OCEAN SCIENCE

Biomixing of the Oceans?

Although the idea that small swimming organisms could change the ocean's circulation has attracted attention, their movements do not cause enough mixing.

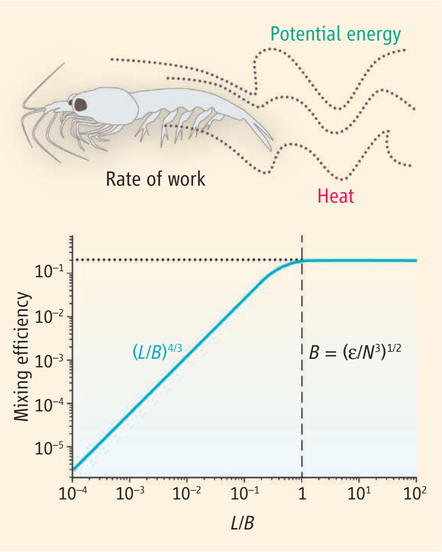
André W. Visser

Every now and then, an idea comes along that is so appealing, it seems bad manners to challenge it. Biomixing—the action of swimming organisms in mixing the world's oceans—is one such idea that has gained recent purchase. If correct, biomixing has far-reaching consequences for our understanding of the oceans. But can swimming organisms actually achieve significant mixing? Central to this question is their mixing efficiency.

Biomixing is certainly an engaging notion. For instance, at the global scale, it suggests that billions of small organisms paddling away in the deep oceans stir cold deep water upward, thus contributing to global circulation (*1*) and climate. At more local scales, it suggests that schools of krill and other marine animals (*2*) plough the thermocline, mixing nutrient-rich water upward and thereby fertilizing their own feeding grounds. Swimming organisms do seem to dissipate substantial amounts of mechanical energy. There are even observations showing considerably elevated dissipation rates in the wake of a migrating school of krill (*3*). The case for biomixing thus seems to be compelling.

However, in these studies, the dissipation of mechanical energy is equated with mixing. Yet, most of the biomixing is purportedly achieved by small but numerous zooplankton with diameters of 1 cm or less. Can mechanical energy at these small scales achieve any substantial mixing (that is, increase the potential energy of the water column) before it is dissipated as heat?

Turbulence in the oceans is generated by a variety of mechanisms, including tides, winds, and swimming animals. It cascades energy from large scales to ever smaller scales, where it is eventually dissipated. Turbulence is effective in mixing because it is active over a range of scales; stretching and folding of the fluid at large scales facilitates molecular diffusion at smaller scales.



The efficiency of mixing. (**Top**) The turbulent kinetic energy generated by a swimming animal dissipates either as heat or in increasing the potential energy of a stratified water column. (**Bottom**) The mixing efficiency Γ (that is, the proportion of kinetic energy that goes into potential-energy increase) is a function of the integral length scale *L* and the buoyancy length scale *B*. For a swimming animal, *L* is the size of the animal itself. Small animals tend to be much less efficient at mixing than larger animals, depending on the ratio *L*/*B*. For animals of a given size (that is, *L*), mixing efficiency decreases as dissipation rate increases, either because individual animals swim faster or because they aggregate in denser assemblages.

The efficiency of turbulence in mixing a stratified water column is expressed by Γ, the ratio of the change in potential energy to the work done. Mixing efficiency is controlled by three parameters: the integral frequency *L* (the scale at which turbulent kinetic energy is imparted to the flow), the rate of turbulent energy dissipation ε (equivalent to the rate of work done), and the buoyancy length scale *N* (a measure of the stratification of the water column). The latter two parameters can be conveniently combined as the buoyancy length scale $B = (\varepsilon/N^3)^{1/2}$. Theoretical considerations (*4*, *5*) and observations (*6*, *7*) indicate that when $L \geq B$, the mixing efficiency is at its maximum. However, when $L < B$, the mixing efficiency can be orders of magnitude less (see the figure).

The net dissipation rate due to an assemblage of swimming organisms depends on the power expended per individual and the number of individuals per unit volume (*2*). Thus, the dissipation rate ε of a school of krill—assuming a body length of 1 to 1.5 cm, a swimming speed of 5 to 10 cm s^{-1}, and a number density of 5000 individuals m^{-3}—is equal to 10^{-5} to 10^{-4} W kg^{-1}, consistent with observations (*3*). How much mixing does this represent?

An organism of a given body size λ cannot inject energy into a flow at length scales larger than itself. Thus $L \approx \lambda$, consistent with observations for grid-generated turbulence (*8*). The buoyancy frequency for the surface ocean is typically 10^{-2} s^{-1} or less, so that the buoyancy length scale associated with the above measurements is 3 to 10 m, and the corresponding mixing efficiency $\Gamma = 10^{-4}$ to 10^{-2}. Hence, only 1% at most of the mechanical energy dissipated by the swimming school of krill and other marine animals actually goes into mixing. The dissipation rate measured in the wake of a dense assemblage of swimming organisms may indeed be considerably higher than that associated with oceanic turbulence, but it does not necessarily follow that the corresponding mixing is also proportionally higher.

The case for biomixing as an important component of the meridional overturning circulation is fraught with the same problem. Considering tides and winds alone, there is an apparent shortfall of ~1 TW in the energy budget driving this circulation (*9*, *10*). The oceanic biosphere captures solar energy at a rate of ~63 TW (*1*, *11*). If only a small percentage of this captured solar energy makes its way into mechanical energy of swimming, the energy budget can apparently be closed. One terawatt corresponds to an average dissipation rate of 10^{-9} W kg^{-1} in the deep oceans, where the buoyancy frequency is typically 10^{-3} s^{-1} or less (*12*). Thus, a mean buoyancy length scale for the deep ocean is 1 m or greater. However, most of the biomass of the oceans is concentrated in small organisms such as copepods ($\lambda \approx 1$ mm). The efficiency of these organisms in mixing is only 10^{-3}. It is only when one comes to larger, but much less abundant, organisms, such as fish and marine mammals, that the mixing efficiency approaches its maximum.

Dissipation is the end product of turbulence. It is also the most readily measured turbulence parameter in the ocean. However, important aspects of turbulence—such as mixing—also depend on the larger scales of

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turbulent motion (*13*, *14*). By whatever means one approaches the calculation of biomixing of the oceans, one will always be confronted by the fact that the mixing efficiency of small organisms is extremely low. Most of the mechanical energy they impart to the oceans is dissipated almost immediately as heat. There may be a case to be made for biomixing by larger animals on a local scale, but their relatively low abundance means that they are unlikely to be important contributors to global circulation.

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5. The rate at which potential energy increases due to turbulent mixing is KN^2, where K is the turbulent diffusivity. The ratio KN^2/ε defines the mixing efficiency Γ, the fraction of total energy that goes into mixing. The remaining $(1 - \Gamma)\varepsilon$ is the rate at which turbulent kinetic energy is dissipated as heat, and an energy balance requires that $\varepsilon = KN^2 + (1 - \Gamma)\varepsilon$. Turbulent diffusivity can be estimated from Richardson's law, $K \approx [(1 - \Gamma)\varepsilon L^4]^{1/3}$. The form of the mixing efficiency as a function of the integral length scale L and the buoyancy scale $B = (\varepsilon/N^3)^{1/2}$ thus follows: $\Gamma \approx \Gamma_0$ for $L \geq B$, and $\Gamma \approx (L/B)^{4/3}$ for $L < B$. Theoretically, Γ_0 can approach 1, although observations indicate that it is close to 0.2 (*15, 16*).
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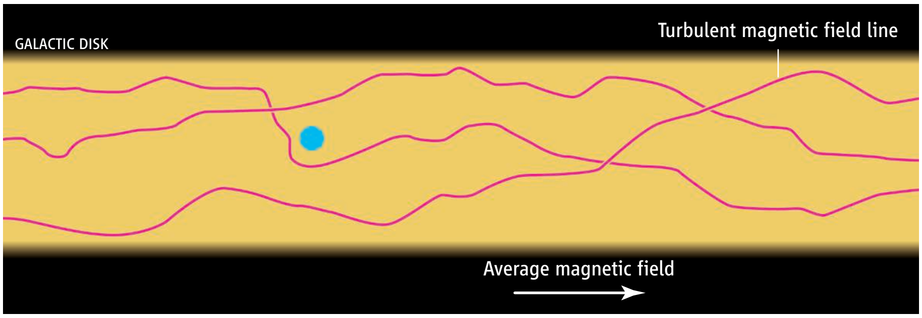
PLANETARY SCIENCE

A Local Wiggle in the Turbulent Interstellar Magnetic Field

Conflicting measurements of the magnetic field outside the solar system now make sense.

J. R. Jokipii

Recent observations, both remotely and in situ with the Voyager space probes, are clearing away some of the mystery about the interstellar magnetic field that lies just outside the solar system. On page 875 of this issue, Opher *et al.* (*1*) report a new analysis showing that previous measurements of the field (*2*, *3*), initially indicating quite different fields, are in fact consistent with each other [also suggested by Gurnett *et al.* (*4*)]. Also, it now seems clear that the very local interstellar magnetic field points in a quite different direction from that obtained from numerous previous ground-based measurements, which were averages over large distances. This discrepancy can now be understood as a natural consequence of fluid turbulence in the interstellar medium, in which the magnetic-field direction changes dramatically over shorter scales than could be measured previously. The insights gained will help researchers better understand the interstellar medium and the nature of its interaction with the plasma environment around the Sun.



Local disturbance. Schematic illustration of the braided and intertwined turbulent interstellar magnetic field. The average magnetic field is parallel to the plane of the galactic disk, and the filled blue circle represents the heliosphere, where the local magnetic field has a pronounced deviation from the average.

A stream of ionized particles—the solar wind—is continuously emitted by the Sun and has carved out a bubble in the interstellar plasma, called the heliosphere, which extends outward from the Sun more than 100 astronomical units (AU) (1 AU is the distance from the Sun to Earth) in all directions. The ionized regions of the interstellar gas and its magnetic field are largely excluded from this bubble. This local interstellar magnetic field, immediately outside of the heliosphere, is an important factor in determining the interaction of the interstellar medium with the heliosphere. The interaction determines, among other things, the effects of the heliosphere on the galactic cosmic rays, an important part of Earth's environment in space.

Until recently, observations of the interstellar plasma and magnetic field were restricted to effects averaged over long lines of sight to distant objects, corresponding to spatial scales of tens of parsecs (1 parsec, or pc, is 3×10^{18} cm, or 200,000 AU), more than a thousand times the scale of the heliosphere. These observations yielded accurate information about the interstellar plasma and the magnitude and direction of the magnetic field, but the spatial resolution was limited by the averaging to scales of several parsecs or more (*5*).

From these measurements, the magnetic field was found to be approximately in the galactic plane, along a spiral arm. However, there is a complication: The interstellar medium is turbulent, with pronounced fluctuations of fluid parameters such as density, with a coherence scale (typical scale of the largest fluctuations in the turbulence) on the order of 1 to 10 pc (*6*, *7*). Because the interstellar plasma is a hydromagnetic fluid, there is no electric field in the frame of the fluid and the magnetic field is dragged with the plasma motions. As a result, plasma flows and magnetic field should vary on similar scales.

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