Examples of vertical density currents wholly within the domain of laminar flow, one in a water solution, the other in air, have come to my attention. Both examples illustrate new ways of introducing and dispersing microscopic particles into static fluids and both demonstrate that a stable, clearly defined layer of dispersed particles forms first and that the vertical density currents originate and flow from the lower part of this layer. The new information comes from wholly unrelated lines of research, one in virology, and the other in mycology. Neither investigation was aimed at hydrodynamics yet both provide good experimental support for vertical density currents.

In an earlier paper (Bradley 1965), I showed by experiments that, given a supply of particles dispersed in the upper part of a body of fluid, a vertical density current will form and flow downward if the effective diameters of the particles are appreciably less than 0.14 mm and when the space between the particles reaches some critical minimum. Such vertical density currents, in quiet fluid, flow in stream tubes that have a circular cross section and a diameter $d$, that varies inversely as the difference in specific gravity of the density current $\delta_s$, and the surrounding fluid $F$, of density $\rho$.

$$d \propto \frac{1}{\delta_s - \rho F}.$$

The terminal velocity of such currents also varies inversely as the difference in specific gravities. As long as $\delta_s > \rho F$ such density currents will continue to flow under the force of gravity.

In none of those experiments was I able to create an essentially uniform dispersion of particles in the near surface fluids, such as would be expected in the milky epilimnion of a lake in which calcite crystals are forming.

Since that paper was published I have learned of two entirely independent means of introducing particles into a fluid that ensure almost ideal uniformity of dispersion. Interestingly enough, these two means also demonstrate that a clearly defined and stable layer of apparently uniformly dispersed particles forms first and that the vertical density currents originate from the underside of such layers. Furthermore, the two experiments that revealed these means of dispersing particles into quiescent fluids also demonstrated the formation and characteristics of vertical density currents much more effectively than my own experiments, though that was not the purpose of either experiment. Possibly this additional information will make a mathematical treatment of vertical density currents more tractable.

The first of these two experiments was called to my attention by Dr. R. L. Steere of the U.S. Department of Agriculture, who described to me his method for iso-
lating viruses from macerated tissue. His mechanism, which he called diffusion filtration, is both simple and ingenious for his purpose and at the same time beautifully illustrates the formation and characteristics of vertical density currents. His Fig. 10-29 (Steere 1964) is reproduced here as Fig. 1. Particularly noteworthy is the thin stratum of particles (viruses) that forms first, and from the underside of that stratum a family of vertical, thin, apparently cylindrical density currents develops. The difference in density between the density currents and the buffered solution through which they flow must be extremely small. The virus particles accumulate at the bottom of the flask and are recovered.

The second excellent example of vertical density currents also illustrates the value of serendipity, because I discovered it by the chance opening of a book on, of all things, fungi. This experiment was set up by A. H. Reginald Buller to demonstrate the continuous release of spores from the gills of mushrooms. My Fig. 2 is redrawn from his illustration (Buller 1909), which also was a drawing. Perhaps the most remarkable thing about this experiment is the fact that the fluid was air. As in the procedure used to isolate virus particles, a thin, well-defined, and very stable layer of suspended spores formed immediately below the surface, but in this case only a single density current flowed downward from the bottom of that layer—perhaps because of the asymmetry of the source, or because more spores were being released near the margin of the mushroom cap.

In both these experiments the mechanisms for feeding particles into the system are far superior to those I contrived. These two utterly different mechanisms were automatic, uniform, and continuous, and guaranteed steadier rates of feed and more uniform dispersion of the particles. Moreover, in both experiments the particles originate from a source already within the fluid so there are no interfacial boundaries for them to pass through such as the surface film or a chemocline.

What happens at the base of the layer of homogeneously dispersed particles to transform them into vertical density currents is an intriguing problem. This layer must be mechanically unstable because its aggregate density, fluid plus suspended particles, exceeds that of the fluid below. Moreover, it appears from my earlier experiments that a critical density has to develop locally to initiate downward flow in a stream tube as contrasted with uniform sedimentation. One possible mechanism was suggested by H. R. Shaw to account for the local concentrations. This is the presence of weak disturbances in the fluid close to the lower boundary of the layer of dispersed particles. At the loci of downward convergences between such disturbances, the suspended particles would be brought into closer proximity...
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Fig. 2. Vertical density current of fungus spores in air. Mushroom spores are ejected continuously from a segment of a mature cap of *Polystictus versicolor*, which is pinned to a cork block on the beaker cover. According to Buller (1909, p. 97), "The density of the stream remains very regular for hours or even days." The stream of spores moves downward 1 to 2 mm per sec and breaks up only by convection countercurrents set up within the beaker. The falling spores form a distinct layer below the gills of the mushroom and the vertical density current drains off from that reservoir. [Modified slightly from Buller (1909, Fig. 37, p. 97).]

and, conceivably, also given a slight downward impetus. Continuous streaming ensues when the kinetic energy of the downward motions exceeds the energy dissipated by the viscous forces in the displaced fluid—air or water in the cases cited. This suggests that the critical density and the thickness of the layer of dispersed particles will depend on the viscosity of the fluid medium. An interesting demonstration of this might be provided by the spore experiment if the density of the air inside the container were controlled by partial evacuation. The observed tendency to regular spacing of vertical density currents in the virus columns (Fig. 1) would be a consequence of this mechanism. From the standpoint of energy, the suggested stability conditions are analogous to those attending the onset of thermal convection in a fluid heated from below, or, more appropriately, cooled from above. The analogy, however, obviously does not extend to the fully developed flow, and further systematic studies of possible regimes of flow are needed.

It is interesting that some sort of equilibrium is established between the supply of particles from above and their rate of draining away through the stream tubes, so that the thickness of the layer of suspended particles remains essentially constant for hours or even days.

It seems clear from the experiments of Steere and of Buller that both the virus particles and the fungus spores created so small a density excess over the fluid medium that the density currents reached a constant velocity almost at once and kept well within the domain of laminar flow. Such vertical density currents are nearly ideal in that they are simple cylindrical stream tubes, not complicated by involutions or any other manifestation of apparent vorticity. I suspect that the vertical density currents observed by Steere, for example, come much closer to simulating conditions that exist in some natural environments, such as a lake, than did my own experiments.

We now have, it seems, an interesting variety of demonstrations of vertical density currents in widely diverse fluids. The time is perhaps opportune for an interested mathematical physicist to develop the theory of vertical density currents so that these observations can be better understood and applied to a broader spectrum of flow phenomena, in air, water, molten rock, and perhaps even in the "solid" earth.

REFERENCES

