Temperature structure and turbulent mixing processes in Cumbrian lakes.

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Abstract

The lakes of the English Lake District, like all lakes, become density stratified during the summer, when they are most biologically active. This means that they are warmest near their surfaces, and coolest at their beds. This constrains the vertical transport of heat and chemicals because it forms a stable state that requires considerable mixing energy to overcome. When vertical transport does occur, the mixing energy is provided by the wind, which produces turbulence and wave motions within the stratified waterbody. The vertical motion these produce is crucial for a wide variety of ecological and chemical processes within lakes that require linkages to be made between the near-bed and near-surface water. This paper describes some of the work done in Lake District lakes to try to provide a fuller understanding of how these physical processes operate in their contexts, and what the implications are for the water quality and ecological health of the lakes. Key findings include evidence that the vertical structure of turbulent mixing rates is the same in these relatively shallow lakes as in much larger lakes, being relatively high at the surface and near the bed, but very low in the centre of the water column; details of a distinction between small, well-sheltered lakes which are dominated by solar radiation forcing and others which are wind-forcing dominated; and a fuller understanding of the role played by aquatic vegetation around lakes' edges in determining the extent of mixing and stratification.

Keywords

Lakes, Lake District, hydrodynamics, turbulent mixing, water quality, EU Water Framework Directive.

Introduction

All lakes undergo complex patterns of temperature variation. The nature of these variations is, of course, determined by the meteorological and climatological context within which each lake is found. The two primary controls are surface heat fluxes (which include those due to solar heating and nocturnal cooling, for example) and wind-induced mixing. The former determines the amount of heat energy supplied to the lake and the latter determines the extent to which that energy is mixed downwards within the lake.

Given that the supply of heat varies primarily (though by no means exclusively) on seasonal and daily time scales, it is not surprising that lake temperature variations are also dominated by variations on these time scales. Generally, so long as a lake is not very shallow, the surface water will heat up and cool down more rapidly and over a greater temperature range than the deep water. When the surface water cools to below the temperature of the water below it, it becomes denser, so a state known as *unstable density stratification* occurs and the surface water sinks, causing the water column to mix towards an isothermal state (in which the water temperature is the same from surface to bed). However, when the surface water heats more rapidly that the water below it, it becomes less dense and a state of *stable density stratification* is set up. Thus during winter months, lakes tend to be isothermal, whereas during summer months they tend to be stably stratified, with warm water at the surface and cooler water beneath.

The details of this pattern vary from one climatic zone to another. Where lakes become ice-covered in winter, they undergo two periods of stratification each year: one in the summer, as described above, and the other when they are ice-covered because of the well-known, peculiar property of water that its densest state is as a liquid at ~4°C. Where daily temperature variations cover a range comparable to or larger than the corresponding seasonal variations (in equatorial regions, for example) lakes may undergo many cycles of mixing and re-stratification during a year. Other, special cases of lakes are always stratified, while some are never stratified. In the north west of England, however, and specifically in the Lake District, the lakes are typically *monomictic*, i.e. they undergo one stratification-mixing cycle each year, being stratified in the summer and isothermal in the winter.

When a lake becomes stratified, its water column can usually be divided into three distinct layers. The uppermost of these – known as the *epilimnion* (from Greek, meaning literally 'near lake') – is relatively well-mixed (by the surface wind stress), subject to wind-driven currents and waves, relatively well-lit and the location where phytoplankton are concentrated. Beneath this lies the *metalimnion* ('middle lake') which is characterized by a strong vertical temperature gradient, usually occurring over quite a short vertical distance. Finally, there is the *hypolimnion* ('under lake') which is dark and relatively devoid of currents and waves, except near its top where interfacial waves can form within the sharp density gradient of the *metalimnion* and near its bottom where near-bed water motions may occur.

Superimposed on this general structure, a menagerie of hydrodynamic processes combine to form the overall physical character of each lake waterbody. These may be driven by meteorological forcing such as solar radiation or wind as described above, but may also be due to a variety of other factors. Inflows and outflows to the lake, whether natural (rivers or streams) or artificial (e.g. offtakes for water supply), quasi-point source (rivers or streams again) or diffuse (rainfall runoff from fields, which occurs all around the lakeshore rather than just at specific points) are often dominant factors here. Interactions within the waterbody, such as wave-current interactions or the impact of nocturnal sinking of surface-cooled water on the *metalimnion*, may also be important, as may interactions between the waterbody and the lake bed such as interfacial wave breaking where the *metalimnion* meets the bed (see below for a fuller explanation of this process).

The aim of this paper is to give an overview, and detail some key outputs, of work that has been done over the last few years in some of the Cumbrian lakes to try to gain a fuller understanding of how these processes play out in these specific contexts, and what their implications are for the ecological health and water quality of these crucial elements of the natural heritage of NW England.

Methods and Fieldsites

Most of our work has taken place on Esthwaite Water (Figure 1; see also http://www.multimap.com; http://www.bodc.ac.uk/about/brochures_and_posters/documents/mfmb_oi06.pdf), one of the smaller Cumbrian lakes, which is near the village of Hawkshead and between the larger lakes of Windermere and Coniston Water. The reason for this is that it has a permanent monitoring buoy, comprising a meteorological station and a chain of thermistors which measure temperature every metre down the water column to the bed, which at the location of the buoy has a depth of approximately 13 metres. The buoy is deployed and operated by CEH, the Centre for Ecology and Hydrology (Lancaster), a UK Natural Environment Research Council research institute, with whom much of the work described here has been carried out. The data archive from this buoy – which logs data every minute, twenty four hours a day – provides a comprehensive and crucial context within which we can interpret the more specific and time-limited data sets we are able to collect during field campaigns.

Esthwaite Water has a surface area of approximately 1km^2 (100 hectares) and is divided into two roughly equal-size basins (and one much smaller one), which are separated by a relatively narrow section where the bed shoals to a sill of approximately 8 metres depth. The deepest point in the lake is in the northern basin and is approximately 15 metres deep, and the average water depth across the whole lake is ~6.4 metres. In ecological terms, the lake is classified as eutrophic, meaning that there is an ample supply of nutrients to the lake.

Some of the work described here was carried out in Priest Pot (see websites as for Esthwaite Water), which is a very small lake ('pond' is a better word) just to the north of Esthwaite Water. Priest Pot is notable for its unusually high microbiological species diversity, which appears to be caused by the large number of habitat niches (conditions of light, heat, food supply, absence of predators and/or competition etc.) found within it. It has a surface area of approximately 1 hectare (100 m^2) a maximum depth of ~3.5 metres located approximately at its centre and is roughly elliptical, with concentric depth contours centred on the point of maximum depth. Other important characteristics of this pond are that it is strongly sheltered by the surrounding canopy of mature bushes and trees and that it sits within marshland, suggesting that groundwater exchange with the pond water is significant.

The other lake covered in this paper is Ullswater, the second largest (by volume and surface area) and third deepest of the Cumbrian lakes. Ullswater is approximately 12km long and 62 metres deep at its deepest point. The data described here, however, were taken at a relatively shallow location within a bay at the south end of the lake, where the depth varied between approximately 30 cm and 10 metres.

Most of the data presented in this paper were collected using a thermal micro-scale profiler known as SCAMP (Self-Contained Autonomous Micro-Profiler – Figure 2; see also http://www.pme.com for details). This device is designed to measure temperature profiles with 1mm resolution, thus

enabling details of the vertical temperature profile and turbulent mixing processes going on within the lake to be quantified with great accuracy. Examples of these profiles are shown in Figure 3. It is deployed by dropping it over the side of a boat, whereupon it sinks to a pre-determined depth, at which it releases a recoverable weight. This makes the instrument buoyant, and it rises to the surface (Figure 4) at a speed of approximately 10 cms^{-1}, recording data via fast response thermistors at a rate of 100 Hz (samples per second), thus giving the 1mm resolution. It avoids sampling the water it has just stirred up itself during its descent by means of a baffle, which causes it to fall at an angle of 45° but rise vertically through a previously undisturbed column of water.

The length of time between each profile varies depending on the depth of water being sampled, but is typically a few minutes. Each profile is clearly a quasi-instantaneous 'snapshot' of the water column, which may not be representative of the general conditions. As a result, a sampling event usually consists of recording several profiles over a period of a few hours, and averaging all the results.

Figure 1: A view of the north end of Esthwaite Water, showing lakeshore and catchment environments typical of the all the lakes discussed in this paper (photo courtesy of E Mackay)

The data obtained may be processed to provide a wide range of parameters that describe the temperature profile and the statistics of the turbulent mixing events sampled. Most straightforwardly, the temperature at each depth can be determined, and the temperature or density gradient can be quantified. This is important because it represents the potential energy contained within the water, or the resistance to vertical mixing that is provided by the stable density gradient caused by thermal variations, as described above. Thus the amount of wind energy required to mix the lake, or to transport nutrients or plankton a given vertical distance can be calculated, for example. There are various ways of quantifying this density gradient, but arguably the most common is known as the buoyancy frequency and is represented by the letter N:

$$N = \sqrt{\frac{g}{\rho_0}\frac{\partial \rho}{\partial z}} \qquad [1]$$

in which g represents gravitational acceleration (=9.81 ms^{-2}), ρ_0 represents a mean density value for water (usually taken as 1000 kgm^{-3}) and $\partial\rho/\partial z$ represents the vertical density gradient. This variable is called a 'frequency' because it represents the rate at which waves would oscillate within the fluid if it was perturbed: the stronger the density gradient, the more rapidly the waves would oscillate. Clearly, N can be calculated as an average value for the whole depth of the lake by using an average density gradient value, or can be calculated for specific sub-sections of the density profile such as the three layers described above. Each approach has different advantages.

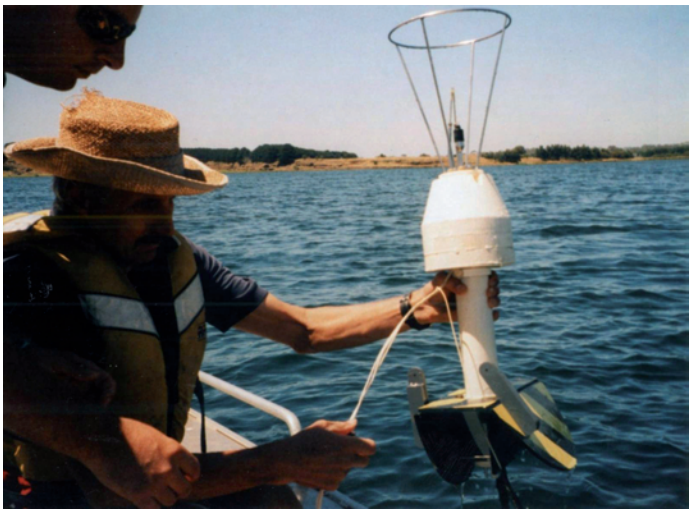

Figure 2: The SCAMP instrument ready for deployment (photo by the author)

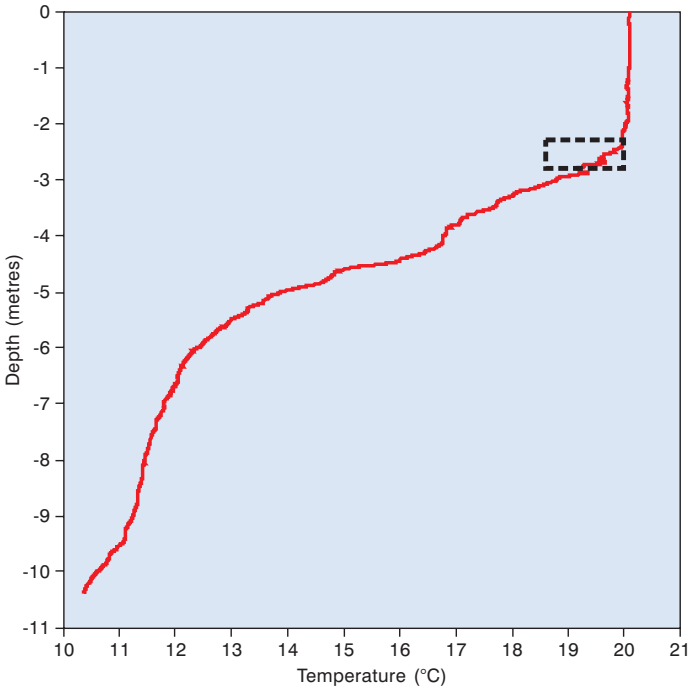

Figure 3: A typical temperature profile of a lake (Esthwaite Water) measured by SCAMP.

Figure 4: SCAMP in the water, having taken a profile and returned to the surface (photo by the author)

As well as density gradient information, the other main body of information that can be derived from the high resolution temperature profiles measured by SCAMP concerns the turbulent mixing that is occurring in the lake. Turbulent mixing is the primary way in which dissolved and particulate matter, plankton, and anything that cannot propel itself through the water gets transported vertically, and is thus crucial for in determining the ecological and chemical nature of lakes. Information about turbulent mixing is derived from the extent to which the profile deviates from monotonicity – how 'mixed up' it is. An example of how turbulence mixes up the density profile is shown in Figure 5. Here, the 'lumps' in the profile show that some of the cooler fluid has been moved up within the profile and some of the warmer fluid moved down, and the temperature and density have not yet diffused themselves back into a smoothly varying profile. These vertical transfers are caused by turbulent eddies, so we can determine the size of the eddies and, by using fundamental theories of turbulence, we can derive information about their energy content, rotation speed and decay rate. All this tells us how fast the lake is being mixed and thus how effectively the different parts of the lake, and the biogeochemical sources or sinks that they contain, are being linked together, which is crucial information for developing a quantitative, useful understanding of the lakes' behaviour.

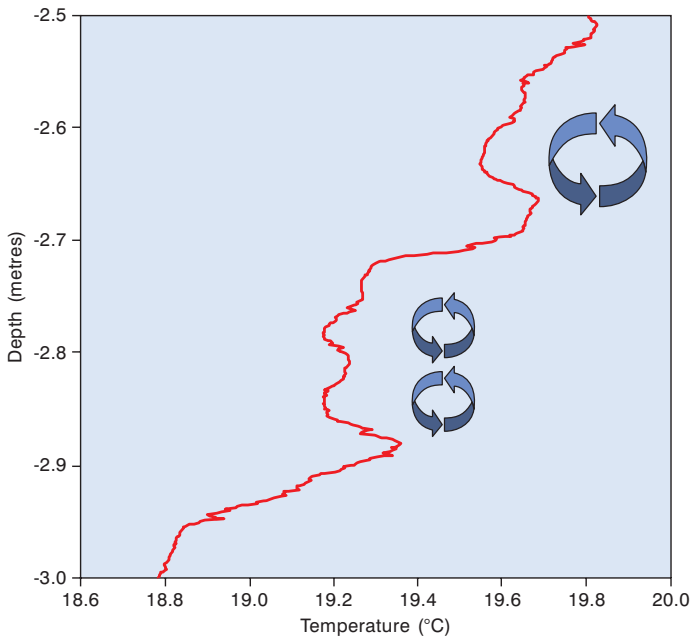

Figure 5: Detail of Figure 3, showing the effects of turbulent overturns on the temperature profile. Sketched of the overturns are shown for illustration. The location of this part of the profile is shown within the full profile in Figure 3 by the dashed box.

Alongside SCAMP data and the temperature and meteorological measurements obtained via the CEH monitoring buoy, we have also taken an extensive series of samples of phosphorus concentrations and associated physico-chemical parameters such as pH, light attenuation and iron concentrations. Phosphorus is important because it is often the 'limiting' nutrient in the Cumbrian lakes – the one that determines how much primary biological production can occur – and one focus of our work has been to try to determine when, from where and how much phosphorus is supplied to the plankton in the epilimnion of the lakes.

Results and Discussion

Typical, raw SCAMP profiles from Esthwaite Water, Priest Pot and Ullswater are shown in Figure 6. This shows these profiles once they have been 'Thorpe-ordered' (Thorpe, 1977), i.e. the temperature values have been rearranged into decreasing order, so that the profile is monotonic. Note that, superimposed on the general three-layer structure, there is a multiplicity of more subtle layering in the temperature gradient, with mixed sub-layers and 'mini-metalimnia' of a range of different sizes and gradients. This may be the product of incomplete turbulent mixing events, but may also be the result of internal wave motions within the water, stretching or squashing the profile at different depths. These internal waves arise because of the density gradient within the fluid. Imagine a piece of water is somehow forced up within such a gradient: it will find itself at a height where the ambient water is warmer and less dense than it is itself. Because this piece of water is denser than the ambient water, it will fall back down. Just as in any oscillatory motion, when it reaches its starting level, it will have excess momentum so will continue downwards to a region where it is warmer and less dense than the surrounding water, so there will be a restoring force that slows it down, then returns it to its starting level, at which point it will have excess upward momentum so it will continue upwards again. Thus a wave-like motion will be set up in the interior of the water rather than at the surface. Such internal wave motions occur in stratified waterbodies whenever they are disturbed. One of the things we are working on in analysing these profiles is to determine how much information we can extract about the internal waves within the water from them. However, we are not yet at a stage where we have results to report from this line of work.

Figure 7 shows the Thorpe scales derived from each of the profiles in Figure 6. These represent the distance each density value has to be moved in order to change the raw profile into the Thorpe-ordered profile. Thus, they are a measure of the size of the turbulent eddies that are doing the mixing. Note that turbulence only occurs in fairly small portions of the profile at any one time, and that it occurs most extensively in the epilimnion. This is to be expected: not only is this the part of the lake that is closest to the wind, which does much of the turbulence generation, there is also much less resistance from the density gradient to vertical turbulent transport in this well-mixed region.

By deriving spectra of the turbulent eddy sizes represented by these Thorpe scales, and fitting these spectra to the Batchelor spectrum, which represents what we expect the spectra to look like from theoretical considerations (Batchelor, 1959; Dillon and Caldwell, 1980), we can determine values of the vertical turbulent diffusivity (denoted KZ), which is the key measure of the rate at which heat or concentrations of biogeochemical substances within the water are mixed.

Plots of KZ for the three lakes, and for different locations within Esthwaite Water are shown in Figure 8. Note that in all three plots, there are relatively high values for the eddy diffusivity at the top and bottom of the water column, with relatively low values in between. This is consistent with what is expected: lake water mixes quite easily near the surface – where it is nearly isothermal, so the buoyancy forces that might constrain vertical motions are very small – and near the bed where the effect of the water shearing along the bed produces turbulent mixing. In the middle of the water column, in contrast, there are only limited forces trying to cause mixing and the water is strongly stratified, which strongly damps the mixing. This pattern has previously been observed mainly in large, deep lakes, such as Lake Geneva, the rift valley lakes of Eastern Africa or the North American Great Lakes where the epilimnion and hypolimnion are relatively strongly de-coupled from each other. What our work has shown is that this is also the pattern in smaller lakes where climatic conditions are such that the lakes become strongly stratified in the summer. The unusually high values of KZ in the Ullswater data reflect the important role of submerged aquatic vegetation in determining the physical structure of the water: these high values are caused by the water becoming more turbulent as it moves through the complex array of stems and leaves that were located at the sampling site in this lake and forms multiple turbulent wakes.

Our work has also brought to light an important distinction between lakes that are dominated by wind forcing, and those that are dominated by solar radiation forcing. In Preist Pot, for example (see Folkard et al. 2007 for

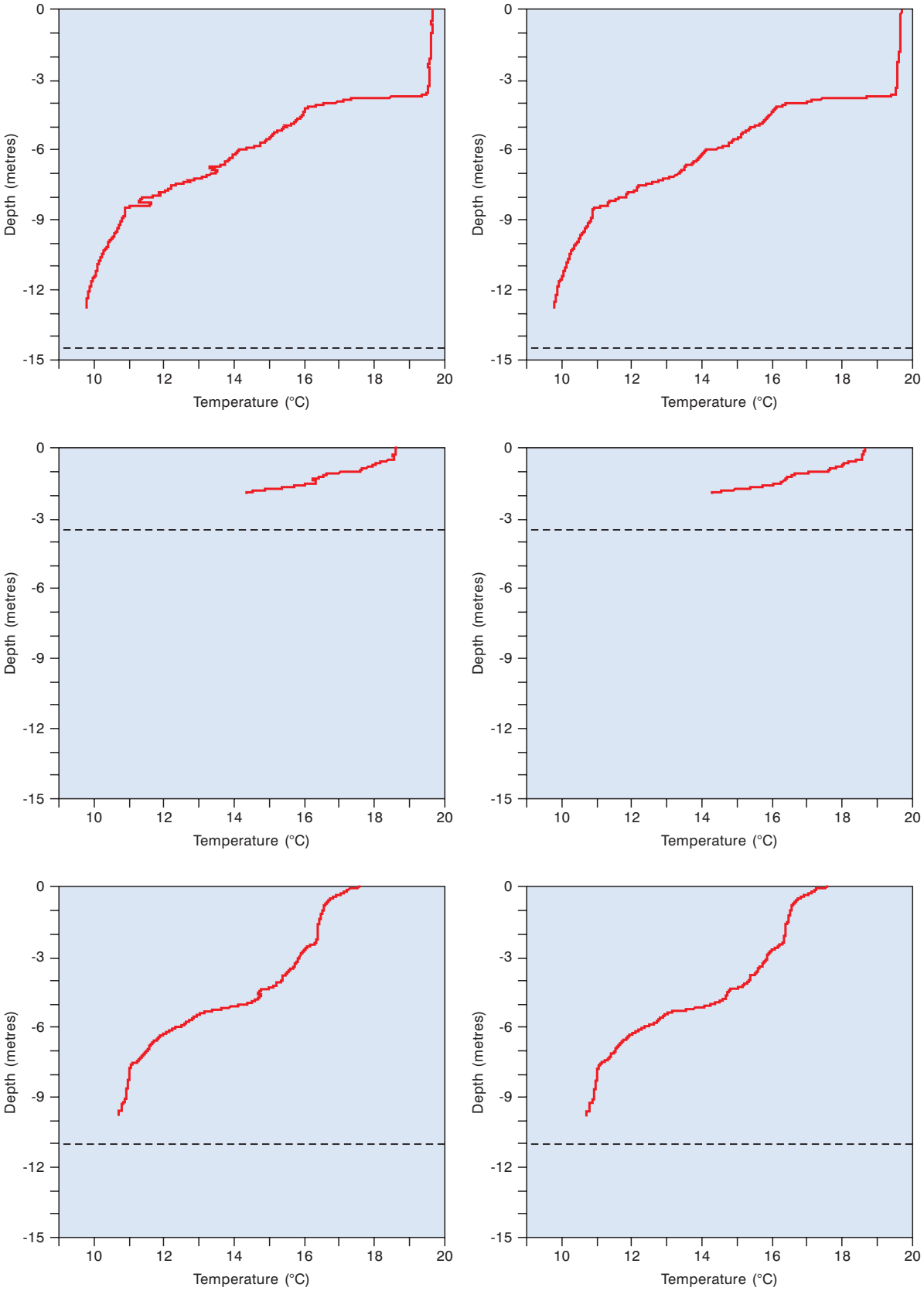

Figure 6: Comparison of raw (left) and Thorpe-ordered (right) profiles for Esthwaite Water (top), Priest Pot (middle) and Ullswater (bottom). Axes are kept constant between plots for comparison.

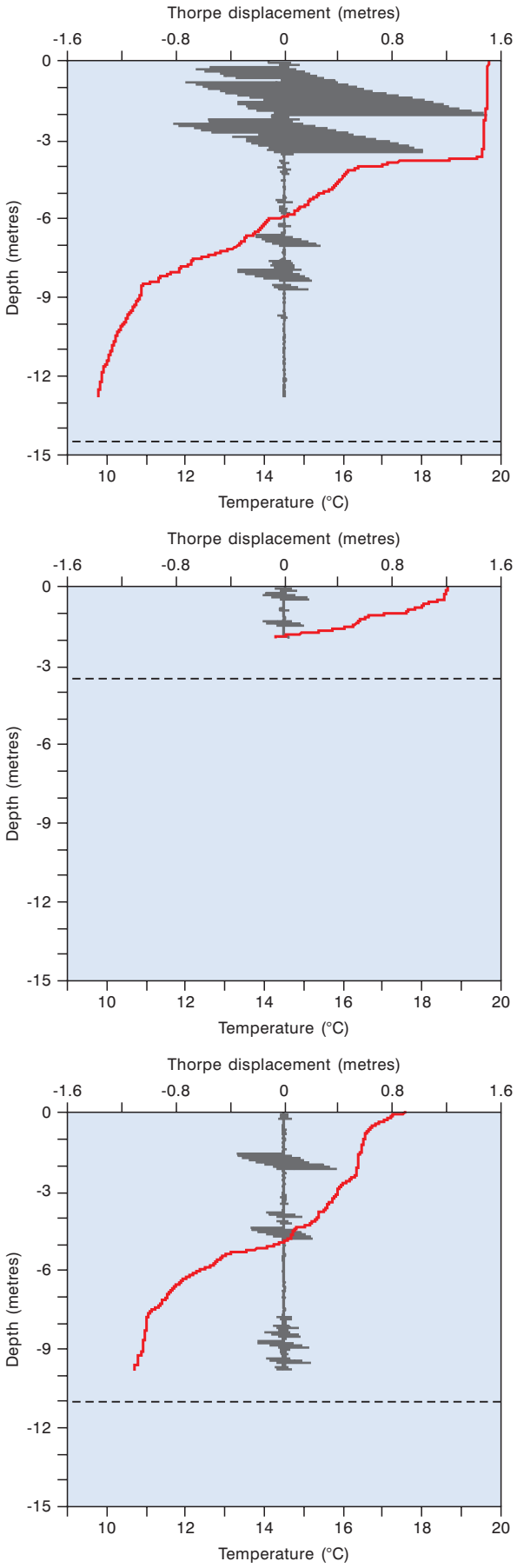

Figure 7: Plots of Thorpe displacements superimposed on the temperature profiles for Esthwaite Water (top), Priest Pot (middle) and Ullswater (bottom). Note the patchiness of the overturns indicated by the Thorpe displacements.

more details), we found that the stratification of the surface layer was determined primarily by the daily variations in solar heating, and that the sheltering of the pond by the surrounding trees was sufficient to ensure that the wind did little to control the stratification. Only once a nearly-isothermal layer was created by overnight surface water cooling was what wind there was able to create turbulence within that layer. Within more open lakes, however, such as Esthwaite Water and Ullswater, the wind plays a major role in mixing the surface waters. Indeed, when the wind blows at a significant speed from one direction for a period of days, it can set up motions that move the whole body of water in the lake to the downwind end of the basin. When the wind dies away, the water sloshes back and forth in a wave-like motion as it settles back to its equilibrium position. This wave-like motion occurs both at the water surface and within the water column, in particular in the metalimnion where internal wave motions can be observed as the thermocline rises and falls through the water column. The speed of these waves, which are known as 'internal seiches' is much slower than surface waves (because the density differences that are driving them are much smaller than those between the water and the air at the water surface) and typically these oscillations persist over several days.

Another issue that our work has focussed upon is the effect that aquatic vegetation around the lakes' edges has on turbulent mixing and stratification. In summary, we have found that in solar-radiation dominated lakes, such as Priest Pot, the primary role of vegetation is in shading the water beneath it. This makes the vegetated water column less stratified than the open water, with the result that vertical turbulent mixing is easier there. This is very important in terms of supplying nutrients to the plants themselves and in particular to the epiphytic communities – organisms that live on the plants. Greater vertical mixing means that it is easier for these epiphytes to gain access to nutrients from the bed sediments, which means that they can grow more easily. In wind-dominated lakes, however, the main role of vegetation appears to be damping of wave energy, with the results that the opposite thermal structure occurs: the water in the vegetated zone is more stratified, whilst the open water is more fully-mixed. This makes vertical turbulent mixing in the vegetated zone weaker, implying that nutrient supply from the bed sediment to the epiphytes will be weakened by this phenomenon.

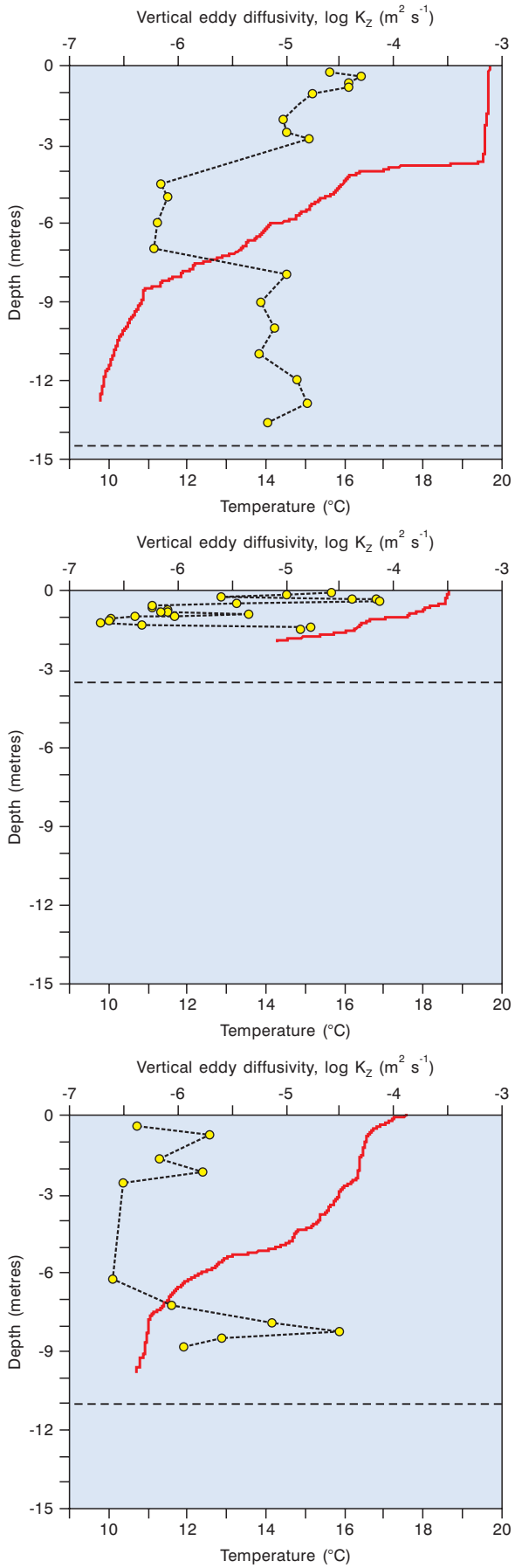

Figure 8: Plots of the vertical turbulent eddy diffusivity KZ (in logarithmic form) superimposed on the temperature profiles for Esthwaite Water (top), Priest Pot (middle) and Ullswater (bottom).

Future work

We have a number of ongoing threads of research in the Lake District continuing on the themes discussed above. We are working on analysis of the detailed structure of thermal profiles to try to determine how much information we can extract from them, in particular regarding the turbulence and internal wave fields of which they provide records. We are also interested in understanding the details of the littoral zone hydrodynamics – the littoral zone being the region where the water is shallow enough for the sunlight to reach the lake bed, so that rooted plants are able to photosynthesise and grow – since this area is particularly important for a wide range of fundamental scientific issues. For example, expulsion of methane, carbon dioxide and nitrous oxide – all greenhouse gases – are relatively high in this zone, so its understanding has implication for our understanding of climate change; second, the presence of vegetation provides sanctuary and nursery habitats for fish and other larger organisms, so the littoral zone is important for the sustenance of biodiversity; third, the littoral zone acts as a buffer between the land and the main body of the lake, in the same way as riparian zones and hyporheic zones (regions immediately beneath the river bed where groundwater and surface water mix and interact) can buffer river channels, so they are important for controlling pollution levels in lakes.

The underlying justification for all these studies of the physics of lakes lies in the chemical and biological implications of our findings. As such, while all of our work is guided by this fact, much of it is explicitly multi-disciplinary. In particular, we are interested in the pathways and budgets of phosphorus, since it is the limiting nutrient in many Cumbrian lakes, and much of our ongoing and future work is directed towards a clearer understanding of this key issue.

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