FINESTRUCTURE, MICROSTRUCTURE, AND THIN LAYERS

By Thomas Osborn

WE ARE ALL FAMILIAR with the irregular profiles from modern, high resolution conductivity-temperature-depth profilers (commonly called CTDs) freely falling vertical profilers, and towed thermistor chains (Figs. 1 and 2). In fact sufficient resolution was available back in the 1930s with the advent of the Bathythermograph (BT) (Eckart, 1948) and even earlier through the use of the thermocouple (Schmidt, 1914; and Hacker, 1933). Figures 3 and 4 show thin layers of biological material. Fish and copepods which swim can easily form layers, but what about some of the particles which are very small, neutrally buoyant, and only swim slowly, if at all. Are their profiles related to the temperature, density, or their gradients? The easily measured profiles of temperature, salinity, density etc., carry a signature of the relevant physical processes. How much do they tell us about the formation of the biological and chemical layers?

Microstructure refers to the signatures of oceanic turbulence at scales where moleulcar viscosity and diffusion are important. Quantitative measurements at these scales (millimeters to centimeters) provide estimates of the cross-isopycnal diffusion rates. Finestructure is the label for larger features where the stratification limits the motion to the horizontal plane. Signatures of this stirring motion have horizontal scales substantially greater than their vertical scales. Eckart (1948) created the paradigm of stirring and mixing, which shows the significance of the predominantly horizontal flow field, and the boundary conditions, in producing these irregular vertical distributions and layers.

Thin layers are superficially like the physical finestructure features in thickness and extent. This similarity is a result of the density stratification which forces most of the motion to be horizontal and makes sharp vertical gradients out of weak horizontal gradients. In fact, it is useful to consider thin layers as the biochemical equivalent of the finestructure in temperature, salinity, or density, with the caveat that the biological and chemical layers are forced by biochemical processes as well as physical processes. The biochemical processes interact and couple with the physical processes. However, while the coupling of processes may bind the biochemical layers to temperature, salinity, or density layers, it is the vertical shear of the horizontal currents in conjunction with the horizontal gradients that have a major role in forming both thin layers and finestructure. Since the horizontal variations of biological, chemical, and physical parameters can differ significantly, there is no *a*

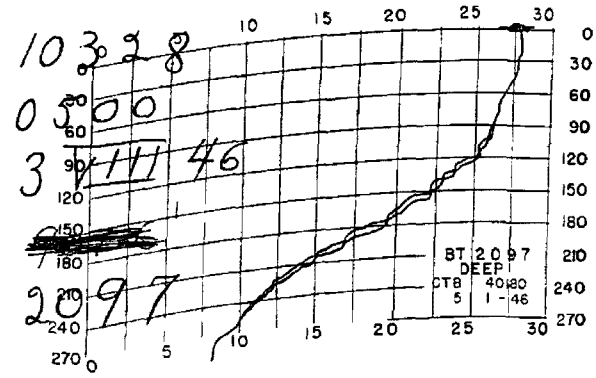

Fig. 1: Bathythermograph trace from Eckart (1948) showing temperature finestructure.

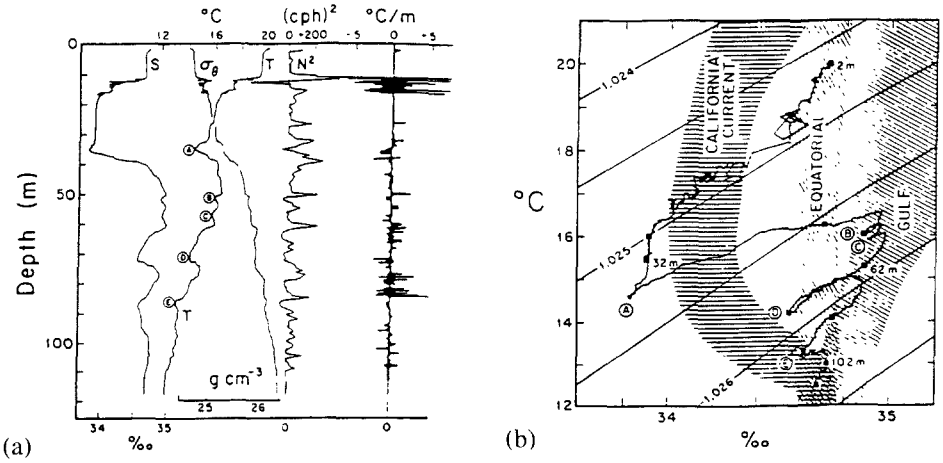

*Fig. 2: (**a**) Temperature, salinity, and potential density averaged over 0.03 m off Cabo San Lucas showing a multitude of intrusions and finestructure features (modified figure from Gregg 1975). N^2 is averaged over ~0.8 m to show the finestructure in the density. The temperature gradient has not been smoothed, showing how the variance is at the microstructure scales and the finestructure is not visible without averaging. (**b**) T-S diagram showing the different water masses in the region that contribute to the vertical profile.*

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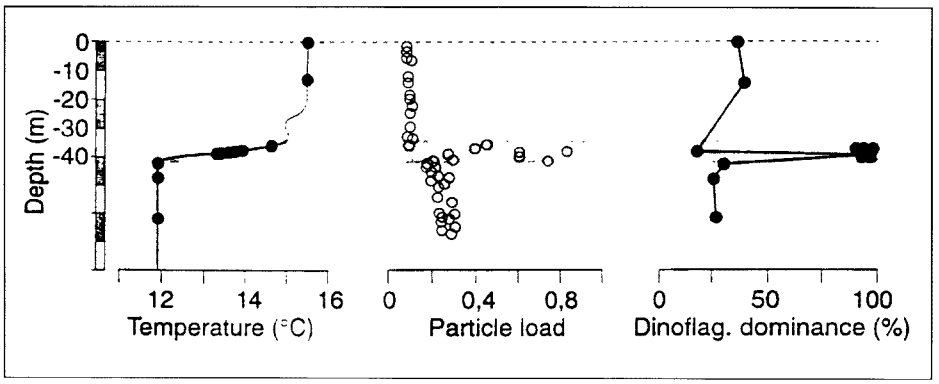

Fig. 3: Vertical profiles of La Rochelle, France, with an in situ particle size profiler after Gentien et al. (1995) showing temperature, particle load, and percentage of dinoflagellates (% total phytoplankton). The closed and open circles are the locations of water samples.

priori reason for thin layers and fine structure features to be firmly locked together. Crucial, first order, measurements include the vertical profile of the horizontal velocity with resolution at the vertical scale of the thin layers and finestructure in conjunction with the variation in horizontal and vertical distributions of the biological, chemical, and physical fields.

Carl Eckart: Stirring and Mixing

In his early and very insightful paper, Eckart related the finestructure in temperature profiles collected with a BT, to the physical processes of stirring and mixing. Stirring of the fluid is accomplished by the spatial variations of the velocity and has two effects (Fig. 5). First, it increases the interfacial area between water parcels with different characteristics, and, second, it increases the property gradients across those interfaces. Both of these effects increase the rate of transport by molecular diffusion. When molecular diffusion smoothes out all the spatial variations, the fluid becomes uniform, i.e., well mixed. Mixing is molecular diffusion removing the inhomogeneities created by the stirring.

Microstructure and Finestructure

Finestructure and microstructure are both signatures of the stirring. Microstructure is at the smallest scales, where molecular viscosity significantly affects the flow, and finestructure at larger scales where stratification is important (Gargett *et al.*, 1984).

Microstructure has scales that range from tens of centimeters downward, and the measurements are usually in terms of derivatives with respect to a spatial coordinate. The variance of the derivatives is concentrated at these scales and, for the case of velocity shear, determines the energy dissipation. Also, at these small scales the effect of stratification is limited, and the flow approaches isotropy. Both the temperature and velocity microstructure measurements produce estimates of the vertical eddy diffusivity (Osborn and Cox, 1972; Osborn, 1980), which compare favorably with direct measurements (Toole *et al.*, 1994; Ledwell *et al.*, 1993). This direct and quantitative application of the microstructure measurements has probably been a major reason why so much effort has been focused on microstructure for the last 25 years.

Finestructure as a term seems to apply to any wiggle or irregularity in a temperature, salinity, or density profile that can be seen by a CTD with vertical resolution of a meter. Fedorov (1978), in the introduction to the English edition of his book, uses the term "fine stratification," and the editor, J.S. Turner, identifies the generally accepted English equivalent as "finestructure." The signatures are interpreted as layers of the water extending much further horizontally than vertically. These features can be generated *in situ* by vertical mixing, they can be the result of intrusions from adjacent water masses, or they can be the ephemeral signatures of internal waves. In any case, they are the result of relative motion in the water. The T-S diagram (a plot of temperature against salinity) is a useful tool in separating intrusive finestructure from the effects of local mixing or internal waves Ochoa (1987).

Finestructure can be identified either by looking at the property directly or at the gradient profile (Grant *et al.*, 1961), if the gradient has been smoothed either by averaging the data or by using a sensor with limited frequency response. Full spectral resolution of the derivative reveals the microstructure scale variations that often obscure the mean trend. In Figure 2 the density profile and the N^2 profile was averaged over 0.8 m vertically and shows the finestructure, while the temperature gradient profile reveals the microstructure. Looking at finestructure with vertical gradient profiles involves an implicit averaging scale. The averaging scale is often not specified because it is "buried" in the details of the observing instrument and its role in how the data appears to the observer may not be appreciated.

Given that finestructure appears in both temperature and "averaged" gradient profiles, we must bear in mind that the two views of the same water are very different. First, an intrusion is usually thicker than its edges, at least the high gradient portion of its boundaries, so that while the temperature trace has one thick intrusion of order ≤10 m, the gradient profile sees two thinner boundaries, on the order of 1 m vertically. Again, Figure 2 has a nice example of a 20 m thick salinity minimum that is much less obvious from the profile of N^2. Second, although finestructure in the temperature and its gradient arise due to spatial variations in the temperature and velocity field, we will see that the way in which these phenomena cause temperature finestructure is not the same manner by which they cause finestructure in the temperature gradient. When we compare biological and chemical thin layers to the finestructure, we must be careful to recognize the different mechanisms for generating the finestructure.

Eckart's Analysis

Eckart started from the heat equation (neglecting solar heating) written in tensor notation (i.e., summation over repeated indices) but no Reynolds' decomposition.

$$\frac{D\vartheta}{Dt} = \kappa \frac{\partial^2 \vartheta}{\partial x_i \partial x_i} \quad \text{with} \quad \frac{D}{Dt} = \frac{\partial}{\partial t} + u_i \frac{\partial}{\partial x_i} \qquad (1)$$

where ϑ is the temperature, κ the molecular diffusivity for heat, i and j(=1, 2, or 3) are indices, x_i are the three coordinate axes (i = 1 is the x axis, i = 2 is the y

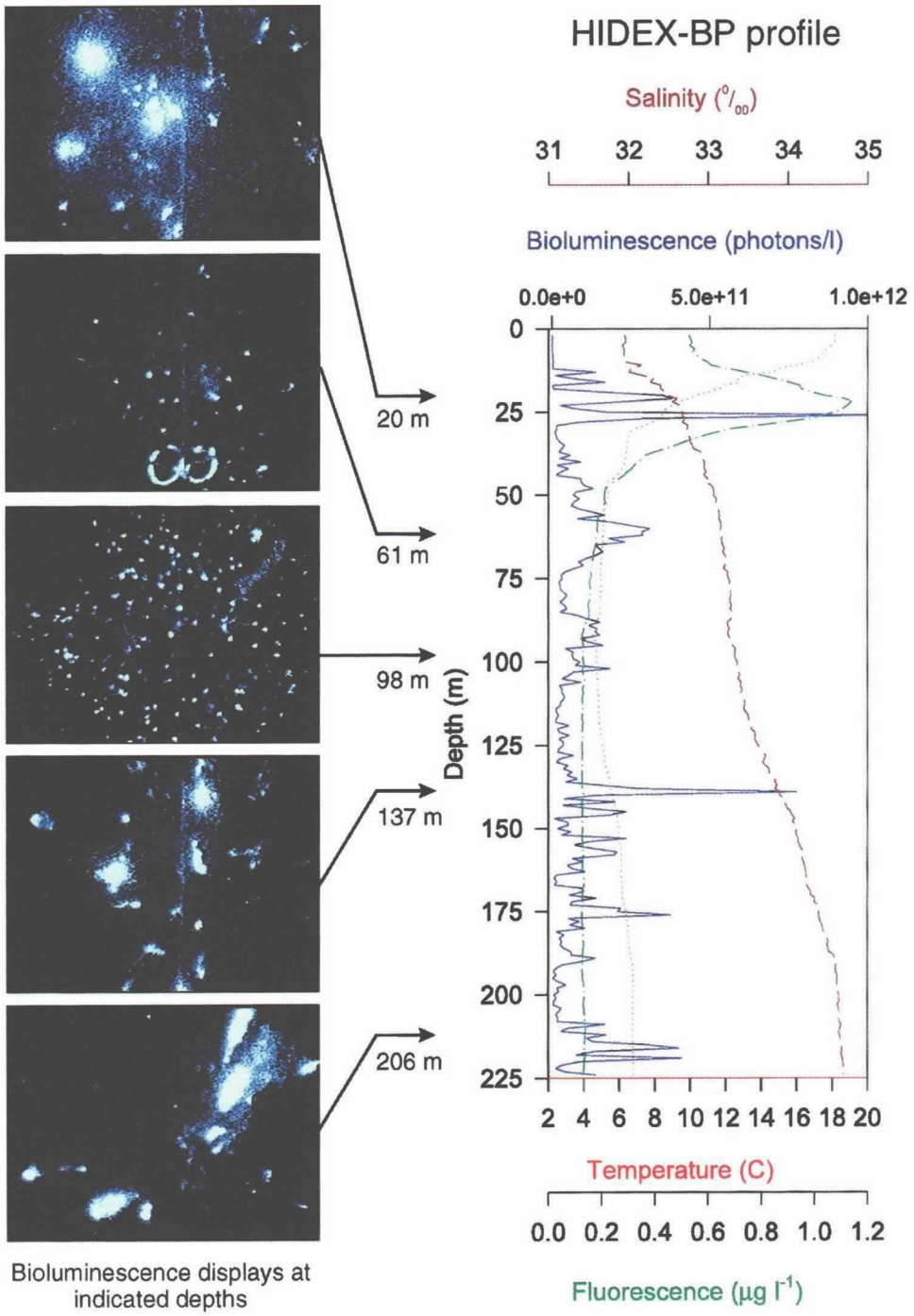

Fig. 4: Profile of bioluminescence from the Gulf of Maine (Widder, 1997). Individual video frames (1 m wide) at the indicated depths show the different displays associated with the peaks in bioluminescence. At 20 and 137 m, the picture is characteristic of copepods. At 61 and 98 m, there are dinoflagellates. At 61 m there is a lobate ctenophore and at 206 m a cydippid ctenophore.

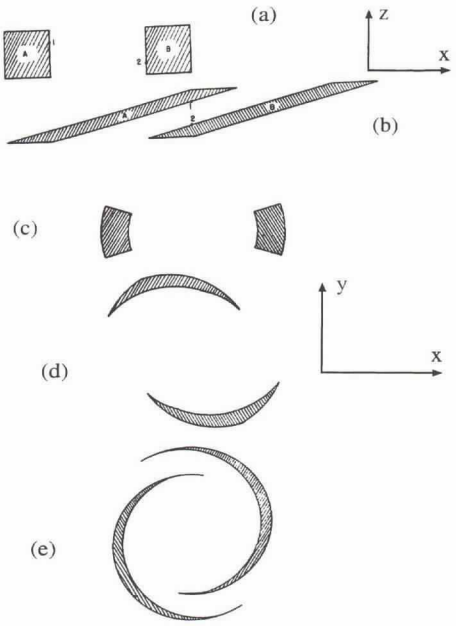

*Fig. 5: Schematic after Eckart (1948) showing (**a** and **b**) the effect of a laminar, vertical shear on two adjacent water parcels. The shear converts a horizontal variation into a strong vertical difference. The stirring increases the gradient and the interfacial area between the parcels. A circular eddy (**c, d,** and **e**) can increase lateral gradients, as long as the motion is not a pure rotation. Given the stratification of the ocean, a circular eddy is likely to be horizontal and may well involve vertical shear.*

axis, and i = 3 is the z axis) and u_i is the water velocity vector (whose components are u_1, u_2, and u_3, which correspond to u, v, and w in regular notation).

Because of the advective term, the gradient operator and the total derivative operator do not commute, but rather:

$$\frac{\partial}{\partial x_j}\frac{D}{Dt} = \frac{D}{Dt}\frac{\partial}{\partial x_j} + \frac{\partial u_i}{\partial x_j}\frac{\partial}{\partial x_i} \qquad (2)$$

and

$$\frac{D}{Dt}\frac{\partial \vartheta}{\partial x_j} = \kappa \frac{\partial}{\partial x_j}\frac{\partial^2 \vartheta}{\partial x_i^2} - \frac{\partial u_i}{\partial x_j}\frac{\partial \vartheta}{\partial x_i}. \qquad (3)$$

Multiplying by the gradient gives:

$$\frac{1}{2}\frac{D}{Dt}\left(\frac{\partial \vartheta}{\partial x_j}\right)^2 = \kappa \frac{\partial}{\partial x_j}\left(\frac{\partial \vartheta}{\partial x_j}\frac{\partial^2 \vartheta}{\partial x_i \partial x_i}\right) - \kappa\left(\frac{\partial^2 \vartheta}{\partial x_i \partial x_i}\right)^2 - \frac{\partial u_i}{\partial x_j}\frac{\partial \vartheta}{\partial x_i}\frac{\partial \vartheta}{\partial x_j}. \qquad (4)$$

Define the following by taking integrals over a volume of fluid.

$$G^2 = \iiint \left(\frac{\partial \vartheta}{\partial x_j}\right)^2 d\tau$$

$$I^2 = \iiint \left(\frac{\partial^2 \vartheta}{\partial x_i \partial x_i}\right)^2 d\tau$$

$$S = \iiint \frac{\partial u_i}{\partial x_j}\frac{\partial \vartheta}{\partial x_i}\frac{\partial \vartheta}{\partial x_j} d\tau \qquad (5)$$

G^2 and I^2 cannot be negative quantities.

As we follow that volume of fluid along its path, the following equation holds:

$$\frac{1}{2}\frac{d}{dt}G^2 = \iint_{\text{boundary}} \hat{r}\cdot\nabla\vartheta \frac{D\vartheta}{Dt} d\sigma - \kappa I^2 - S. \qquad (6)$$

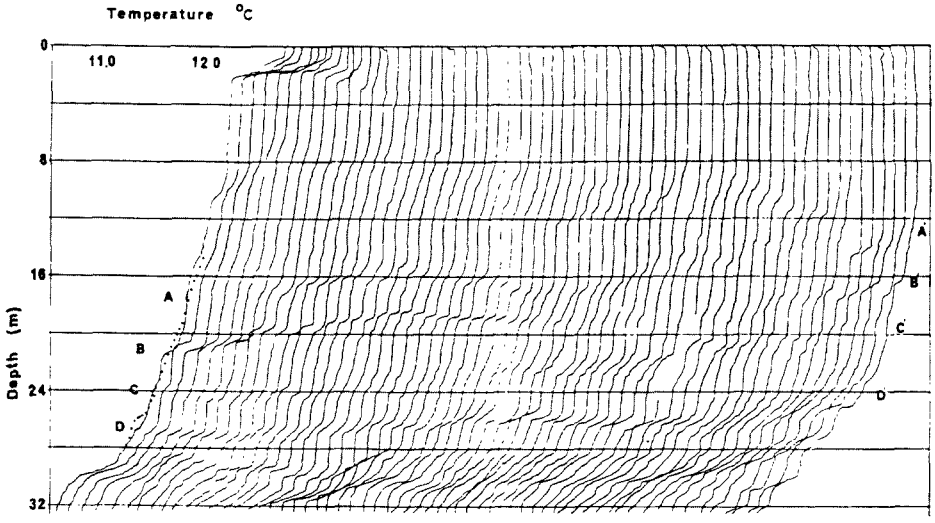

Fig. 6: From Lazier (1973) showing the time variability of the finestructure due to internal waves. The profiles of temperature versus depth have a common depth axis, but each successive profile is displaced to the right by 0.108°C. The dotted line at the left represents the average profile over the 12 h of observation.

where $\hat{r}$ is an outward pointing, unit vector at the boundary.

The magnitude of the gradient can change for three reasons: 1) heat flux *and* temperature change on the boundary, 2) molecular diffusion, and 3) spatial variations in the motion.

Because κ and I^2 are both positive quantities, molecular diffusion cannot increase the magnitude of the gradient. Thus, aside from a combination of a heat flux and temperature change at the boundary, the magnitude of the gradient can only increase due to motion. Interestingly enough, vorticity is not required.

Because,

$$\frac{\partial u_i}{\partial x_j} = \frac{1}{2}\left\{\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right\} + \frac{1}{2}\left\{\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right\} \qquad (7)$$

and the second term, which is half the vorticity, is antisymmetric while the rest of the integrand is symmetric:

$$S = \frac{1}{2}\int\int\int\int \left\{\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right\} \frac{\partial \vartheta}{\partial x_i}\frac{\partial \vartheta}{\partial x_j} d\tau. \qquad (8)$$

Following that derivation, Eckart used a simple example.

At $t = 0$, $\vartheta = ax + bz + c$, and there is only horizontal motion in the x direction.

$$\frac{\partial \vartheta}{\partial t} + u(z)\frac{\partial \vartheta}{\partial x} = \kappa \nabla^2 \vartheta \qquad (9)$$

If we start from a situation like Figure 5, with large enough spatial scale that molecular effects are negligible initially, then the solution to the above equation and boundary conditions is:

$$\vartheta \equiv \vartheta_0 = a[x - u(z)t] + bz + c$$

and

$$\frac{\partial \vartheta}{\partial z} = b - at\frac{\partial u}{\partial z}. \qquad (10)$$

For a while the magnitude of the vertical component of the temperature gradient can increase or decrease, depending on values of a, b, and $\partial u/\partial z$, but eventually the time-dependent term will dominate and the magnitude of the gradient will increase. As the stirring continues and the gradient becomes stronger, the importance of the molecular diffusivity term increases and will, eventually, have to be taken into account. Then the balance will include the destruction of gradient variance by molecular diffusion. Eckart points out that there is no general proof that the magnitude of the gradient will always increase continually, noting that a velocity that oscillates in time would produce a gradient that oscillates in time. A prescient foreshadowing of the reversible finestructure caused by internal waves seen in Figure 6 from Lazier (1973).

The derivation of Eckart's shows that the velocity field and the boundary conditions generate the structure in both the temperature and the temperature gradient profiles. The same derivation also applies to a nonreactive chemical compound, including salinity, the only change being to replace the thermal diffusivity by the appropriate chemical diffusivity. Now we see why in frontal regions the salinity and temperature profiles, and especially their finestructure, don't track each other (e.g., Fig. 2). The T-S relation is a melange of different water types, another way of saying the boundary conditions and horizontal gradients are different for temperature and salinity. Thus, the stirring of velocity field produces different results. An injected patch of dye with a different initial distribution from either the temperature or salinity would also evolve a profile and finestructure that differed from the temperature, salinity, and their gradients. Kullenberg's (1974) experiments show the time development of such dye patches and the effects of shear in creating finestructure layers.

It is important to note that the intrusion of a layer into a vertical profile can occur due to the vertical shear over an extended vertical region rather than advection of just the "intruding layer." Intrusions can appear because of shear, not just by the interleaving of adjacent water bodies. The shear produces layers from what were previously horizontal differences. Given the large amount of velocity shear and the spatial heterogeneity of the coastal ocean, it is not surprising that there is structure in the physical and biological parameters. Intrusions that cross isopycnals (Gregg and McKenzie, 1979) can also arise from shear in a stratified region with large horizontal gradients.

Thin Layer Generation

It is necessary to differentiate between biological thin layers and chemical thin layers composed of reactive compounds. Organisms obey a conservation equation similar to the heat equation but with sources and sinks due to biological processes. They have the possibility of motion relative to the water but lack the molecular diffusion term. Reactive chemical elements also satisfy a slightly different conservation equa-

tion allowing for chemical reactions as well as molecular diffusion (Eckart, 1940). For the sake of simplicity, we will consider the biological layer with the concentration specified as $n = n(x, y, z, t)$ in units of numbers per unit volume. There is summation over the repeated subscripts.

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial x_i}(nV_i) = \gamma \qquad (11)$$

The velocity of the organisms is $V_i = V_i(x, y, z, t)$ (absolute velocity in space, not relative to the water), and γ, is the net rate of production of the species. The velocity of the species relative to the flow is

$$v_i = V_i - u_i. \qquad (12)$$

Here u_i is the water velocity, the same meaning as in the earlier derivation. The relative motion can arise from swimming, sinking/rising due to buoyancy differences, slippage relative to the flow due to inertia, or the effects of finite size leading to relative motion.

The flux of particles relative to the water is

$$J_i = (nv_i). \qquad (13)$$

γ can be written as the sum of two terms, the cell division (birth) rate and the mortality rate. These are frequently written as proportional to the local concentration, although there is no requirement that the factors of proportionality are constant in time or space. Let's define the local production rate of cells = $\mu \cdot n$, and the local mortality rate of cells = $m \cdot n$.

Rearranging and using the equation of continuity $\partial u_i/\partial x_i = 0$.

$$\frac{Dn}{Dt} = \mu \cdot n - m \cdot n - \frac{\partial J_i}{\partial x_i} \qquad (14)$$

There is biological generation and disappearance of organisms, and their motion relative to the water can be convergent or divergent, i.e., $\partial J_i/\partial x_i \neq 0$. Both of these mechanisms lead to local increases or decreases in concentration while following the same patch of water. The only way to have a large group of some species in a given parcel of water is for them to have grown there or to have moved relative to the water. In terms of Eckart's picture of the initial conditions in Figure 5a, that state could be generated by growth and/or aggregation. There is no diffusion of the organisms due to the potentially turbulent water motion because, as in the previous derivation of Eckart, there has been no decomposition of the flow into a "mean and fluctuating part." Therefore, following the flow means tracking the original water parcel no matter how convoluted it becomes. Advection can change the concentration at a fixed location, but it does not change the concentration in a given parcel of water.

The reference frame of a stationary observer, a mooring, a specific vertical profile, or a fixed sampling grid, is on the Eulerian reference frame. Then the time rate of change of the concentration at the fixed point is the partial derivative with respect to time, which in expanded form is:

$$\frac{\partial n}{\partial t} = \mu \cdot n - m \cdot n - \frac{\partial J_x}{\partial x} - \frac{\partial J_y}{\partial y} - \frac{\partial J_z}{\partial z} - u\frac{\partial n}{\partial x} - v\frac{\partial n}{\partial y} - w\frac{\partial n}{\partial z} \qquad (15)$$

The fixed observer is measuring $\partial n/\partial t$ and the advective term, $-u(\partial n/\partial x) - v(\partial n/\partial y) - w(\partial n/\partial z)$, appears to be a "source" of organisms. The profiles in Figures 3 and 4 are in the framework of a fixed observer. The thin layers seen there may have grown *in situ*, be due to aggregation from relative motion, or may be due to the lateral intrusion of water already containing high concentrations of those particles. This lateral intrusion can be accomplished by a sheared flow as shown by Eckart's schematics in Figure 5. A thin layer could also be produced by the erosion of a thicker layer (this would be an advective effect, the carrying away of water and particles) through predation or some other form of enhanced mortality rate. As well, physical processes affect birth rate, mortality, and relative motion. The coupling of physical processes back into biological rates and activities means that μ, m, and the J_is are all functions of position and time, as well as the history of the organism and its environment.

Discussion and Conclusions

Compare equation (15) to the equivalent version of equation (1) and equation (3) written explicitly for the vertical component of the temperature gradient.

$$\frac{\partial \vartheta}{\partial t} = \kappa\left(\frac{\partial^2 \vartheta}{\partial x^2} + \frac{\partial^2 \vartheta}{\partial y^2} + \frac{\partial^2 \vartheta}{\partial z^2}\right) - u\frac{\partial \vartheta}{\partial x} - v\frac{\partial \vartheta}{\partial y} - w\frac{\partial \vartheta}{\partial z} \qquad (16)$$

and

$$\frac{\partial}{\partial t}\left(\frac{\partial \vartheta}{\partial z}\right) = \kappa\left[\frac{\partial^2\left(\frac{\partial \vartheta}{\partial z}\right)}{\partial x^2} + \frac{\partial^2\left(\frac{\partial \vartheta}{\partial z}\right)}{\partial y^2} + \frac{\partial^2\left(\frac{\partial \vartheta}{\partial z}\right)}{\partial z^2}\right] - \frac{\partial u}{\partial z}\frac{\partial \vartheta}{\partial x} - \frac{\partial v}{\partial z}\frac{\partial \vartheta}{\partial y} - \frac{\partial w}{\partial z}\frac{\partial \vartheta}{\partial z} - u\frac{\partial\left(\frac{\partial \vartheta}{\partial z}\right)}{\partial x} - v\frac{\partial\left(\frac{\partial \vartheta}{\partial z}\right)}{\partial y} - w\frac{\partial\left(\frac{\partial \vartheta}{\partial z}\right)}{\partial z} \qquad (17)$$

The temperature changes because of molecular diffusion and advection while the vertical component of the temperature gradient has comparable terms plus the additional one due to the shearing of the velocity. The equation for the time development of the density of organisms (Eq. 15) looks much like the temperature equation, without molecular diffusion, but with the addition of birth, mortality, and relative motion. Thus the distribution of temperature, salinity, their gradients, and biological concentrations are all strongly affected by the local, time-dependent, velocity distribution as well as the large scale sources and sinks for temporal and spatial variability (e.g., fronts, river discharge, storms). It is appropriate to think of thin layers as "biological finestructure" because there is the strong role of the advection, but we must also bear in mind the dissimilar aspects of the source and sink terms.

All three equations contain advection. The temperature and temperature gradient equations also contain a molecular diffusion term. There is no term comparable with molecular diffusion in the particle equation because there is no requirement for the biological concentration to diffuse at the molecular level. However, the equation for biological concentrations contains a divergence term, $\partial J_i/\partial x_i$, which has a similar mathematical form to the heat flux but with no constraint that the flux be down gradient because the biological term involves behavior. The temperature gradient equation contains terms involving products of the velocity and temperature derivatives. These terms can generate or remove finestructure.

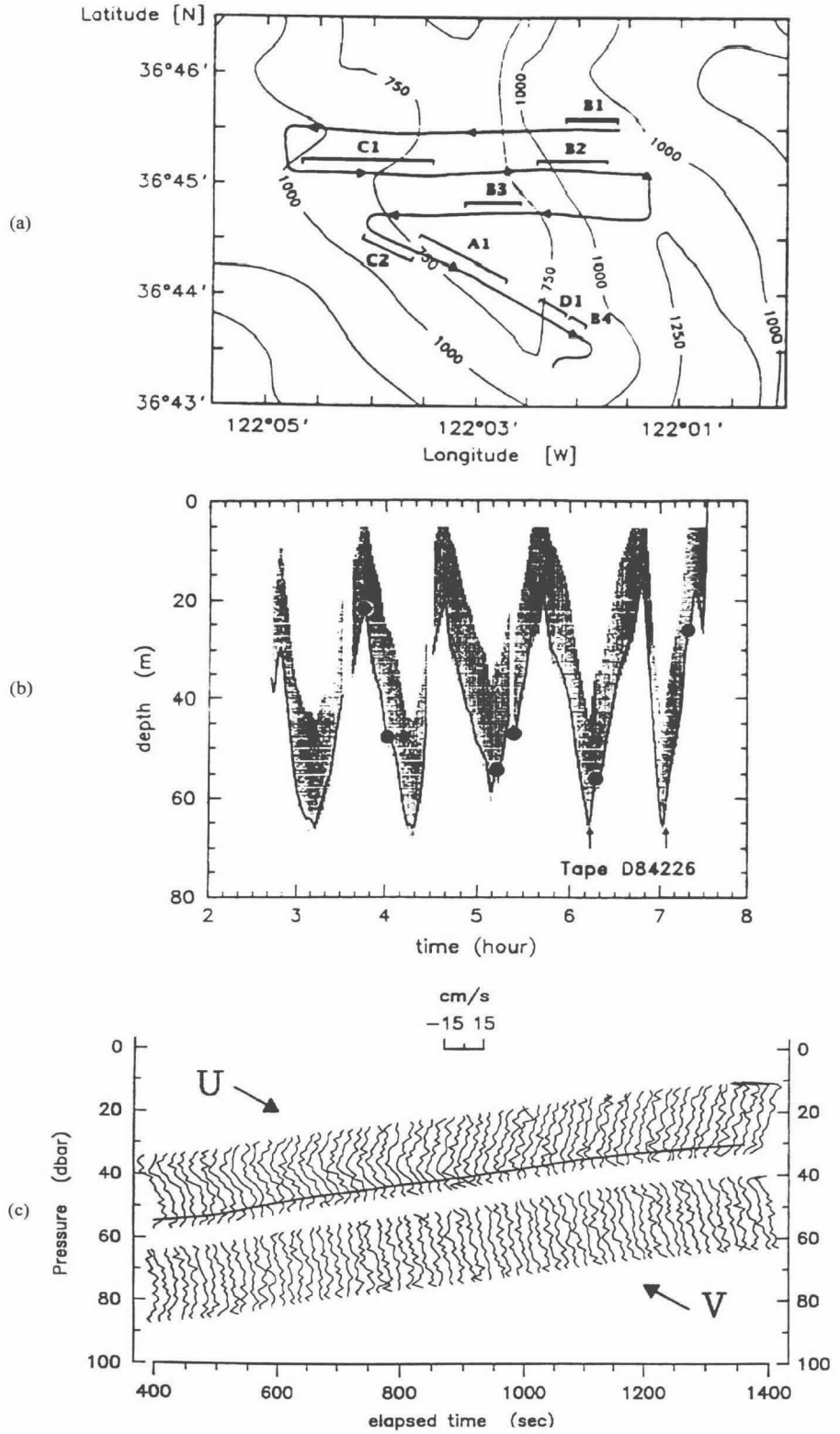

*Fig. 7: (**a**) Track pattern of the submarine Dolphin in Monterey Bay. The labeled brackets refer to different shear layers. (**b**) Pressure profile during the dive. The filled circles correspond to changes in heading shown in **a**. The shaded region indicates the range of the acoustic Doppler profiler. (**c**) Time series of 15-s average velocity profiles with a 1-m vertical sample interval, for the rising portion of the southeastward leg in **a**. The horizontal axis is elapsed time. U is along the axis of the submarine, and V is perpendicular to the axis of the vessel. The U profiles are plotted at the correct depth, whereas the V profiles have been shifted down 30 m for clarity of the display. Note the extensive shear apparent in the U velocity component from the start of the record to time 950 s (from Itsweire et al., 1989). This shear layer is labeled C2 in **a**.*

The particle equation contains birth and mortality, which do not appear in the temperature gradient equation. Because these terms represent a source/sink in the interior of the volume of the fluid, they are mathematically similar to the terms for the generation/destruction of finestructure by shear in the temperature gradient equation. Again, however, they have a large behavioral component and are not just a signature of the physical processes. As well, the source/sink need not be spatially co-located with the generation of temperature gradient finestructure.

Because the effect of the advection depends on the velocity field and the distribution of the concentration (temperature, salinity, density, or particles), there is no *a priori* reason why the temperature/salinity/density finestructure or their gradient finestructure should line up with the finestructure of biological layers. Some alignment is inevitable because both are subject to the same velocity field, which is dominantly horizontal. But the fact that the physical and biological/chemical parameters are layered does not mean that the layers actually coincide. It is even more difficult to see why a nonswimming organism (or a chemical species) would align with the gradient finestructure, because there are significantly different source terms for the different features. Detailed resolution of the shear versus depth with resolution comparable with, or better than, the scales of the thin layers and finestructure is crucial.

The preceding analyses avoided the question of "turbulent diffusion" and the possible destruction of finestructure and thin layers by turbulent mixing. Such an analysis is possible (Donaghay and Osborn, 1997). It produces additional divergence terms (arising from the advective terms) in equation (15), which would spread the layer, depending on the spatial distribution of the turbulence relative to the layer or finestructure. Turbulent diffusion can be incorporated into equations (16) and (17) by increasing the molecular diffusivity. However, that analysis is pushing the theoretical framework because the motion that produces the microstructure and finestructure is the turbulent mixing. When we consider all these processes, there is no longer the separation of scale necessary for the Reynolds decomposition into mean and fluctuating

parts. Work on thin layers and finestructure brings us into the temporal and spatial scales where the streakiness of the horizontal stretching and the cross-isopycnal (essentially/almost vertical) transport by the turbulence are active and interactive. Again, we are asking, how does the velocity field interact with the vertical and horizontal distribution of the other parameters in the water column?

If, as Eckart's paradigm suggests, shear is the forcing for much finestructure and thin layers, where does it come from? Two important sources are tidal currents and inertial currents. In coastal waters, these motions are sheared and rotate their direction with time, which makes it unlikely that they produce reversible finestructure. Itsweire and Osborne (1988) and Itsweire *et al.* (1989) observed layers ≥10 m thick where the shear exceeded 10^{-2} s^{-1}, and rotated in the horizontal plane at the local inertial frequency (Fig. 7). In such a flow, points that start initially with only a vertical separation of 10 m, will be 1 km apart horizontally in just 3 hours. Those shear layers were probably some form of near-inertial motion, and therefore the shear propagated vertically and horizontally. As such, it could generate finestructure features at different depths as it moved through the water column. Information about the spatial and temporal distribution of the vertical velocity shear in the water column at the vertical scales of thin layers and finestructure is difficult to procure. Ship-mounted acoustic doppler current profilers (ADCPs) with sufficient resolution for those shear layers haven't had sufficient range to reach below the upper layer. Surface waves induce significant vertical displacement of the vessel. Moorings give a time series but don't show the spatial distribution. Technological developments are improving the situation, but the measurements are still sparse.

If we consider the index of papers in the *Journal of Physical Oceanography* since its inception, the relative dearth of papers on finestructure compared with microstructure is striking. I would suggest this situation is due to the combination of observational difficulty and the lack of a quantitative structure for the application of the results. I know from personal experience that it is much easier to make and operate one microstructure instrument than to produce and operate simultaneously several finestructure profilers. Thermistor chains, which give beautiful two-dimensional cuts through the ocean, are also very difficult to produce, calibrate, and operate (Mack, 1989).

Thin layers and finestructure are difficult to sample and resolve, given their three-dimensional and highly time-dependent nature. A good description of thin layers is needed. We need to have a good three-dimensional description and to compare and contrast measurements of the fine-scale physical processes at the same time in order to ascertain the spatial distributions and the interrelationships between the biological fields, the physical/chemical fields, the local advection, and turbulence. This is a first step in identifying the processes and interactions. What are the temporal and spatial scales?

1) *Vertical scales.* How thin are the layers? Although this question is easy to ask and seems appropriate for descriptive purposes, great care must be taken that it is approached in an appropriate context. One of the early questions about finestructure was how thin do the layers become. The answer is that the layers become thinner and thinner as you look more closely, but the dynamics also become different. Somewhere below the 1-m vertical scale, the phenomena becomes small-scale turbulence and not the lateral layers with aspect ratio on the order of 1,000 that were being studied. One is easily sucked down this path because it is the same measurement (usually temperature gradient), and so you naturally think it is the same process as one goes to finer and finer scales.

2) *Horizontal scales.* How far do thin layers extend? Are they continuous, or do they have holes or are just broken into quasi-continuous patches? What are the growth and mortality rates? How are the distributions related to the density profile, the temperature profile, finestructure features, and the occurrence of turbulence?

3) *Time scales.* How long do they last? Are they related to tidal and inertial processes. How quickly do they form? Short time scales (in a Lagrangian framework) suggest aggregation over growth.

4) *Stratification.* How are thin layers related to the density surfaces? Do they cross density surfaces? Are some thin layers examples of the accumulation of particles at density interfaces?

The fascinating measurements by Kullenberg (1974) show the variability of the signatures from the spreading and layering of dye patches. Due to the passive nature of the dye, this variability arises from physical processes alone. When biological processes combine and interact with this situation, there will be strong coupling between the physical, biological, and chemical processes. Turbulence affects organisms directly through their survival rates, reproduction rates, feeding rates, and predation rates. Internal waves and convection in the upper layer affect the light history and growth of phytoplankton by advecting them into, and out of, favorable environments. When looking at the dynamics of thin layers, it will be important to relate the growth and mortality of the organisms to the basic physical parameters. These include not just temperature, light, and nutrients, but also local turbulence levels and history, local shear, and internal wave activity, as well as the mean circulation. The coupling of biological and physical processes will be rich.

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