Temperature Microstructure as a Tracer of Turbulence and Mixing

The smallest temperature variations in natural waters extend over fractions of millimeters. These so-called temperature microstructures can be used as a tracer of turbulent mixing processes and their small-scale dynamics. This methodology allows us to differentiate between different effects that cause mixing in natural waters such as wind and cooling.

In classic tracer applications, concentration variations of a substance are measured as a function of time and space, which allows us to determine transport and transformation rates for the water constituents of interest. “Standing” waters, such as lakes and oceans, are almost always density stratified and exhibit well-defined temperature gradients. In such situations, temperature variations (ΔT', Fig. 1) may be used as a natural tracer. Since temperature is a conservative parameter over time periods of seconds to minutes, temperature variations are a direct reflection of turbulent transport processes. This is the basis for the temperature microstructure method, which attempts to determine mixing rates from a large set of ΔT' measurements. In a stratified body of water, turbulent currents occur primarily in the horizontal direction, while vertical mixing is drastically reduced. However, the turbulent vertical mixing is still 100 to one million times faster than the ever present molecular diffusion (K_T or K_S; see Table 1). Since vertical mass transfer is calculated as the product of turbulent diffusivity, K_v ($m^2\ s^{-1}$), times the concentration gradient, $\partial C/\partial z$ ($mol\ m^{-4}$; z = depth), the determination of K_v is of great practical importance.

The Principle

What is the relationship between temperature microstructures and mixing rates? The basic principle is illustrated in figure 1 using a temperature profile from Lake Neuchâtel. If a temperature gradient $\partial T/\partial z$ is present, neighboring water parcels have slightly different temperatures. Turbulent mixing of the water parcels causes temperature variations that are described by the term $\Delta T' \approx L' \cdot (\partial T/\partial z)$, where L' represents the vertical excursion of the water parcel from its equilibrium position. *In situ* high resolution measurements of ΔT' and the vertical gradient, $\partial T/\partial z$, therefore, yield information about the extent L' and the frequency of turbulent eddies (Fig. 1). Two different statistical models (see box) are available to convert the two measured parameters into mixing rates ($m^2\ s^{-1}$) and turbulent energy dissipation ($W\ kg^{-1}$) [Details in 1]. Eddy dimensions can vary, depending on the stratification and the available energy, from millimeters to several meters, such as in oceans or in Lake Baikal. Variations over distances of less than 1 m are called *temperature microstructures.*

The Measurement

Complete resolution of temperature or velocity microstructures on a millimeter scale is critical for successful measurements of turbulence. Profiles are typically measured with free sinking or rising probes, often operated from ships, or in more recent developments, freely floating and controlled via satellites. The probe has to move at a speed that is faster than the turbulent velocity, w' (Table 1); however, the thermal equilibration time scale of the sensors of approximately one-hundredth of a second requires the lowest possible probe velocity. As a compromise, probes are typically moved at velocities of 5 to 10 cm s^{-1}, which yields a vertical resolution of the temperature profile of 0.5 to 1 mm. It is important that the fast responding temperature sensors are mounted at the tip of the probe in order to sense the undisturbed waters.

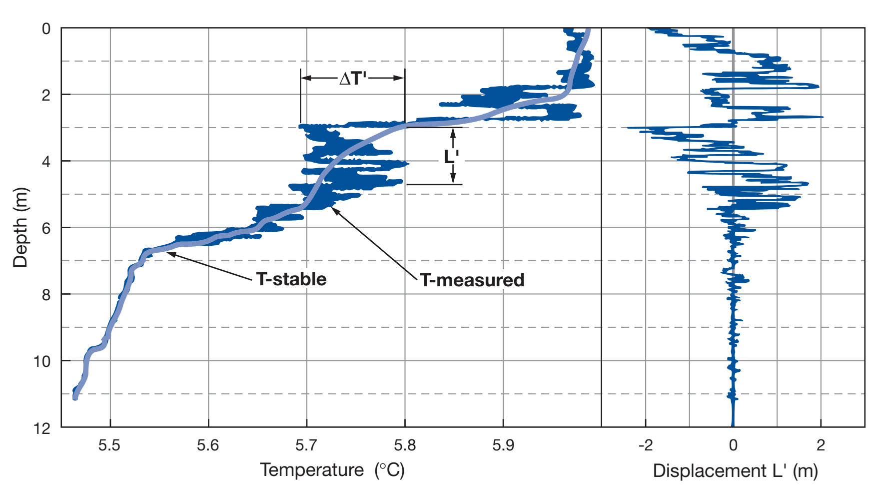

Fig. 1: Temperature profile in Lake Neuchâtel (left, T-measured) and the corresponding excursion profile of vertical displacements (L', on right). The excursions L' reach distances of up to 2 m relative to the stable equilibrium position (no turbulence; left, T-stable). The temperature variations ΔT' are created by turbulent mixing of neighboring water parcels of differing temperature.

Symbol	Property	Typical Range
$\Delta T'$	Temperature variations (local) in lakes	0.0001 to 0.1 °C
K_v	Vertical turbulent diffusivity (mixing rate $K_v = w' \cdot L'$)	10^{-7} to 10^{-4} $m^2 s^{-1}$
K_T	Molecular diffusivity (temperature)	$1.4 \cdot 10^{-7}$ $m^2 s^{-1}$
K_S	Molecular diffusivity of solutes	around 10^{-9} $m^2 s^{-1}$
L'	Vertical site of eddies	cm to several m
w'	Vertical velocity of eddies ($w' = (\varepsilon/N)^{1/2}$)	0.01 to 10 cm s^{-1}
ε	Dissipation of turbulent energy into heat	10^{-11} to 10^{-6} W kg^{-1}
N^2	Stability of the water column ($N^2 = -1/\rho \cdot \partial\rho/\partial z$)	10^{-9} to 10^{-2} s^{-2}

Table 1: Range of turbulent properties in stratified natural waters.

The Application

Turbulent diffusion in stratified waters is important in many different ways. In oceans, for example, turbulence influences the fate of climate-controlling gases or of heat transfer between the equator and polar regions. In lakes, turbulence has an impact on the distribution of nutrients and pollutants, algal production, transport of oxygen and other redox parameters, and ultimately impacts the formation of sediments. The measurement of vertical diffusivity in natural waters is rather delicate, since mixing against the stratification occurs slowly and is spatially and temporally very heterogeneous. Figure 1 illustrates how turbulent and inactive zones alternate.

Traditionally, vertical mixing rates have been determined "indirectly" by following the distribution of a tracer over time or via heat budgets. In such an approach, we are only able to observe the integrated result of all turbulent mixing processes. However, it is not possible to identify inactive or particularly turbulent zones nor to determine the mixing intensity at any specific location or point in time. In contrast, direct measurement of temperature microstructures also includes turbulent events and resolves them temporally and spatially. This allowed us, for example, to document the role that the sediment-water interface layer plays in turbulent mixing processes in the hypolimnion of medium and small lakes (Fig. 2) [2]. Measurements in Lake Baikal [3] and in near-shore areas of oceans indicate that, even in large water bodies, processes near the sediments largely control vertical mixing.

Another benefit of this method is that we can examine turbulence under different physical boundary conditions. We are now able to correctly represent and parameterize different physical mixing processes in models and can determine the paths and residence times of mechanical energy. This allows us, for example, to distinguish between wind impact and the effects of cooling – a task which was difficult to achieve using classic tracer methods.

This work has received long-term support from the Swiss National Science Foundation and EAWAG.

Cox number method: **This method compares the gradient of temperature variations $\Delta T'$ (or more precisely, $[\partial T'/\partial z]^2$) to the average gradient $[\partial T/\partial z]^2$. The ratio of these two numbers, the so-called Cox number, is a measure for determining how much larger the turbulent mixing rate compared to the molecular diffusion rate (see Table 1 for typical values) is.**

Dissipation method: **This method uses the information in the fine structure of the measured temperature fluctuations. The more intensive the turbulence, the smaller the eddies can be before they are smoothed out by the viscosity of water. From these smallest structures, we can draw conclusions about the dissipation of turbulent energy (Table 1). Dissipation is the classic measure for the intensity of turbulence in natural systems.**

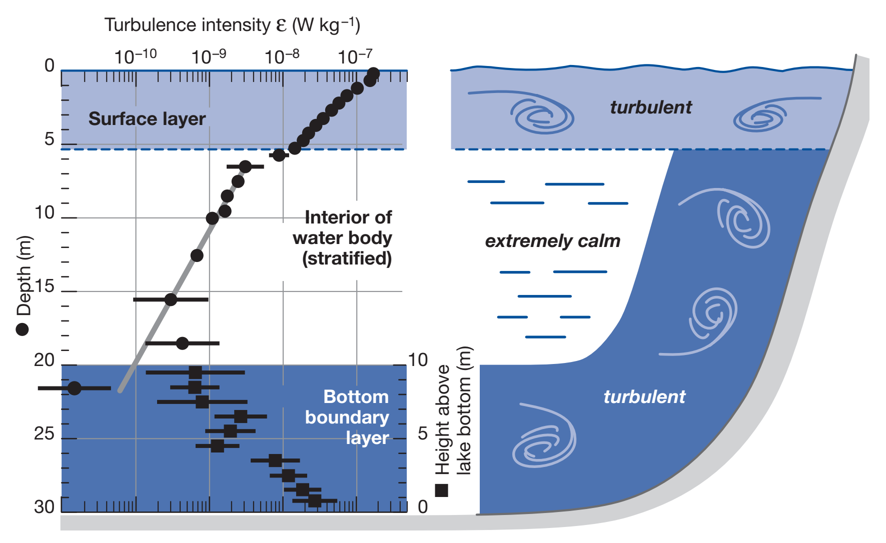

Fig. 2: Typical profile of turbulence intensity in a lake (here: Lake Alpnach). At the surface, turbulent energy is created by direct wind impact and by cooling. Turbulence decreases with depth and is additionally dampened by stratification. In the interior of the water body, conditions are extremely calm. Above the lake bottom, turbulence intensity increases, mostly due to friction with the bottom.

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