Supplementary Information

for “New observational constraints on warm rain processes and their climate implications”

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Brief summary of ground-based retrieval method and uncertainties

Innovative methods were developed by Wu et al. (2020) to decompose drizzle and cloud reflectivity in a cloud layer from ARM cloud radar measurements and then simultaneously retrieve cloud and drizzle microphysical properties. During ACE-ENA, the mean retrieved (aircraft in situ measured) cloud-droplet number concentration \( N_c \), liquid water content \( LWC_c \) and mass weighted mean radius \( r_c = \left( \frac{3LWC_c}{4N_c\pi\rho_w} \right)^{1/3} \) are \( 70 \text{ cm}^3 \) (\( 60 \text{ cm}^3 \)), \( 0.21 \text{ g m}^{-3} \) (\( 0.22 \text{ g m}^{-3} \)) and \( 8.9 \text{ µm} \) (\( 9.5 \text{ µm} \)), respectively. The mean retrieved (aircraft \textit{in-situ} measured) drizzle drop \( N_d \), \( LWC_d \), and mass weighted mean radius \( r_d \) are \( 0.07 \text{ cm}^3 \) (\( 0.08 \text{ cm}^3 \)), \( 0.052 \text{ g m}^{-3} \) (\( 0.066 \text{ g m}^{-3} \)), and \( 55.8 \text{ µm} \) (\( 58.1 \text{ µm} \)), respectively. The retrieved cloud and drizzle microphysical properties agree well with the aircraft in situ measurements in both time series and vertical structure, with estimated median retrieval errors are \(~15\%\) for \( r_c \), \(~35\%\) for \( N_c \), \(~30\%\) for \( LWC_c \) and \( r_d \), and \(~50\%\) for \( N_d \) and \( LWC_d \). The detailed comparisons between the new retrievals and aircraft \textit{in-situ} measurements for all cases during ACE-ENA, as well as their retrieval uncertainties, were fully discussed in Wu et al. (2020). Figure S1 demonstrates both retrievals and calculated properties using KK scheme.

Fig. S1. Profiles of (a) cloud and (d) drizzle liquid water content (\( LWC_c \) (ret) and \( LWC_d \) (ret)), mass-weighted (b) cloud-droplet mean radius \( r_c \) (ret) and (c) drizzle drop mean radius \( r_d \) (ret) from ground-based observations on July 18, 2017 during ACE-ENA field campaign. (e) \( LWC_d \) (KK) calculated from the Khairoutdinov & Kogan (2000) parameterization (KK). (f) Ratios of the \( LWC_d \) calculated from KK and retrieved from ground-based observations. The temporal resolution is 1 min and vertical resolution is 30 m.
Fig. S2. a-b. The temporal variation of the profiles of autoconversion ($R_{auto}$) and accretion ($R_{accr}$) calculated using the Khairoutdinov & Kogan (2000) parameterization based on the newly retrieved MBL cloud and drizzle microphysical properties. c-d. The profiles of constrained $A'(Z)$ and $B'(Z)$ in the updated KK scheme. The temporal resolution is 1 min and vertical resolution is 30 m.
**Fig. S3.** LWP and SWCF from CESM2. LWP is overestimated in CESM2 by 50% compared with satellite observations.
Fig. S4. Changes in a-b. liquid water path ($\Delta$LWP=LWP(NKK) - LWP(KK)), c-d. frequency of rain (FREQR), and e-f. large-scale stratiform precipitation in CESM simulations using the NKK and KK schemes. Upper row: both autoconversion and accretion. Lower row: autoconversion only. G=global, M=mid-latitudes (30-60 °N/S).
**Fig. S5.** a,c. Changes in low-level stratiform cloud fraction (ΔCF=CF(NKK) - CF(KK)), b,d. fractional changes (%) in low-level stratiform CF using the NKK and KK schemes. Upper row: both autoconversion and accretion. Lower row: autoconversion only. G=global, M=mid-latitudes (30-60 °N/S).