Reply

DAVID M. SCHULTZ

Division of Atmospheric Sciences, Department of Physical Sciences, University of Helsinki, and Finnish Meteorological Institute, Helsinki, Finland

ADAM J. DURANT*

Department of Geological/Mining Engineering and Sciences, Michigan Technological University, Houghton, Michigan

JERRY M. STRAKA

School of Meteorology, University of Oklahoma, Norman, Oklahoma

TIMOTHY J. GARRETT

Department of Meteorology, University of Utah, Salt Lake City, Utah

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ABSTRACT

Doswell has proposed a mechanism for mammatus called double-diffusive convection, the mechanism responsible for salt fingers in the ocean. The physics of salt fingers and mammatus are different. Unlike the ocean where the diffusivity is related to molecular motions within solution, the hydrometeors in clouds are affected by inertial and gravitational forces. Doswell misinterprets the vertical temperature profiles through mammatus and fails to understand the role of settling in volcanic ash clouds. Furthermore, given that mixing is a much more effective means of transferring heat in the atmosphere and given idealized numerical model simulations of mammatus showing that the destabilizing effect of subcloud sublimation is an effective mechanism for mammatus, this reply argues that double-diffusive convection is unlikely to explain mammatus, either in cumulonimbus anvils or in volcanic ash clouds.

In preparing our review article on mammatus (Schultz et al. 2006), we were amazed at the number of previously published papers that would make claims about mammatus mechanisms without considering the observational evidence or offering simple physical arguments to support or refute their proposed mechanisms. Before and after publication of our review, some people would make the claim to us that salt fingers formed by double-diffusive convection in the ocean were analogous to mammatus. Admittedly, the physical appearance of salt fingers and their development along a boundary between two fluids provides a seductive analogy to mammatus. Repeatedly, we asked these proponents of the salt-fingers analogy for a simple physical argument, scale analysis, or theoretical calculation that could serve as a testable hypothesis to support or refute this proposed mechanism. Yet, we have received none. Unfortunately, Doswell's (2008) comment admits to not delivering such supporting evidence either.

Like Doswell (2008), we can only make speculative comments for and against double-diffusive convection as a possible mechanism for mammatus, not having quantitatively evaluated the mechanism ourselves. What we do know is that the physics of double-diffusive convection differs from that of moist convection in a

* Current affiliation: Department of Geographical Sciences, and Department of Earth Sciences, University of Bristol, Bristol, United Kingdom.

Corresponding author address: Dr. David M. Schultz, Finnish Meteorological Institute, Erik Palménin Aukio 1, P.O. Box 503, FI-00100, Helsinki, Finland.
E-mail: david.schultz@fmi.fi

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cloud. In salt fingers, the diffusivity applies to molecular motions within a solution, whereas clouds are composed of hydrometeors, whose motions are determined by inertial and gravitational forces. [As an aside, Jevons's (1857) claim that he created laboratory analogs to cirrus clouds was discredited by Schmitt (1995), who showed that he produced salt fingers instead.]

Our intuition tells us that the slow time scale of thermal diffusion in the atmosphere is too long over the large spatial scales of mammatus to match the observed time scale (order of 10 min), especially when mixing is a much more effective process for transporting heat in the atmosphere. Double-diffusive convection may occur at many scales, but dominates on the Kolmogorov microscale where molecular viscosity becomes important. Turbulence is isotropic at this scale, and stresses therefore are zero. The Kolmogorov microscale η, the length scale of the diffusion, is given by

$$\eta = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}, \qquad (1)$$

where ν is the kinematic molecular viscosity for air (1.5×10^{-5} m^2 s^{-1}) and ε is the dissipation rate at the molecular scale (10^{-2} to 10^{-4} m^2 s^{-3} for atmospheric turbulence). Thus, the length scale of the diffusion η is on the order of 0.1 mm. Given that ν for water vapor is similar to that of air (i.e., 2.11×10^{-5} m^2 s^{-1}), the Kolmogorov scale in clouds is similar. On scales relevant to volcanic mammatus (e.g., tens to hundreds of meters), turbulent diffusivities are most important when considering the rates of ash particle settling and diffusion of heat. These diffusivities are determined primarily by the properties of large turbulent eddies and are greater than typical volcanic particle terminal fall velocities. Therefore, assuming that the turbulent diffusivities for volcanic particles and heat will be of the same order of magnitude, double-diffusive convection does not seem a strong candidate mechanism for mammatus formation in volcanic clouds. A more detailed investigation of the different diffusivities of components in the volcanic clouds is required to constrain the relevant magnitudes and to evaluate double-diffusive convection as a mechanism for volcanic mammatus generation.

Moreover, recently completed modeling experiments indicate that double-diffusive convection is not necessary to numerically simulate cumulonimbus anvil mammatus (Kanak and Straka 2006; Kanak et al. 2008). These model experiments showed that when a cloud model was initialized with four soundings where mammatus were observed, mammatus formed each time (Kanak et al. 2008). When the cloud model was initialized with a sounding where mammatus were not observed, mammatus did not form (Kanak et al. 2008). Importantly, the diagnosis of one of the model simulations producing mammatus shows that the biggest contribution to buoyancy is the cooling due to sublimation (Kanak and Straka 2006). Sensitivity tests showed that formation of mammatus was inhibited for high subcloud relative humidity, suggesting that sublimation may play an important role in mammatus production (Kanak et al. 2008). Thus, we see no reason to advance a questionable mechanism for mammatus when our experiments reveal the resultant mechanism and are capable of distinguishing cumulonimbus anvils that produce mammatus from those that do not.

Finally, Doswell (2008) makes three statements that deserve clarification. First, Doswell (2008) states that double-diffusive convection requires the cloudy air to be warmer than the subcloud air. If this is indeed a requirement for double-diffusive convection in the atmosphere (which we are not sure that it is), then unfortunately, some observed soundings through anvils with mammatus show a decrease in temperature across cloud base (e.g., Figs. 1a,c,d in Kanak et al. 2008). In fact, our simulations initialized with these soundings produce inversions at cloud base as subcloud sublimation occurs in conjunction with the mammatus (Figs. 1b–d in Kanak et al. 2008). In addition, at least one simulation produces a superadiabatic lapse rate (Fig. 1d in Kanak et al. 2008), also a result of the subcloud sublimation. Thus, the subcloud inversion and superadiabatic layers that Doswell (2008) argues are possible evidence for double-diffusive convection are actually a result of the sublimation (Kanak et al. 2008). For volcanic ash clouds, if we assume that they are neutrally buoyant, then the ideal gas law can be used to estimate the temperature excess required to offset the negative buoyancy due to the weight of the hydrometeors and ash. Such calculations for the 3.7-h-old ash cloud from the 16–17 September 1992 Mt. Spurr eruption produce a 0.04°C temperature excess inside the cloud (Durant 2007), a value essentially unobservable. Thus, any evidence for the cloud being warmer than the subcloud air is weak and inconsistent.

Second, when discussing whether volcanic ash clouds may be associated with double-diffusive convection, Doswell (2008) claims that they are comparable to colloidal solutions, but fails to quantify the sizes of particles one may expect to find in volcanic clouds, which is needed to assess the validity of this comparison. In a colloidal system, when the dispersed phase consists of particles smaller than about 10^{-9} m, the settling velocities of individual particles may be so minutely small that the system behaves more like a homogeneous solution (Huschke 1959, p. 120). Volcanic clouds contain gaseous constituents, hydrometeors, inorganic aerosol particles, and volcanic ash, which is fragmented silicate particles ranging in size from less than 1×10^{-6} to 2×10^{-3} m (e.g., Sparks et al. 1997). The total fraction of particles less than 1×10^{-6} m in volcanic clouds is poorly characterized, but generally negligible (e.g., Rose et al. 2001). Additionally, early in the evolution of the cloud, the vast proportion of particles are predominantly larger than the size range that may define a colloidal particle. For example, mammatus were observed on the volcanic cloud generated during the eruption of Mount St. Helens, Washington, in 1980 (Fig. 2h in Schultz et al. 2006). Durant et al. (2008, manuscript submitted to *J. Geophys. Res.*) show that the particle size distribution fallout collected about 330 km downwind from the volcano (where mammatus were observed) was polymodal with a mean particle size of 19 μm and a maximum particle size between 250 and 354 μm (however, the fraction of particles in this coarse size fraction was only 0.14% by weight). Although the small settling velocities of mean-sized particles ($\leq 10^{-2}$ m s^{-1}) are generally less than the vertical motions in mammatus (typically 1–3 m s^{-1}), volcanic clouds with mammatus contain particles that rapidly separate from the dispersion medium, which calls into question the analogy to a colloidal solution.

Third, Doswell (2008) states that volcanic clouds "are not all that dissimilar from pyrocumulonimbus clouds" and "likely contain water particulates as well as ash particles." The analogy between volcanic plumes and cumulonimbus has been noted for some time (e.g., Oswalt et al. 1996; Hoblitt 2000; Tupper et al. 2005). Gaseous volcanic emissions may contain up to 99% water by mole (e.g., Symonds et al. 1994), and ash particles act as sites for hydrometeor formation (e.g., Sparks et al. 1997; Herzog et al. 1998). Thus, as stated in section 4g of Schultz et al. (2006), phase changes of water in volcanic ash clouds could be quite important to mammatus formation.

Summarizing our response, Doswell (2008) proposed a mechanism for mammatus called double-diffusive convection, stating he is "not prepared to offer any convincing evidence on behalf of this hypothesis." Neither are we. Quantitative evidence supporting or refuting double-diffusive convection as a mechanism for mammatus is needed, although our intuition suggests this mechanism is not likely, and evidence presented in this paper indicates this mechanism is not necessary for mammatus formation. Furthermore, Doswell (2008) misinterprets the observed data that cloudy air is warmer than the subcloud air during mammatus formation and misunderstands the role of settling in volcanic clouds. For us to consider further the salt-finger analogy to mammatus, Doswell should provide, at a minimum, an appropriate scale analysis and not just conjecture.

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