THEORETICAL ANALYSIS OF CLOUD AND MIST DROPLETS WITH RADIATION AND MASS TRANSFER

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Radiative heat transfer between water droplets in air and a remote heat sink or source (e.g., cloud tops to higher cooler layers or solar irradiation) and associated mass transport is modeled, including droplet-vapor conduction, droplet absorption and emission, vapor-phase mass transfer, and liquid-vapor phase change. In this presentation, a quasi-explicit, uncoupled, droplet sub-model is described that has sufficiently fast computation time that it can be incorporated in cloud microphysics models and other large-scale simulations. Assumptions include quasi-steady droplet energy and diffusion-dominated vapor transport. Two common situations fall within the latter category: (1) dilute in water vapor and (2) near saturation. These two common conditions often co-exist, as in clouds and room-temperature mists. For dilute and/or near-saturation conditions, mass and conductive energy fluxes in the vapor-phase around a droplet are dominated by molecular diffusion compared with bulk advective fluid motion. (This is also referred to as the low mass-transfer-rate regime, or 'no-blowing' condition; note that this is not the same thing as 'no-ventilation' or no droplet-vapor relative motion.) Radiatively, droplets are approximated as gray emitting-absorbing spheres in the geometric optics regime. The small contributions of water-vapor radiation and interfacial phase-change radiation are neglected. If necessary, rigorous droplet Mie single-scattering/absorption calculations and non-gray, multiple-scattering radiative-transfer calculations could easily be incorporated. As formulated, the sub-model retains sufficient physical fidelity that it can simulate behavior in optically thin edge-regions of clouds, where the thermodynamic state can easily be temporarily non-dilute and/or far from saturation. This versatility extends even to conditions of relatively low relative humidity and low pressure, where evaporative cooling can induce significant drop in temperature and possibly induce homogeneous freezing. Model validation is shown by comparison with 'exact' results from implicit, coupled equations based on similar assumptions. Validation of the underlying assumptions of both models (quasi-explicit-uncoupled and implicit-coupled) is shown by comparison with experimental results in which ambient subsaturation-induced droplet evaporation is significantly augmented by CO_2 laser irradiation. Comparison with the implicit-coupled model results shows that modeling accuracy of a few percent in the 'D-squared' evaporation rate 'constant' is achievable with the uncoupled, quasi-explicit model, even at conditions far from saturation and in the presence of significant radiative flux. Comparison with the laboratory measurements confirms the appropriateness of the basic modeling assumptions noted above. Implications are presented for modeling cloud microphysics, both with respect to liquid droplets overcoming the condensation-coalescence barrier in "warm" (non-freezing) clouds and with respect to droplets freezing in "cold" clouds, both of which are topics of current importance and interest in atmospheric science. Incorporation of a droplet sub-model like this into large-scale cloud simulations could lead to more accurate predictions of phenomena like cloud-top freezing and enhanced condensational growth, particularly in mid-latitude cyclones.

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