
October 2007				
November 2007				
December 2007	Data analysis			Input data for the 3 D model
Januray 2008				
February 2008				
March 2008				
April 2008				
May 2008				
June 2008				
July 2008				
August 2008				
September 2008				

October 2008		
November 2008		Analyse the Model output
December 2008		
Januray 2009		
February 2009		
March 2009		
April 2009		
May 2009		
June 2009		
July 2009	Analysing the results and writing	
August 2009		
September 2009		
October 2009		
November 2009		
December 2009		
Januray 2010		
February 2010		
March 2010		
April 2010		

References

Berg, P., P. Røy, et al. (2003). "Oxygen uptake by aquatic sediments measured with a novel non-invasive eddy-correlation technique." Mar. Ecol. Prog. Ser. **261**: 75-83.

Etemad-Shahidi, A. and J. Imberger (2001). "Anatomy of Turbulence in Thermally Stratified Lakes." Limnology and Oceanography **46**(5): 1158-1170.

Fricker, P. D. and H. M. Nepf (2000). "Bathymetry, stratification, and internal seiche structure." J. Geophys. Res. **105**(C6): 14237-14251.

Garrett, C. (2003). "Internal tides and ocean mixing." Science **301**: 1858–1859.

Gloor, M., A. Wüest, et al. (1994). "Benthic Boundary Mixing and Resuspension Induced by Internal Seiches." Hydrobiologia **284**: 59 - 68.

Goudsmit, G. H., F. Peeters, et al. (1997). "Boundary versus internal diapycnal mixing in stratified natural waters." Journal of Geophysical Research(102): 27'903-27'914.

Imberger, J. (1998a). "Physical Processes in Lakes and Oceans." Coastal Estuarine Stud. 54, Washington, DC: Am. Geophys. Union.

Imberger, J. (1998b). "Flux paths in a stratified lake: a review." See Imberger 1998a: 1–18.

Ledwell, J. R., A. J. Watson, et al. (1998). "Mixing of a tracer in the pycnocline." Journal Of Geophysical Research Oceans. Sep **103**(C10): 21499-21529.

Lerman, A., D. M. Imboden, et al. (1995). Physics and chemistry of lakes, Springer-Verlag.

Lorke, A., B. Müller, et al. (2003). "Breathing sediments: The control of diffusive transport across the sediment-water interface by periodic boundary-layer turbulence." Limnology and Oceanography **48**(6): 2077-2085.

Lorke, A., F. Peeters, et al. (2005). "Shear-induced convective mixing in bottom boundary layers on slopes." Limnology and Oceanography **50**(5): 1612-1619.

Lorke, A., L. Umlauf, et al. (2002). "Dynamics of Turbulence in Low-Speed Oscillationg Bottom-Boundary Layers of Stratified Basins." Environmental Fluid Mechanics **2**: 291–313.

Lorke, A. and A. Wüest (2005). "Application of coherent ADCP for turbulence measurements in the bottom boundary layer." Journal of Atmospheric and Oceanic Technology **22**: 1821-1828.

MacIntyre, S., K. M. Flynn, et al. (1999). "Boundary mixing and nutrient fluxes in Mono Lake, California." Limnology and Oceanography **44**(3): 512-529.

McGinnis, D. F. and A. Wüest (2005). "Lake Hydrodynamics." McGraw-Hill Yearbook of Science & Technology.

Münnich, M., A. Wüest, et al. (1992). "Observations of the second vertical mode of the internal seiche in an alpine lake." Limnology and Oceanography **37**: 1705-1719.

Saggio, A. and J. Imberger (1998). "Internal wave weather in a stratified lake." Limnology and Oceanography **43**(8): 1780-1795.

Slinn, D. N. and M. D. Levine (2003). "Modeling internal tides and mixing over ocean ridges." Thirteenth'Aha Huliko'a Hawaiian Winter Workshop on Near Boundary Processes and their Parameterization. SOEST Special Publication: 59--68.

Thorpe, S. A. (1996). "The cross-slope transport of momentum by internal gravity waves generated by alongslope currents over topography." Journal of Physical Oceanography **26**: 191–204.

Wuest, A., G. Piepke, et al. (2000b). "Turbulent kinetic energy balance as a tool for estimating vertical diffusivity in windforced stratified waters." Limnology and Oceanography(45): 1388–400.

Wüest, A., D. C. v. Senden, et al. (1996). "Comparison of diapycnal diffusivity measured by tracer and microstructure techniques." Dyn Atmosph Oceans(24): 27-39.

Wyngaard, J. C. and O. R. Coté (1971). "The Budgets of Turbulent Kinetic Energy and Temperature Variance in the Atmospheric Surface Layer." Journal of the Atmospheric Sciences **28**(2): 190–201.