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Sub-cloud Rain Evaporation in the North Atlantic Ocean during ATOMIC Campaign

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Sub-cloud rain evaporation in trade-wind regions significantly contributes to the boundary layer mass and energy budgets. However, parameterizing marine rain evaporation is difficult due to the sparse availability of well-resolved rain observations and the challenges of sampling short-lived marine cumulus clouds. In this study, 1-Hz raindrop size distribution (RSD) observations, sampled during the Atlantic Tradewind Ocean-Atmosphere Mesoscale Interaction Campaign (ATOMIC) held in January-February 2020, are used to initialize a one-dimensional evaporation model to evaluate rain evaporation flux (F_e) in the sub-cloud layer for 22 case studies. Fe varies from 1 to 70 Wm^{-2} for 7 out of 22 cases where rain is sampled within ±100 m of ceilometer-based cloud base (700 m). These F_e values are comparable to radiative and surface fluxes in previous modeling and observational shallow cloud studies. The remaining cases where rain is sampled 800-1300 m above the cloud base have less reliable F_e due to unaccounted collision-coalescence growth as raindrops fall from sampling height to cloud base. The role of collision-coalescence growth is evident from the lower total raindrop concentration (N_0) and slightly higher geometrical mean diameter (D_g) near cloud base compared to those sampled at higher altitudes. These microphysical parameters are found to not only influence the magnitude of vertically integrated F_e but also impact its vertical distribution. Comparatively, thermodynamic factors only influence the vertical distribution of F_e and not its vertically integrated magnitude. The rain evaporation is also detected by the modeled enrichment of stable isotope ratios of deuterium and oxygen in precipitation (dD_p and $d18O_p$, respectively). The enriched dD_p and $d18O_p$ modeled at surface closely match observations from three independent surface sources, validating our isotope model. The enrichment modeled in both dD_p and $d18O_p$ is proportional to F_e for the 7 cases close to cloud base. Compared to precipitation isotope ratios, water vapor isotope ratios cannot resolve the evaporation signals due to small ratio of evaporated to background water vapor. This increases our confidence in using rainwater isotope sampling to study sub-cloud rain evaporation in future campaigns. The substantial F_e in these shallow precipitating cumulus clouds also confirms the importance of rain evaporation in boundary layer energy budgets.