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# Spatial and Temporal characteristics of Double-Diffusive Layering in Relic Seawater

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## Abstract

Thermohaline staircases indicative of double-diffusive instabilities are examined in Powell Lake, British Columbia. Temperature and salinity profiles in the relic seawater at the bottom of this lake are vertically divided into regions of smooth variation and high gradients, and regions of more irregular variation with weaker background gradients, forming a series of large-scale steps 5-20 m tall. The depths of these large-scale steps has not changed over 5 years, although their bulk characteristics are slowly evolving. Staircases with fine-structure steps about 0.7 m high consistently occur within the weak gradient regions of the deepest large-scale steps. These fine-structure steps result from double-diffusive layers that can be tracked over the entire lake, and from year to year for over 3 years. The depth of these layers varies consistently in different surveys and when a particular layer is slightly shallower, the temperature within it is slightly warmer.

## 1 Introduction

Staircase fine-structure in vertical profiles of temperature and salinity, resulting from double-diffusive instabilities in regions where both temperature and salinity increase with depth, are widespread in high-latitude oceans (Kelley et al., 2003; Radko, 2013). Although individual steps in these staircases may be no more than a meter or so tall, these staircase structures, and perhaps even individual steps, can sometimes be horizontally coherent over tens to hundreds of kilometers.

Although much is known about these staircases, current unknowns still include the initial formation and temporal stability of staircase structures and of individual steps, and the factors governing horizontal coherence and variability of individual steps. Here we study these questions by examining similar staircase structures in the more logistically accessible deep waters of a dynamically quiet meromictic lake. This lake is stably stratified due to the presence of relic seawater near its bottom, but is geothermally heated from below.

## 2 Site and Methods

Powell Lake, British Columbia (50°N, 124°W) was a fjord at the end of the last ice age. When the ice retreated the local coastline rose more than 100 m in only a few hundred years (Clague and James, 2002) leaving a lake with a surface about 50 m above sea level. The special nature of Powell Lake's multi-basin topography has prevented the relic seawater in some basins from being flushed by advective processes in the last 10,000 years (Williams et al., 1961). Modelling by Sanderson et al. (1986) suggests that the present bottom salinity is approximately consistent with losses by molecular diffusion alone from an original salinity<sup>1</sup> of around 33 g kg<sup>-1</sup>, and that the large-scale temperature gradient is in quasi-steady state with a geothermal heat flux independently estimated

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<sup>1</sup>All salinities are on the TEOS-10 Reference-Composition Salinity Scale (IOC et al., 2010).

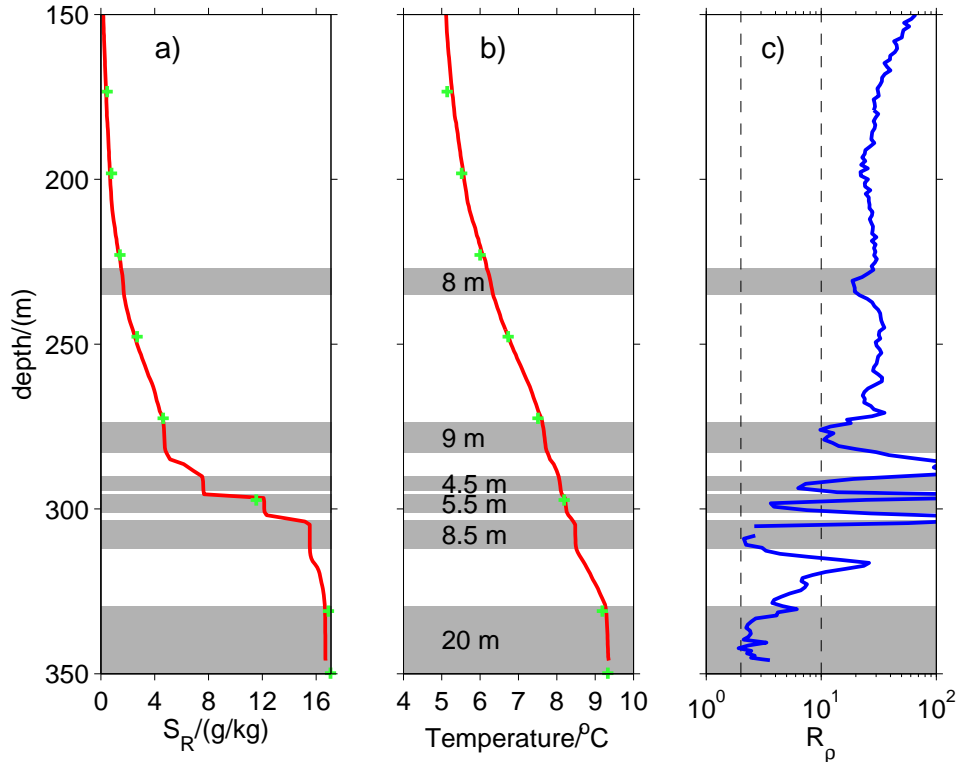


Figure 1: a) Salinity, b) Temperature, and c) Density ratio  $R_\rho$  profiles in Powell Lake. Green markers are measurements of Williams et al. (1961). Grey banding shows weak-gradient regions making up the large-scale steps. Fine-structure steps are not visible at this scale.

to be about  $27 \text{ mW m}^{-2}$  (Hyndman, 1976). Although small-scale signatures of double-diffusive instabilities were identified many years ago (Osborn, 1973) they have not been systematically studied until recently (Scheifele et al., 2014; Zaloga, 2016).

The basic tool for our observational studies has been slow lowering of SBE-25 CTD profilers during annual visits from 2009 to 2015. By working at night, or in other calm conditions, a consistent lowering rate of  $10 \text{ cm s}^{-1}$  is possible, providing a vertical resolution of  $\sim 1.5 \text{ cm}$ . This is sufficient to resolve staircases in the lake containing sequences of temperature/salinity jumps of around  $4 \text{ m}^\circ\text{C}$  and  $2 \text{ mg kg}^{-1}$  across interfaces 10-20 cm thick, separated by mixed layers about 70 cm high (Scheifele et al., 2014).

To observe temporal variations over periods less than a year, a mooring was deployed from October to December of 2014 (Zaloga, 2016). The mooring consisted of a) 36 precision temperature sensors spaced 4 – 7 cm apart in a rigid vertical array 2 m tall, about 7 m above the bottom, b) S4 current meters attached one meter above and one meter below the rigid array, c) several temperature sensors near the bottom and at a height of 29 m above the bottom. Sampling rates were around 1 Hz.

### 3 Results

Lake surface waters have a salinity of only  $6 \text{ mg kg}^{-1}$ . In the southern basin, which is about 10 km long and 1.5 km wide, waters below 125 m are permanently anoxic, and bottom waters at a depth of 350 m currently have a salinity of nearly  $17 \text{ g kg}^{-1}$  (Fig. 1a), with most of the increase occurring between 270 and 300 m. In contrast, temperatures increase quasi-linearly from  $5^\circ\text{C}$  at 125 m to about  $9^\circ\text{C}$  at the bottom.

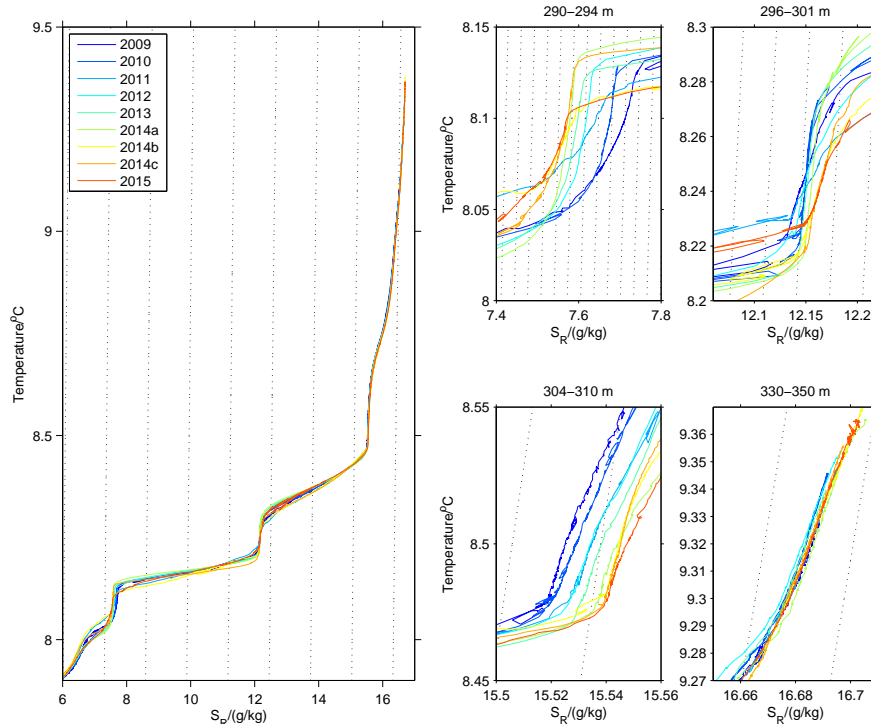


Figure 2: Changes in the  $T/S_R$  characteristics of Powell Lake over 2009-2015. Panels at right are closeups of the changes in the lowest 4 large-scale steps. Dotted lines are isopycnals with a spacing of  $1 \text{ kg m}^{-3}$  (left panel) and  $0.025 \text{ kg m}^{-3}$  (other panels). Fine-structure steps are present but not visible in these plots.

The increase of temperature and salinity with depth is not completely smooth. The water column is instead divided into regions of rapid variation where single-diffusive processes (and possibly turbulence closer to the surface) govern vertical fluxes, and regions of generally weaker (steeper) gradients, forming up to 6 large-scale steps 5 to 20 m thick (Fig. 1). The background nondimensional density ratio  $R_\rho = (\beta \partial S / \partial z) / (\alpha \partial T / \partial z)$ , where  $\alpha$  and  $\beta$  are thermal expansion and haline contraction coefficients normalizing the large-scale vertical ( $z$ ) gradients in temperature  $T$  and salinity  $S$ , is significantly lower within these large-scale steps, often within the range of 2–10 where double-diffusive steps are typically observed (Kelley et al., 2003).

Bulk characteristics of the large-scale steps are slowly changing. Densities in the bottom-most (330-350 m) have remained stable within  $0.003 \text{ kg m}^{-3}$  over 2009-2015, but have increased by  $0.02 \text{ kg m}^{-3}$  from 304-310 m, and decreased by  $0.1 \text{ kg m}^{-3}$  at 290-294 m (Fig. 2). These density changes are also associated with a slow decrease in  $R_\rho$ . However, the depth of the different large-scale steps has remained constant.

Spectra of horizontal velocity from measurements in the lowest large-scale step have a broad peak for oscillations with periods of 13-21 hours, matching predictions of seiche mode periodicity (Fig. 3). The magnitude of seiching varies, related to changes in weather. Maximum seiche currents over 3 months were less than  $\pm 1 \text{ cm s}^{-1}$  and associated horizontal displacements were less than  $\pm 100 \text{ m}$ . Vertical displacements at a depth 29 m above the bottom sometimes reached  $\pm 1 \text{ m}$ . The mooring does not always see the same layer. However, during a relatively calm week in late November, when maximum seiche currents were well below  $\pm 0.2 \text{ cm s}^{-1}$  and horizontal seiche displacements less than

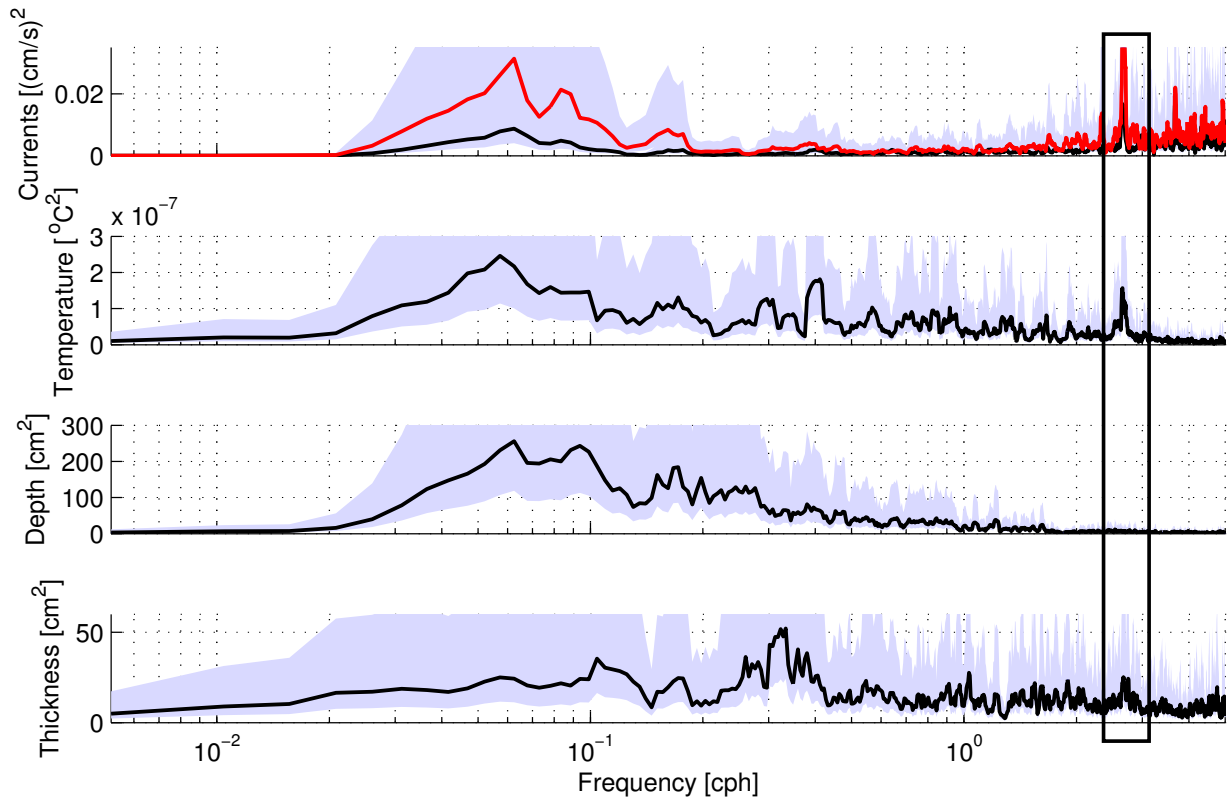


Figure 3: Variance preserving power spectra of the horizontal velocities and the step properties over Nov 17-25, 2014 using a multi-taper method. Shaded regions show the 95% confidence limits. A common peak (shown within the boxed region) with a frequency of 2.73 cph (period 22 minutes) is visible in the step temperature, currents, and step thickness, but not in step depth.

$\pm 25$  m a single fine-structure layer remains consistently within the domain of the vertical array.

Mean statistics of the double-diffusive staircase within this deepest large-scale step have been described previously by Scheifele et al. (2014). We now examine temporal variability in one fine-structure step within this staircase. A 6 hour segment of the mooring record during the calm November week shows variability at time scales of well under an hour in step temperature and other properties (Fig. 4). Particularly prominent are narrow vertical plumes within the step riser. These plumes are about  $0.2 \text{ m}^\circ\text{C}$  warmer than surrounding waters and extend upwards from the bottom diffusive interface. No corresponding cold plumes are seen sinking and a weaker more widespread downwelling is inferred. The warm plumes result in a narrow peak with a period of 22 minutes in spectra of mean step temperature and step thickness over the whole week (Fig. 3). A similar peak with a scale velocity of about  $0.5 \text{ mm s}^{-1}$  is seen in spectra of horizontal currents, but no corresponding peaks appears in spectra of step depth. These peaks thus characterize convective instability processes within the step.

Next we consider the spatial coherence of the steps. Steps in one vertical CTD profile can often be unambiguously linked with steps in neighbouring profiles because the vertical temperature difference between steps is much larger than the horizontal temperature difference within the same step between stations. By continuing this identification in successive profiles, steps can potentially be tracked along the entire lake length, organized into distinct layers.

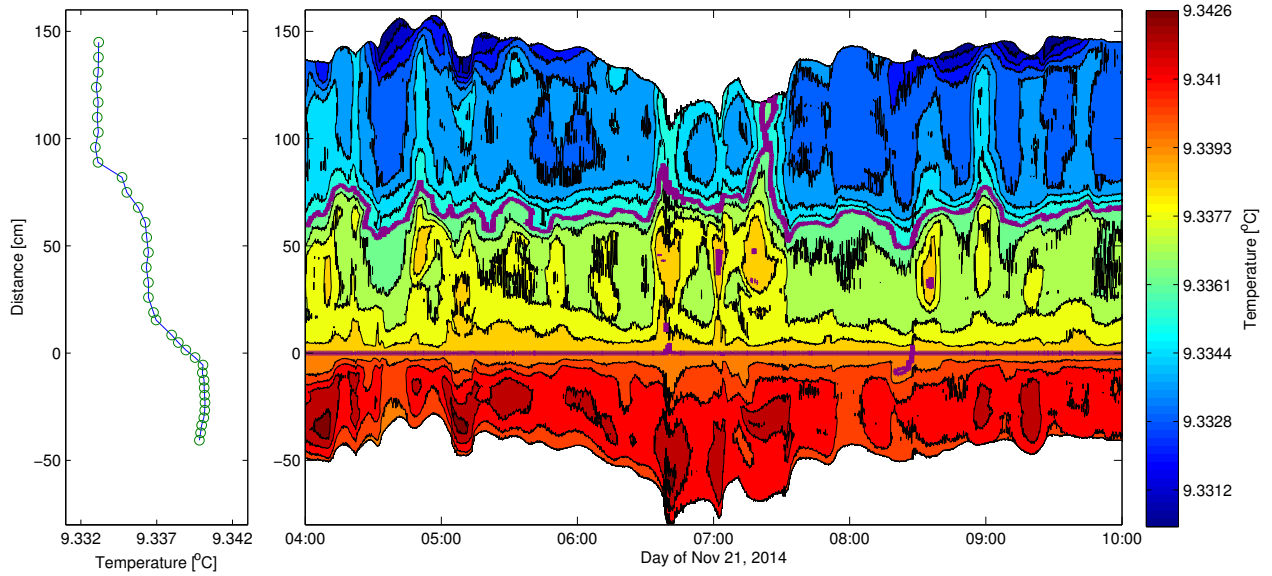


Figure 4: 6 hour segment of temperatures within a step. The initial step profile (as measured by simultaneous measurements at all 36 thermistors) is shown at left for reference. The bottom interface is identified and all profiles are adjusted vertically to present offsets relative to this location. The upper and lower step interfaces are indicated with purple lines.

Identifying layers in 4 consecutive annual surveys (Fig. 5) has the following results: First, we find that layers within a “central” region at depths of 336-347 m where  $R_\rho$  is between 2 and 2.5 can almost always be tracked across the entire basin. However, there is one location (depth 345 m at 49.957 °N) where a break in layer tracking occurs consistently for several years. Above and below the central region,  $R_\rho$  is slightly larger, and many breaks occur when layers cannot be tracked into neighbouring profiles.

Second, layer temperatures are not spatially constant. Temperature variations within a layer can exceed 5 m°C over the whole basin, and the depth of a layer can also vary by up to 2 m. These values are slightly larger than the vertical changes from step to step at a given geographic location.

Third, layers can be identified across years, with similar temperature and depth. The observed variations in layer depth from place to place are larger than might be expected from seiching and seem instead to be permanent features.

Finally, the spatial variations in temperatures of a particular layer are correlated with the spatial variations in depth of that layer. When a layer appears higher in the water column, it is also warmer. The quasi-horizontal buoyancy gradients within a layer due to temperature are larger than those due to salinity ( $|\alpha\partial T/\partial x| > |\beta\partial S/\partial x|$ ).

#### 4 Discussion

Previous laboratory studies have indicated that the convective regime within double diffusive steps varies depending on the local value of  $R_\rho$ . If the results from laboratory and numerical studies (Crapper, 1975; Marmorino and Caldwell, 1976; Flanagan et al., 2013) can be applied here, this would suggest that the majority of the layers in Powell Lake are stable in form, and are in a state of convection governed by intermittent thermal plumes within the steps, with only occasional instances of more turbulent convection present within the interfaces at depths between 336 m and 347 m.

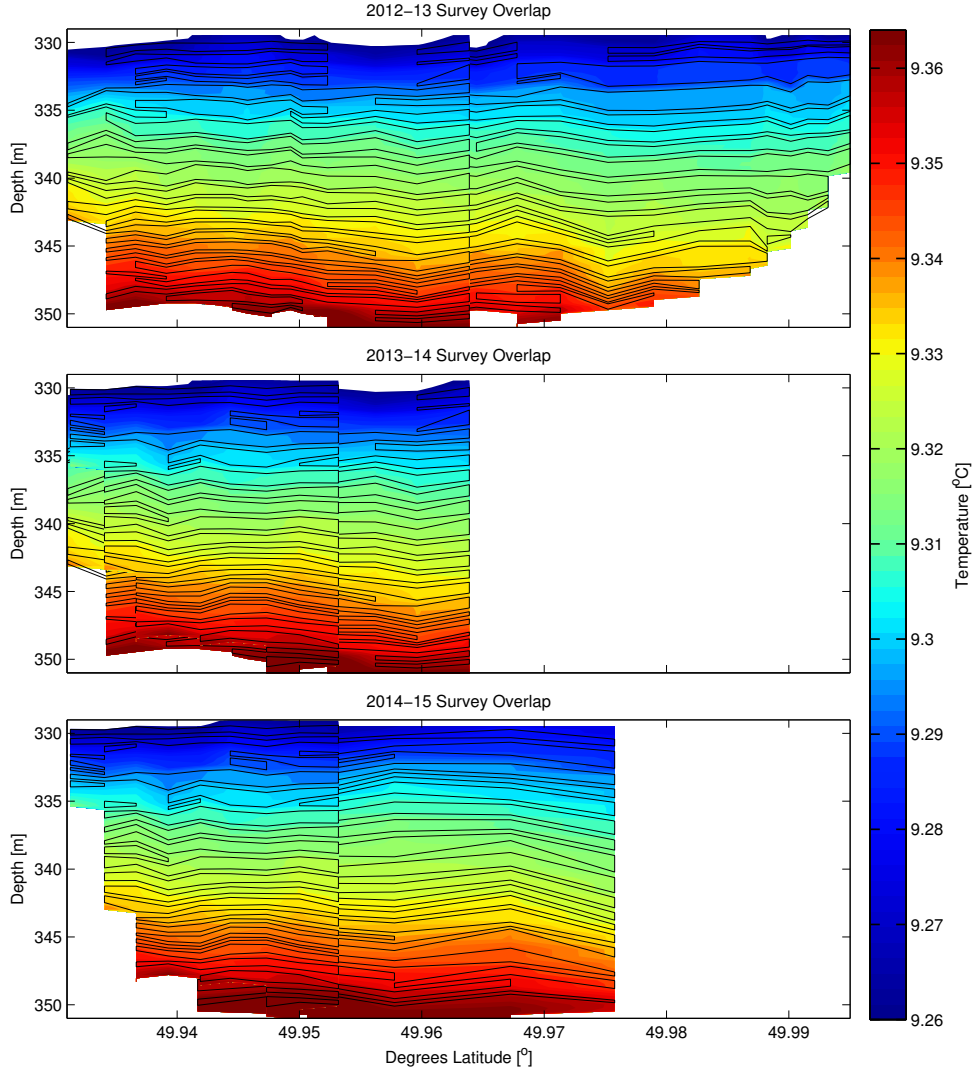


Figure 5: Outline of tracked double-diffusive layers from surveys of the deepest large-scale step in consecutive years, with 0.25 m vertically-binned background temperature in colour. Upper panel shows 2013 survey overlaid on 2012 survey, middle panel shows 2014 overlaid on 2013 surveys, and lowest panel shows 2014 overlaid on 2015. Layers appear to be consistently raised in regions with relatively warmer waters.

This general picture seems to be confirmed by our observations of long-term coherence in layer structure. The lack of spatial coherence above and below the central region (where  $R_\rho$  is larger) may result from a source other than more vigorous forcing. The nondimensional Rayleigh number  $Ra$  which indicates thermal forcing over the whole large-scale step is only  $10^6 - 10^7$  (Scheifele et al., 2014), somewhat smaller than the  $10^8 - 10^{12}$  range seen for  $Ra$  in Lake Kivu and the Arctic (Sommer et al., 2013).

Within a layer, we see a common peak in velocity and temperature spectra. A common spectral peak is also seen in laboratory studies of single component thermal convection (Qiu et al., 2004) associated with convective plumes. The background buoyancy period,  $2\pi/N$ , where  $N = \sqrt{g/\rho\partial\rho/\partial z}$ , for the region where the mooring was deployed is  $\sim 46$  minutes. However, the buoyancy frequency  $N_I$  calculated for the diffusive interface alone has a period  $\sim 23$  minutes, which is remarkably similar to the period of 22 minutes for our observed spectral peak. This result is in close agreement with the observations of Marmorino and Caldwell (1976) suggesting that convective rolls are linked to interface oscillations.

The lower portion of Powell Lake is thus divided vertically into regions where  $R_\rho$  is quite large, and (due to the lack of turbulence) vertical fluxes are largely controlled by molecular diffusion, and regions where  $R_\rho$  is low, and double-diffusive steps are possible. Heat fluxes are not strong enough to completely destabilize these steps, and there is no other source of turbulence, so that layers can have a lifetime of many years. The dominant balance at any location is set by vertical gradients.

Horizontally, there seems to be a consistent spatial pattern in layer temperature and depth, with individual layers being warmer and slightly higher at the southern end of the lake. Within this general pattern we can also see other patterns that seem to recur from year to year, e.g., a local rise in layer depth and temperature near 49.967°N (Fig. 5).

A similar relationship between temperature distribution and layer height has been found in two dimensional laboratory studies of sidewall heating effects (Turner and Chen, 1974; Chen and Liou, 1997). In such cases a horizontal gradient in temperature and salinity is established, and thus the iso-surfaces are not perfectly horizontal. These horizontal gradients drive convection in the form of intrusion-like layers that propagate horizontally at a downward angle. After the layers propagate to fill the entire domain, the overall appearance of the layers is nearly equivalent to those seen in the case of bottom heating apart from one key feature: the layers formed in this way are all sloped rather than aligned with the horizontal. Furthermore, the convection that drives the propagation of these layers is still persistent after they have filled the domain, so that there is an overall layer circulation such that the flow is downslope in the upper portion of the layer and upslope in lower portion of the layer.

We have no direct evidence for such a layered mean flow in Powell Lake. However, it seems unlikely that the heat flux at the bottom of the lake is exactly constant over the entire area, and such a horizontal circulation could act to homogenize the vertical heat fluxes in the lake. Thermal gradients in the single-diffusive region some 30 m from the bottom (i.e. above the bottom large-scale step) are in fact quite uniform over the whole basin (Scheifele et al., 2014).

However, although the above discussion shows an internal consistency to the observations, it does not explain the formation of the different large-scale steps, nor explain why they occur in the depth ranges in which they are seen. The slow variation in large-scale step properties seen over many years (Fig. 2) suggests that linear gradient regions might be subject to a very slow instability, as yet unknown.

## 5 Acknowledgements

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