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Turbulence in the Environment: Why should we Care?

Turbulence in fluids and plasmas is one of the least understood topics in classical continuum physics. The problem is inherently related to chaotic, randomly varying flows, and a simple visual inspection of one single realization might indicate that any attempt to make a nontrivial prediction will be futile. Figure 1 shows an illustrative experiment, where turbulence develops at injection of a high speed "jet" into quiescent surroundings. It came as a surprise when it was demonstrated in the beginning of the 1940-ies that accurate and surprisingly simple analytical expressions could be obtained for some basic statistical averages. For neutral flows, the interest was first concentrated on the *structure functions*, describing some average properties of the spatial velocity variations. These analytical predictions were verified experimentally to a good level of accuracy.

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In spite of significant progress in the studies of turbulence in neutral flows (in water, the atmosphere, etc.), there are still several basic problems, which are not fully understood. As far as plasmas are concerned (i.e. gases composed of charged particles) the situation is even more unfavourable. In this case the sensitivity of the gas to electric and magnetic forces adds to the complexity of the problem, and progress has only been made by significant simplifications, which are not always justifiable. It is, however, important that we improve our understanding of turbulent plasmas, since most of the matter on astrophysical and heliospheric scales is in the plasma state, and is often found to be strongly turbulent.

One of the most important properties of turbulent fluctuations in fluids as well as plasmas is their ability to

Figure 1. The figure shows results from a laboratory experiment with a "jet", where an energetic fluid beam is injected from a localized region in the system. The evolution of a random, turbulent flow is evident, as the injected material propagates at high speed from bottom to top in the figure. Note that the turbulence is manifested in the form of many vortex-like structures, with widely differing scales. Strong turbulence is characterized by having substantial energy distributed over scales of many different sizes.

disperse particles at an anomalously large rate. It is easily demonstrated that in the atmosphere, for instance, the diffusion due to thermal fluctuations is totally negligible. Pollution due to the dispersal of industrial waste would not pose any significant problem, if we had to be concerned with only this mechanism for long distance dispersal of contaminants. Unfortunately, at least in this respect, the atmosphere is usually in a turbulent state, and the turbulent motions are very effective in dispersing particles. Similar observations apply to matter in the plasma state. This implies, for instance, that boundaries in space are maintained only to the extent allowed by the "smoothing out" due to turbulent transport. Magnetized plasmas pose here a particularly important problem: at least under ideal conditions, it should be possible to confine hot dilute plasmas indefinitely by magnetic fields. The fact that turbulent electric fields are transporting plasma across magnetic field lines poses a serious problem for plasma confinement. From a technical point of view, it is expected that turbulent transport across magnetic field lines constitutes the ultimate limitation for confinement of hot plasmas in magnetic fusion experiments, and a number of turbulence related problems have been intensively studied in that context. It has also been found that the conductivity of plasma is controlled by turbulence. This latter problem has been studied even less than turbulent transport, but it is expected to be central for the understanding of the large scale current systems associated with the Earth's magnetosphere.

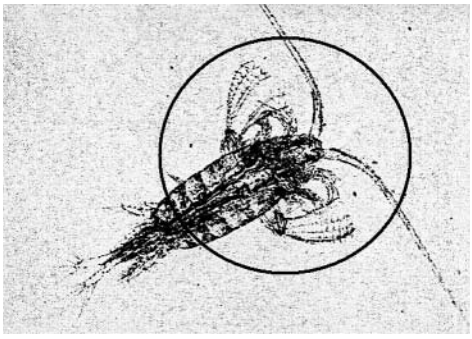

Figure 2. We show here as an illustration "Centopages violaceus", a marine-planktonic copepod. Surrounding it, we might draw a circle, with radius R, illustrating an imagined sphere of influence, with the implication that any prey entering this sphere can be captured.

As an illustrative example for demonstrating the importance of turbulence in the environment, we discuss here the case of aquatic micro-organisms. It is well known that micro organisms in the oceans have very little motion of their own, and can be seen as small particles passively carried along with the local flow velocity. Their food (plankton etc.) is also passively convected by the flows in the environment. In quiet waters, micro-organisms (fish larvae and similar) will therefore be starving because no food enters their immediate vicinity, unless there is a "mixing", which changes the relative distances between predator and prey. The only effective agency for mixing in the environment is turbulent motion. Turbulence is therefore very important for the feeding processes of micro organisms, and studies of the problem of turbulent transport are consequently a mainstream activity in biological sciences. From a mathematical point of view, this problem becomes interesting by involving an "active" boundary, here being the surface of the sphere and having the "reach" of the micro organism as a radius (see Figure 2). This is in contrast to the more standard problem with open systems. This active boundary can here be seen as a perfect absorber, in the sense that we can expect the micro-organism to capture and digest food particles that come within its reach.

Some basic results can be argued by simple dimensional reasoning: We can thus state that the flux, $\mathcal{J}$, to the surface of interception is measured in units of prey pr. time unit. The density of prey, $\mathcal{N}$, is not a significant parameter, since by doubling the prey density we simply double the prey flux. We are thus lead to consider the quantity $\mathcal{J}/\mathcal{N}$, which is measured in units of *length³/time*, but it is up to the observer to decide what the actual units for length and time are. For length, we can take the radius, R, in the sphere of interception, which is the only natural length scale for the problem, as long as R is larger than scales where viscous dissipation is important (for most relevant problems approximately 0.1 – 0.2 mm), while at the same time R is much smaller than the largest structures characterising the turbulence. The relevant time scale must somehow depend on the intensity of the turbulence: with the expectations outlined before, nothing happens without turbulence, and the corresponding time scale is infinite! Turbulence is best characterized by its energy supply, ε, which is defined here as the energy dissipated pr. gram fluid pr. time unit. Now, the units of ε are *length²/time³*, and the only way we can construct a unit of time is by the combination $(R^2/\varepsilon)^{1/3}$. Consequently, we expect that we can write the normalized flux as $\mathcal{J}/\mathcal{N}=R^{7/3}\,\varepsilon^{1/3} f(\,t\,(\varepsilon/R^2)^{1/3})$, with f being a dimensionless function of a dimensionless time-variable. We do not know the function f, but might argue that it approaches a constant for $t \rightarrow \infty$. This conjecture is reasonable from a physical point of view, and it can be tested experimentally. Since f was dimensionless, its asymptotic value is just a universal number, and the parameter variation of $\mathcal{J}/\mathcal{N}$ is then given by the coefficient $R^{7/3}\,\varepsilon^{1/3}$. This scaling law has found experimental support, see Figure 3. It predicts, maybe somewhat unexpectedly, that in order to double the prey flux to an aquatic micro-organism, the energy to the turbulence must be increased eightfold! On the other hand, by doubling its reach, a micro-organism gains more than the factor of four increase in the surface of it sphere of interception, which would only give $R^2 \equiv R^{6/3}$, so the last factor $R^{1/3}$ is gained due to the distribution of energy in the turbulent scales.

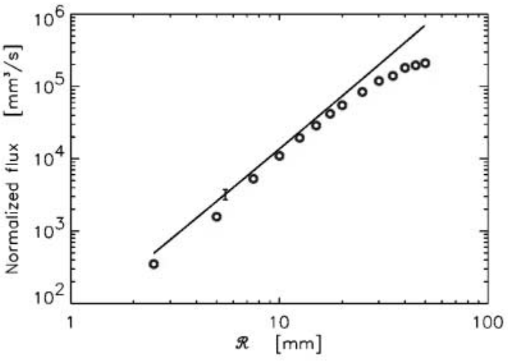

Figure 3. Experimental results from a model laboratory experiment, where the role of micro organisms is taken by small polystyrene spheres. The circles indicate the observed average particle fluxes to a representative "predator", as a function of its "reach" R on a double logarithmic scale. The full line gives the theoretical $R^{7/3}$ result.

This simple model problem (yet important in nature) can, however, also illustrate one of the central, and for the time being not fully resolved, problems in studies of turbulence. We have thus implicitly assumed that

EVERY predator was exposed to the same fluctuation level, as accounted for by ε. This is of course not correct: it is easily verified that some regions of space have enhanced levels of turbulent fluctuations, other smaller, and that the distribution of these regions varies randomly with time. When we take the appropriate averages, we have made an approximation which is unaccounted for, by implicitly replacing ε by its average $\langle\varepsilon\rangle$. In other words: for a dimensional analysis as the one advocated before, we have both $\langle\varepsilon^{1/3}\rangle$ and $\langle\varepsilon\rangle^{1/3}$ being dimensionally correct (here, $\langle\ \rangle$ denotes statistical averages), but with ε being a randomly varying quantity, the two quantities are of course different. Experience shows that the approximation obtained by identifying ε by $\langle\varepsilon\rangle$ works well in practice for the present class of problems, but it is nonetheless a flaw in the analysis, which is closely related to the so-called "intermittency" problem.

The analysis outlined before was somewhat restrictive, in assuming the predator to be absolutely immobile with respect to the flow. Such a simple model is a useful starting point, but studies of movement strategies for small organisms in a turbulent environment indicate that such an organism is in general able to move, at least a little, with respect to the surrounding flow, which itself is in turbulent motion. This problem is presumably studied best by numerical simulations, which are now in progress.

References

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