Comments on "The Mysteries of Mammatus Clouds: Observations and Formation Mechanisms"

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In an intriguing paper, Schultz et al. (2006, hereafter S06) have reviewed observations of mammatus clouds in the scientific literature and offered some candidate mechanisms for the formation of mammatus. This reasonably comprehensive review is both interesting and stimulating. I concur with the authors that although mammatus cloud formations have little or no direct societal impact, they are a fascinating enigma, certainly worthy of careful scientific scrutiny.

One candidate mechanism they did not mention, however, is what is known in oceanography as "double-diffusive convection" (Turner 1973, p. 251 ff.). Its most well-known application is to the thermohaline flows known as "salt fingers." The physical mechanism is that the fluid has two constituents that contribute in opposing ways to buoyancy; increased salinity makes the water more dense, whereas temperature increases make the water less dense. When warm, salty water overlies cold freshwater, the resulting density distribution is nearly neutral and stable to perturbations according to static stability theory, because the two constituents contribute oppositely to buoyancy. However, the rates of diffusion of the two constituents are very different—heat diffuses much more rapidly that salinity, so if a parcel of warm, salty water is perturbed downward, its heat content diffuses more rapidly than the salt. This ultimately causes a negative buoyancy in the descending finger; that is, the perturbation is unstable. The opposite happens in a parcel of cool freshwater perturbed upward. The resulting ascending and descending parcels eventually mix the layers at the interface.

Of interest to the observations presented in S06 is that the stratification produced by the action of salt fingers comes to produce a layered, steplike profile of the constituents (Turner 1973, 270–273; Gregg 1973). The detailed view of stepped temperature profiles (producing very shallow superadiabatic lapse rates in the temperature profiles) in Fig. 10 of S06 could be considered compatible with the oceanographic observations. Turner (1973, p. 270) is careful to point out that layering need not be the result of double-diffusive convection, but this observation is at least consistent with the hypothesis of the presence of double-diffusive convection.

How might this process be associated with mammatus clouds? The presence of particulates that are heavier than air in a "colloidal" solution would play a role comparable to that of salinity—acting to increase the overall density of the air-particulate mixture. Those particulates could be condensed water or volcanic ash particles. If the anvil (or ash) cloud is relatively warm compared to the air below, then the situation would be analogous to that in oceanic thermohaline flows that produce salt fingering. As is the case for thermohaline flows, the diffusion rate of heat would certainly be considerably more rapid than that of the particulates. In fact, particulates such as ash particles should be diffused quite slowly. I will return to this shortly.

For the moment, consider the particulates to be water droplets or ice particles. In the atmosphere, within a descending "finger" initiated by the negative buoyancy produced as a result of double-diffusive convection, the particles would descend with the air, which would be warming as a result of compressional heating, even as their relative warmth as a result of originating in the warm anvil diffuses into the surroundings. If the particles begin to evaporate (or sublimate) as a result, they would contribute their latent heat and the initially unstable descent owing to negative buoyancy would be correspondingly diminished. By the level where all the particles have evaporated, the air would then move ver-

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tically at the dry adiabatic rate, rapidly losing any remaining negative buoyancy, unless the surrounding environment had a nearly dry adiabatic lapse rate.

In between descending fingers, there are ascending fingers. The relatively rapid diffusion of heat into the parcels from the warm anvil would produce a slightly positive buoyancy and might promote the evaporation of at least some of the particulates, but the ascent would cause compressional cooling, counteracting that effect to some extent. The ascending fingers would remain mostly full of particulates and continue to have some small positive buoyancy until heat diffusion equalized the temperatures within and outside the fingers, at which point they would no longer be buoyant.

One advantage to this double-diffusive mechanism is that it is not likely to produce large buoyancy perturbations of either sign, consistent with the relatively modest vertical velocities and relatively long times scales for the mammatus pouches seen in the observations. It also produces convective cells with a roughly polygonal distribution in the horizontal, consistent with the morphology of most mammatus formations. The presence of this mechanism does not preclude some of the others; gravity waves might be superimposed on this to produce linearly organized mammatus, for instance.

An interesting issue arises in the context of volcanic ash clouds. Since ash particles do not evaporate, why would the mammatus pouches not extend a long way beneath the cloud? One way to rationalize this is to realize that volcanic ash clouds are not all that dissimilar from pyrocumulonimbus clouds. They likely contain condensed water particulates as well as ash particles. Large, heavy ash particles mostly fall out relatively close to the eruption column, so the remaining ash particles are small and perhaps of low density (e.g., pumice), with correspondingly small terminal velocities; they could behave more like passive tracers and may not contribute very much to the overall density distribution. The condensed water mass in some eruption clouds might be the dynamically active constituent in producing the double-diffusive convection. The relative rarity of mammatus in volcanic eruption clouds might reflect the rarity of the right conditions within volcanically generated pyrocumulonimbus anvils.

Any thorough analysis of the possible importance of double-diffusive convection in the production of mammatus clouds would require at least the development of order-of-magnitude estimates using the theory of this process, in conjunction with the appropriate observations of the actual distributions of the contributing constituents. Numerical simulations would be valuable, as well. The limited observations of mammatus seem to preclude such an effort at this time. In this correspondence, I am not prepared to offer any convincing evidence on behalf of this hypothesis for explaining at least some mammatus cloud formations. But I would be remiss in not suggesting it, at least, as another candidate mechanism for this intriguing phenomenon.

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