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Double diffusion in meromictic lakes of the temperate climate zone

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Abstract

Meromictic lakes are characterized by strong stable density stratification in and below the chemocline, which separates the oxic mixolimnion from the mostly anoxic monimolimnion. Stable density gradients involve slow vertical exchange, especially in the chemocline, where vertical transport can be as low as molecular. Typically, destabilizing temperature gradients establish in the monimolimnion as a consequence of seasonal changing heat fluxes. At the same time, gradients of solutes extending to the lake bottom stabilize the overall stratification. Double diffusive processes may create local instabilities and subsequently cause convective mixing when the destabilization due to heat gradients exceeds the stabilization by solutes (diffusive regime). This configuration can annually occur in the upper part of the monimolimnion, if seasonal temperature changes in the mixolimnion reach the top of the monimolimnion. We present CTD-measurements from two meromictic mining lakes in Germany, which document the seasonal occurrence of convective mixing in discrete horizontal homogeneous layers within the monimolimnion which can be identified by the characteristic step-like structure. In the deeper layers, the steps emerge with a time delay which is determined by the progression of the mixolimnetic temperature changes into the monimolimnion. Interestingly, the chemocline interface is not degraded by these processes. However, double diffusive convection is essential for the redistribution in the inner parts of the monimolimnion at longer time scales, which is crucial for the assessment of the ecologic development of such lakes.

1 Introduction

The phenomenon of double diffusive convection has been discussed in detail in numerous observational, laboratory, and theoretical studies (e.g. Turner, 1973; Kelley, 2003; Schmitt, 1994). Field observations have been described at first in the ocean at mid and low latitudes where the salt finger regime dominates, and to a lesser extend to

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high latitudes where the diffusive regime occurs. Soon, double diffusion and the step-like structure of the associated salt and temperature profiles were also described in lakes (Hoare, 1966; Newman, 1976). The precondition for the occurrence of diffusive layering in stratified lakes are a density stratified water column stabilized by dissolved or suspended matter and, at the same time, a destabilizing temperature gradient, in the respective depth region. Meromictic lakes in temperate climates in general tend to establish these conditions within their deep water body (monimolimnion), at least temporarily. Therefore they are prone to partial convective mixing caused by double diffusion.

Meromixis is a well known phenomenon, also occurring in lakes located in regions with temperate climate (Boehrer and Schultze, 2008). In the monimolimnia of many of these lakes an unstable thermal stratification persists within a chemically stabilized density profile, often supported by geothermal heating from the sediments, with temperatures well above the point of maximum density. Although it was shown in a few – also natural – lakes that the configuration of the heat and salt stratification in the deep water should be sensitive to double diffusive processes, e.g. in Lake Lugano (Wüest et al., 1992) or in the strongly meromictic Brenda Mines pit lake (Stevens and Lawrence, 1998), the explicit appearance of characteristic double-diffusive steps or staircases was not reported for lakes in temperate climates so far.

We report from observations in 2006–2008 in two meromictic mining lakes in the Lusatian lignite mining district in East Germany (Fig. 1), Lake Waldsee (51° 37′ 14.1″ N, 14° 34′ 16.7″ E), and Lake Moritzteich (51° 35′ 20″ N, 14° 34′ 30″ E). After cessation of lignite mining several decades ago, the lakes have filled mainly by groundwater inflow. Surface areas, volumes and maximum depths are 2387 m^2 and 16.57 ha, 6542 m^3 and $1.26\cdot10^6$ m^3, 4.7 m and 17.4 m, respectively. Mainly gradients of dissolved iron and the carbonate system cause the meromixis in both lakes. Ferrous iron (Fe^{II}) which is transported out of the anoxic monimolimnia by a diffusive net flux becomes oxidized in the oxic layers above. As particular ferric iron (Fe^{III}) it settles back into the monimolimnion, where it eventually redissolves. This chemical cycle results in the formation of distinct chemoclines and implies an evanescent effective transport of the density regulating iron, sustaining the chemical and therefore the stable density stratification within the chemocline (Boehrer et al., 2009).

Similarly for both lakes, double diffusive mixing in the monimolimnion is driven by seasonal cooling of the mixolimnion, reaching temperatures clearly below temperatures within the chemocline and the monimolimnion. However, due to the high stability in the chemocline the effective transport is limited to the level of molecular diffusion (von Rohden et al., 2009). The gradient by solutes is strong enough to stabilize the stratification throughout the mixing period. Below the chemocline where the salt gradients are much smaller, the stratification becomes unstable, when inverse temperature gradients increase due to the ongoing upward heat loss, initiating convection in a localized depth section.

2 Methods

Measurements were done by lowering an automatic CTD-probe (Idronaut Ocean Seven 319, Brugherio, Italy). The accuracy of the conductivity and temperature sensors were 5 μS/cm and 0.01°C, respectively. The resolution was 0.1 μS/cm and 0.001°C. The resolution of the pressure sensor was 0.02 dbar (~2 cm). The sampling frequency was 5 Hz. Figure 2 shows an overview of CTD – profiles. Here 3–6 consecutively taken CTD-profiles were averaged to reduce scattering.

The seasonal cycle of temperature and electrical conductivity associated with the meromixis is shown for the shallow Lake Waldsee in Fig. 2a. To account for variations of the lake surface, the depth scale in all figures refers to the depth scale in meters from a fixed date (26 April 2006).

During the warm period heat proceeds slowly through the chemocline into the monimolimnion towards the lake bottom. Starting with the autumnal cooling, temperature inversions form within and below the chemocline. In winter we find inverse temperature profiles, stabilized by the strong gradient of solutes. The seasonal variation of the chemocline depth is a result of convective mixing in the mixolimnion, which causes an erosive descent of the chemocline predominantly in summer, and an inflow of groundwater into the monimolimnion, supporting an upwards shift (von Rohden et al., 2009). As a consequence of seasonality of transport pattern interacting with the chemical redox cycle, the electrical conductivity (κ_{25}) in the mixolimnion and monimolimnion varies by about 10%.

Figure 2b illustrates the situation in Lake Moritzteich. Similar to Lake Waldsee, heat slowly enters the upper monimolimnion during the warm season starting in April. This heating even continues on while autumnal cooling already starts in the mixolimnion. After temporal forming of local temperature maxima (e.g., on 19 November at ∼12 m), a strong inverse temperature profile establishes with gradients of 2–3°C/m between the fully mixed ∼4°C mixolimnion and the warmer monimolimnion. Heat diffuses out of the monimolimnion along these gradients. In general, the seasonal temperature signal at the top of the chemocline intrudes to a depth of about 16 m, i.e. at least 4 m into the monimolimnion. The reduced vertical transport causes the monimolimnion temperatures to follow the mixolimnion signal with a depth dependent delay. E.g., in the profile of 16 December 2008, the temperature has a local maximum at ∼14 m while the mixolimnion is at cooler values close to 4°C. Towards the bottom, the temperature continues to be inversely stratified with much less variation, ending at a virtually constant value of ∼7.3°C. This indicates a continuous heat flux from the sediments. With respect to conductivity (chemical stratification) we find some kind of a two layer system: the "upper" monimolimnion extends from the chemocline to ∼14 m depth. It is separated by an intermediate layer with an enhanced density gradient from the 'lower' monimolimnion extending from ∼15.8 m to the bottom. This structure as a whole is persisting over the years and shows little variation.

Formulas to calculate water density from measured electrical conductivity and temperature, specific for the investigated lakes, were developed, since standard formulas (e.g. Chen and Millero, 1986) do not apply for the specific hydrochemistry in the investigated lakes. For Lake Waldsee the procedure is explained in detail in Boehrer et

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al. (2009). Laboratory measurements on the temperature dependence of the electrical conductivity $C(T)$ for epilimnion and monimolimnion samples from both lakes were performed. From the linear regression to the data from 1.5°C to 30°C the electrical conductivity for the chosen reference temperature of 25°C could be evaluated:

$$\kappa_{25} = \frac{C(T)}{\alpha_{25}(T-25)+1}, \tag{1}$$

where $\alpha_{25} = 1/(25+n/m)$, with n and m the respective regression coefficients (e.g. Karakas et al., 2003; Boehrer and Schultze, 2008). The specific temperature dependence of the density in the mixolimnion and monimolimnion water (ρ_{mixo} and ρ_{moni}) was determined by measurements using a densitometer (DSA 5000, PAAR, Austria) with a relative accuracy of $2 \cdot 10^{-6}$ and fitting these data by a fourth-order polynomial.

Based on the CTD-casts in the field, the density profiles were then be calculated by

$$\rho(T,\kappa_{25}) = \rho_{\text{mixo}}(T) + \left[\rho_{\text{moni}}(T) - \rho_{\text{mixo}}(T)\right] \cdot \frac{(\kappa_{25}-\kappa_{\text{mixo}})}{(\kappa_{\text{moni}}-\kappa_{\text{mixo}})}, \tag{2}$$

where κ_{mixo} and κ_{moni} are the values of κ_{25} in the mixolimnion and monimolimnion samples of both lakes, considered as representative for the study period.

Based on this density we derived the local stability N^2 (in 1/s^2) and the stability ratio R_ρ:

$$N^2 = -\frac{g}{\rho}\frac{\partial \rho}{\partial z} = -\frac{g}{\rho}\left(\frac{\partial \rho}{\partial T}\frac{\partial T}{\partial z} + \frac{\partial \rho}{\partial \kappa_{25}}\frac{\partial \kappa_{25}}{\partial z}\right), \tag{3}$$

$$R_\rho = \left(\frac{\partial \rho}{\partial \kappa_{25}}\frac{\partial \kappa_{25}}{\partial z}\right) \Big/ \left(\frac{\partial \rho}{\partial T}\frac{\partial T}{\partial z}\right). \tag{4}$$

N^2 quantifies the local density stratification. R_ρ compares the stabilizing salinity gradient with the destabilizing temperature gradient and therefore highlights the sensitivity to double diffusive effects.

The observed step sizes in the CTD-profiles were compared to the theoretical estimation after the semi-empirical approach of Kelley (1984) (in meter):

$$H_{\mathrm{Kelley}} = \left[\frac{\nu}{D_T} 0.25 \times 10^9 R_\rho^{1.1} (R_\rho - 1)\right]^{1/4} \sqrt{\frac{D_T}{N}}, \tag{5}$$

with ν the kinematic viscosity of water ($8.9 \cdot 10^{-7}$ m^2/s) and D_T the molecular diffusion coefficient of heat ($1.4 \cdot 10^{-7}$ m^2/s). H_{Kelley} considers both stabilizing and destabilizing components by parameterization with R_ρ, calculated from measurements with Eqs.(1)–(4).

3 Measurement results and discussion

3.1 Lake Waldsee

Figure 3 exemplary shows late year CTD-profiles from 2006, 2007 and 2008. They document a variety of step formations by double diffusion with respect to depth, size, and time. Partial convective mixing was initiated at the time when destabilizing temperature gradients arose in the chemocline region after onset of the cool season. The profile from November 2006 (Fig. 3a) could be considered as one final step resulting from continuous downward mixing over a time period of several weeks. This event implies complete mixing of the monimolimnion without destroying the chemocline. A more detailed description can be found in (Boehrer et al., 2009). Figure 3b and c indicates several double diffusive steps at different depths with sizes of about one to several decimeters. Although the measurements with their coarse time resolution of ~1 month are snapshots, a slow downwards migration could be alleged from the three profiles in 2008 (Fig. 3c). In general the structures appear much clearer in conductivity than in temperature as should be expected due to its lower molecular diffusivity.

In Fig. 4a the situation before and after onset of step formation in 2008 is shown. Panels (b) and (c) show the respective local stability and the stability ratio. In the first profile (24 September), R_ρ values in the range of ∼5 were present at a depth of ∼2 m, i.e. just below the chemocline, whereas the deeper monimolimnion was still stabilized by both conductivity and temperature (negative R_ρ). The R_ρ-variation from 21 October reflects the existing steps in the double diffusive depth section between 2.5 and 3.3 m, whereas the lowermost part of the monimolimnion is still stable. The estimation of the step sizes after Kelley (1984) yields ∼0.5–1 m in the relevant depth section from 1.9–2.3 m. Although larger, they are of the same order of magnitude as the observed steps in the deeper section, taking into account the transient nature of the structures.

3.2 Lake Moritzteich

In Fig. 5 three examples of double diffusive steps in Lake Moritzteich are presented. Panel (a) suggests two steps in the "upper" monimolimnion layer. They are "left over" from the last period with diffusive heat loss into the mixolimnion by strong inverse temperature gradients in the preceding winter, and extend over ∼1 and ∼1.5 m. In the lower layer we find one step of ∼1 m thickness. Panels (b) and (c) demonstrate well the seasonality and the depth and time dependent occurrence of the step formation, respectively: in the "upper" monimolimnion, staircases with one to six clearly identifiable steps were observed during the cool periods in different years. At least four are present in the plotted example from 12 February 2008 with sizes in the range from 30 to 50 cm, while much less structure is visible in the "lower" part. However, about half a year later, the steps in the upper part disappeared, whereas clear steps of typically 0.5 m height have formed in the layer near the bottom (Fig. 5c, 29 August 2008).

The considerations involve the assumption of horizontal homogeneity of the measured quantities. This assumption was verified several times for both lakes by CTD – casts from different sites at the same date. For Lake Moritzteich, profile sections from the double diffusive zone in the "upper" monimolimnion on 12 March 2008 are plotted in Fig. 6, measured consecutively at three sites (crosses in Fig. 1). Although systematic offsets of a few decimeter between the different sites may exist, e.g. by (weak) internal waves, the number and size of steps coincide.

The observations suggest that the steps in the deeper layer arise with a certain time lag. This delay should be related to the speed at which the thermal (cooling) signal from the upper layer proceeds downwards. Reading off the permanently stably stratified intermediate layer extending from ~14.0 m to ~15.5 m (Δz ~1.5 m) (Fig. 5), the time scale for the propagation of the signal was of the order $\Delta\tau = (\Delta z)^2 / D_T \cong 200$ days, with D_T the coefficient of molecular diffusion of heat. This might explain the observed temporal pattern and suggests that the effective diffusivity in this depth section must be constrained to values close to the molecular level. Thus, cooling at the chemocline in late autumn and winter drives double diffusive convection in the upper half of the monimolimnion until the following late spring, and in the deepest part with a delay of more than half a year. Here, even in late autumn 2008, convective steps could still be observed, while the following cooling period has already started.

From density calculations we derived local stability N^2 and stability ratio R_ρ, exemplary shown in Fig. 7a and b for both situations in 2008 discussed above (Fig. 5b and c). Although the scatter is high, for February 2008 a tendency towards $R_\rho < 30$ approaching the critical value of 1 can be quoted for both depth regions in the "upper" and "lower" monimolimnion, indicating the potential for double diffusive effects. Certainly, R_ρ in the "upper" monimolimnion is already determined by an existing staircase. In August the upper part of the profile was smooth and stably stratified giving negative R_ρ, while the bottom part again reflects a double diffusive situation with existing steps.

Similar to Lake Waldsee the thicknesses of the observed mixed layers are highly variable, though no complete mixing was observed (Boehrer et al., 2009), neither of the whole monimolimnion nor within the different layers. Recalculation with the approach of Kelley (1984) yields a range of values of ~0.5–2 m (Fig. 7c). As in Lake Waldsee, this seems to be up to several times larger than the observations. However, this is not necessarily in contradiction, as calculated step sizes are prognostic estimates, originally based on oceanic conditions with much less temporal (temperature) variability at the boundaries of the relevant double diffusive zones. The quick changes of the boundary conditions at the chemoclines with comparatively large amplitudes may explain this variability in the studied lakes and even might hamper the steps from full development. Nevertheless, the steps can reach sizes in the same range as reported from other lakes with rather small background gradients, e.g., Lake Nyos (Schmid et al., 2004). The overall two-step structure in the monimolimnion of Lake Moritzteich (Fig. 2b) can be considered as the long-term result of the temporally and spatially separate occurrence of double diffusive convection.

4 Conclusions

The observations show that convective mixing triggered by double diffusive processes in monimolimnia of meromictic lakes can be part of the seasonal mixing regime. A precondition is that the mixolimnetic temperature cycle above the monimolimnion is strong enough to initiate destabilizing gradients which can migrate sufficiently deep into the monimolimnion. Such conditions are primarily provided in temperate climates. On the one hand, the occurrence of double diffusion confirms that the exchange between monimolimnion and mixolimnion and within the monimolimnion must in general be as low as molecular. As a result, double diffusion follows the seasonal forcing with a depth dependent time lag. On the other hand, monimolimnia can locally undergo convective mixing, considerably enhancing effective vertical fluxes of heat and solutes. However, the stability of the stratification within the chemocline, i.e. the meromixis itself, is not necessarily degraded by these processes.

Preconditions and forcing of the observed double diffusive mixing is similar to other lakes (e.g., Lake Nyos, Schmid et al., 2004). However, the magnitudes of the forcing, i.e., the extent of the seasonal temperature variation at the top of the monimolimnion as well as the strength of the stabilizing salt and destabilizing temperature gradients are extraordinarily high in the presented examples. The water column in parts is sensitive to double diffusive mixing, although the overall stability in the respective depth regions is high at $N^2 \sim 10^{-3}\,\mathrm{s}^{-2}$ (Figs. 4 and 7). The number and thicknesses of double diffusive steps should be very sensitive to the continuously changing gradients, which might explain the observed discontinuity of the texturing.

It seems obvious that these mechanisms could be widespread among meromictic lakes in temperate climates, as many of them might meet the described preconditions. This should especially be important for existent but also future pit lakes from open-cast mining, because such lakes are above-average prone to meromixis. The resolution of the applied measurement techniques does not allow investigating the dynamics of double diffusive processes in more detail, e.g. the time scale of formation and persistence of steps or the relation of step size to ambient gradients in temperature and salinity. High resolution thermistor chain records and microstructure measurements should be implemented in more detailed investigations.

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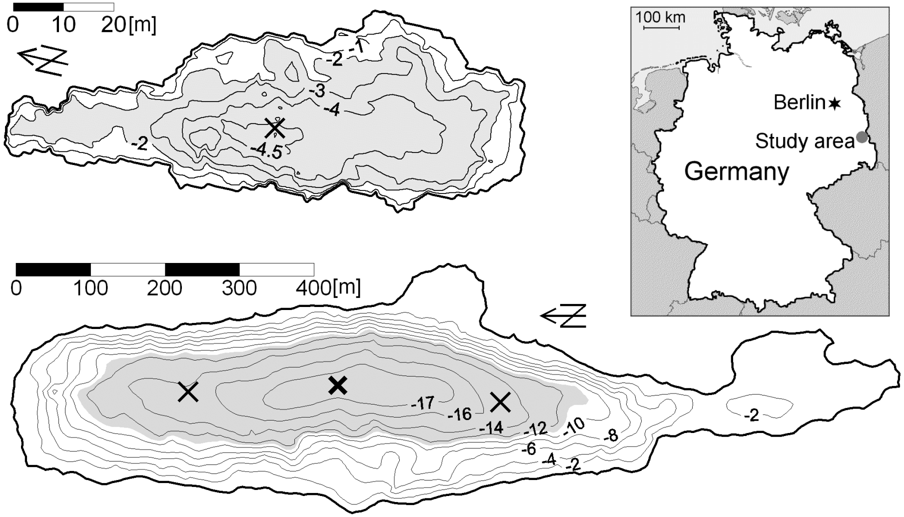

Fig. 1. Bathymetric maps of Lake Waldsee and Lake Moritzteich. The grey shaded areas denote the surfaces of the monimolimnia. Measurements took place at the sites marked by crosses.

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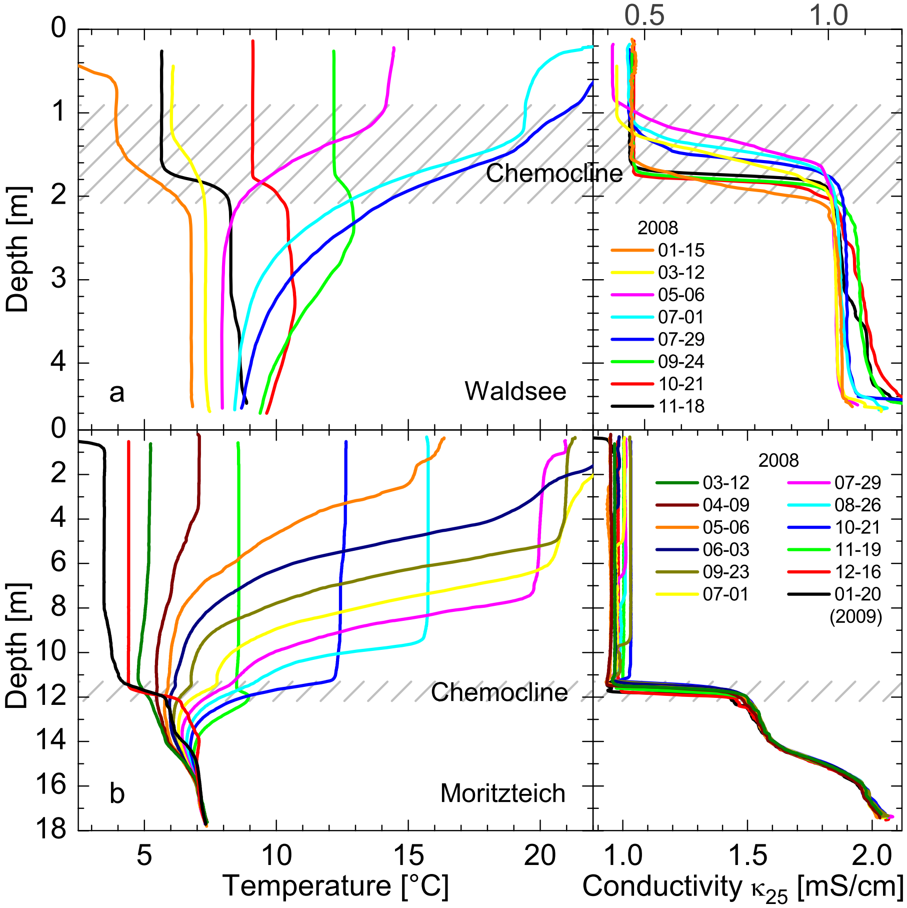

Fig. 2. Selected profiles of temperature and electrical conductivity (corrected to 25°C) of **(a)** Lake Waldsee and **(b)** Lake Moritzteich, illustrating typical seasonal cycles.

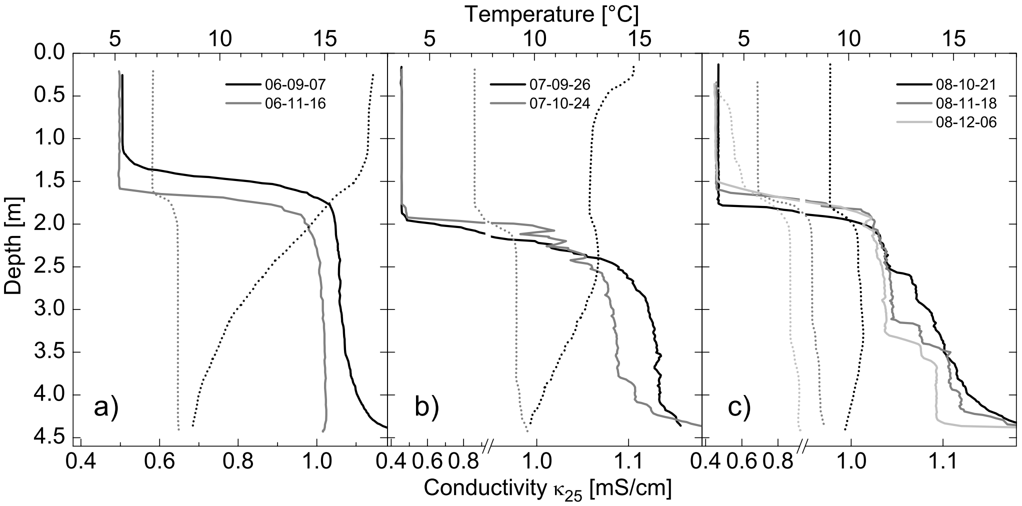

Fig. 3. CTD – profiles at Lake Waldsee from three different years documenting variable shaping of double diffusive mixing (formation of steps) after onset of mixolimnetic cooling: **(a)** (2006) complete overturn of the monimolimnion (= one step), **(b)** (2007) steps close to the bottom, **(c)** (2008) steps within the monimolimnion, migrating downwards with time. In panels (a) and (b) the preceding overall stable situations are plotted for comparison. Note the axis breaks for conductivity in panels (b) and (c).

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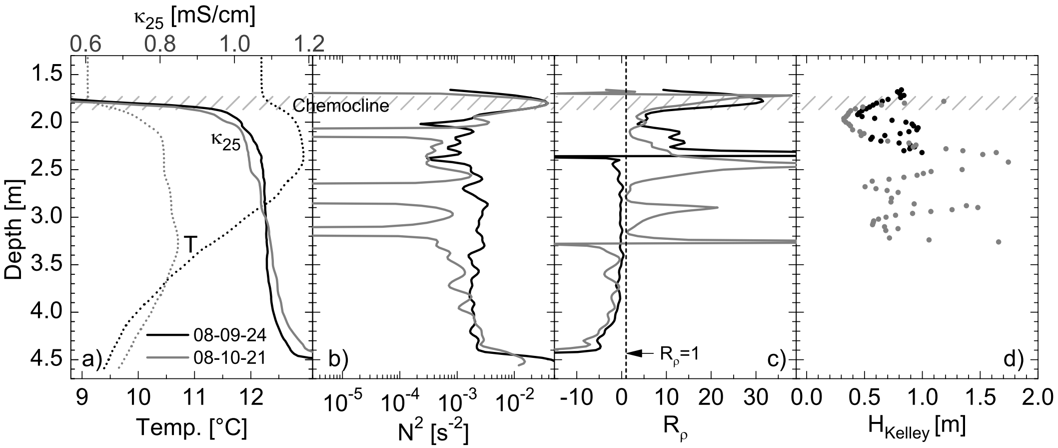

Fig. 4. **(b)** Local stability N^2, **(c)** stability ratio R_ρ, and **(d)** calculated size of potential double diffusive steps in a situation before (24 September 2008) and after (21 October 2008) the onset of convection in the monimolimnion of Lake Waldsee **(a)**.

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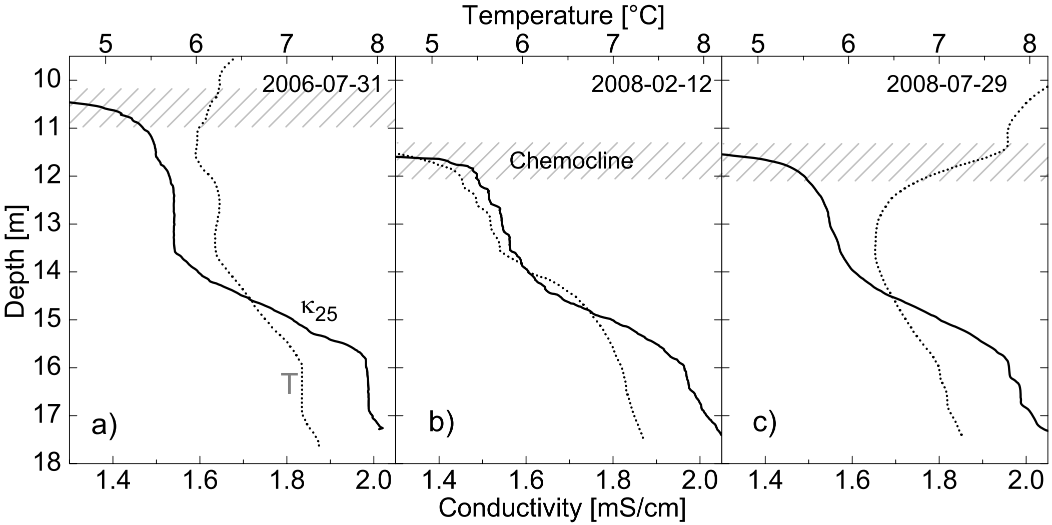

Fig. 5. CTD – profiles at Lake Moritz from two different years documenting variable shaping of double diffusive mixing (formation of steps): **(a)** (2006) two steps in the upper part of the monimolimnion, one step near the bottom, **(b)** (2008, winter) several steps in the upper part, no clear structure near the bottom, **(c)** (2008, summer) steps in the upper part disappeared, step formation near the bottom.

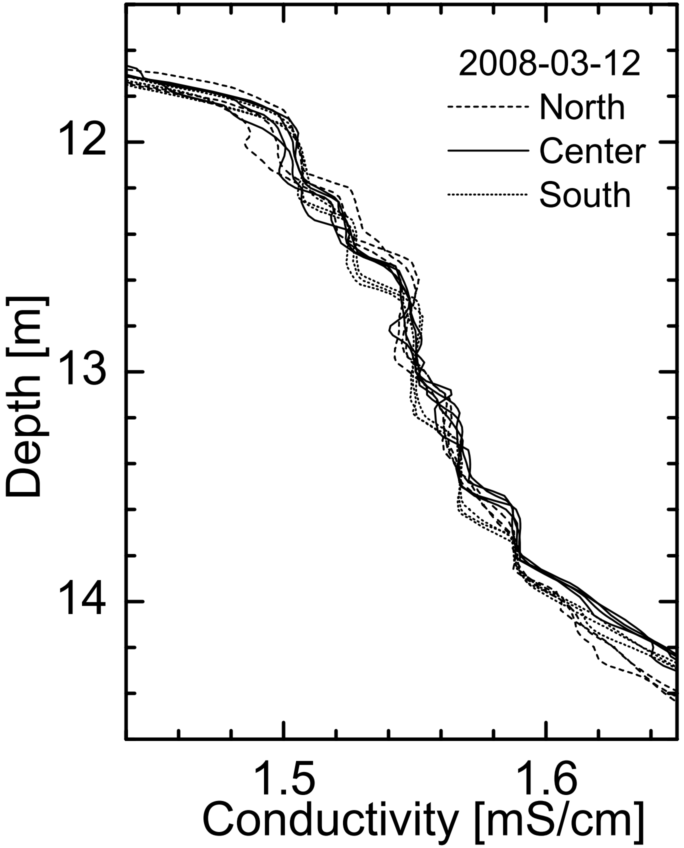

Fig. 6. Consecutively taken CTD – profiles from three different sites at Lake Moritzteich (section of double diffusive zone in the upper part of the monimolimnion) to verify the reproducibility of single measurements and the assumption of horizontal homogeneity.

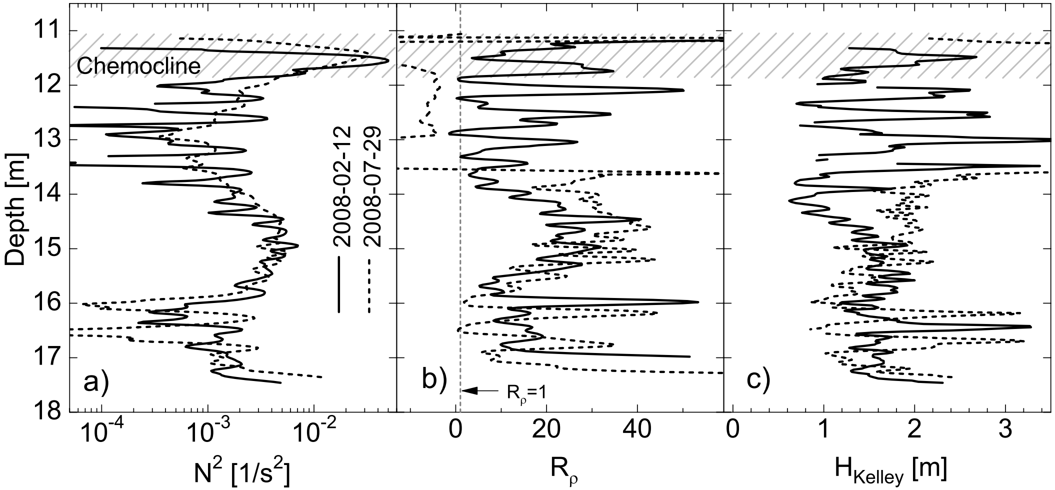

Fig. 7. (a) Local stability N^2, **(b)** stability ratio R_ρ, **(c)** calculated size of potential double diffusive steps for two situations in February and August 2008 in the monimolimnion of Lake Moritzteich.