Appendix: Description of WDM6 Microphysics Scheme

a) Parameters for hydrometeor characteristics

WDM6 microphysics scheme is originally described in Park and Lim (2023). It employs the double-moment approach for the mass mixing ratio (q_x) of X = {c, r, i, s, g} and the total number concentration (N_x) of X = {c, r, i}. Here, c, r, i, s, and g indicate cloud, rain, cloud ice, snow, and graupel, respectively. The characteristics of hydrometeor in the WDM6 scheme are determined by density (ρ_x), the fall velocity (V_x)–diameter (D) relationship, the mass (M_x)– D relationship, and the size distribution ($N_x(D)$). The size distribution of each hydrometeor category X, except cloud water, which does not sediment, is represented by a complete gamma function of the following form:

$$N_X(D)\ [m^{-4}] = N_{0X}\, D^{\mu_X} \exp\{-(\lambda_X D)\}, \tag{A1}$$

$$N_{0X}\ [m^{-4}] = N_X\, \lambda_X^{\mu_X+1}, \tag{A1-1}$$

$$\lambda_X [m^{-1}] = \left[\frac{c_X N_X}{\rho_a q_X} \frac{\Gamma(\mu_X+d_X+1)}{\Gamma(\mu_X+1)}\right]^{1/d_X}. \tag{A1-2}$$

Here, $N_x(D)$ indicates the number concentration of each hydrometeor corresponding to D. μ_X and λ_x represent the shape and slope parameters of the size distribution. N_{0X} and N_x are the intercept parameter and the total number concentration of each hydrometeor, respectively.

Meanwhile, the V_x – D and M_x – D relationships can be expressed as Eqs. (A2) and (A3):

$$V_x\ [m\ s^{-1}] = a_x D^{b_x}, \tag{A2}$$

$$M_x\ [kg] = c_x D^{d_x}, \tag{A3}$$

where a_x, b_x, c_x, and d_x are coefficients that can vary depending on the type of hydrometeor. All particles in the original WDM6 scheme are assumed to be spherical with constant bulk densities. Thus, for each category, $c_x = \pi\rho_x/6$ and $d_x=3$. The coefficients defining the characteristics of hydrometeors in the original WDM6 scheme are summarized in Table A1.

Table A1. Parameters for hydrometeor (rain, ice, snow and graupel) characteristics in WDM6 scheme.

	V_x – D_x relationship		M_x – D_x relationship		Shape parameter (μ_x)	Density (ρ_x)
	a_x	b_x	c_x	d_x		
Rain	841.9	0.8	$\frac{\pi\rho_R}{6}$	3	1	1000
Cloud ice	2.71×10^3	1.0	$\frac{\pi\rho_I}{6}$	3	0	500
Snow	11.72	0.41	$\frac{\pi\rho_S}{6}$	3	0	100
Graupel	330.0	0.8	$\frac{\pi\rho_G}{6}$	3	0	500

b) Microphysical Processes

The governing equations of the mass mixing ratio and the number concentration for each hydrometeor are given by Eqs. (A5) and (A6), respectively:

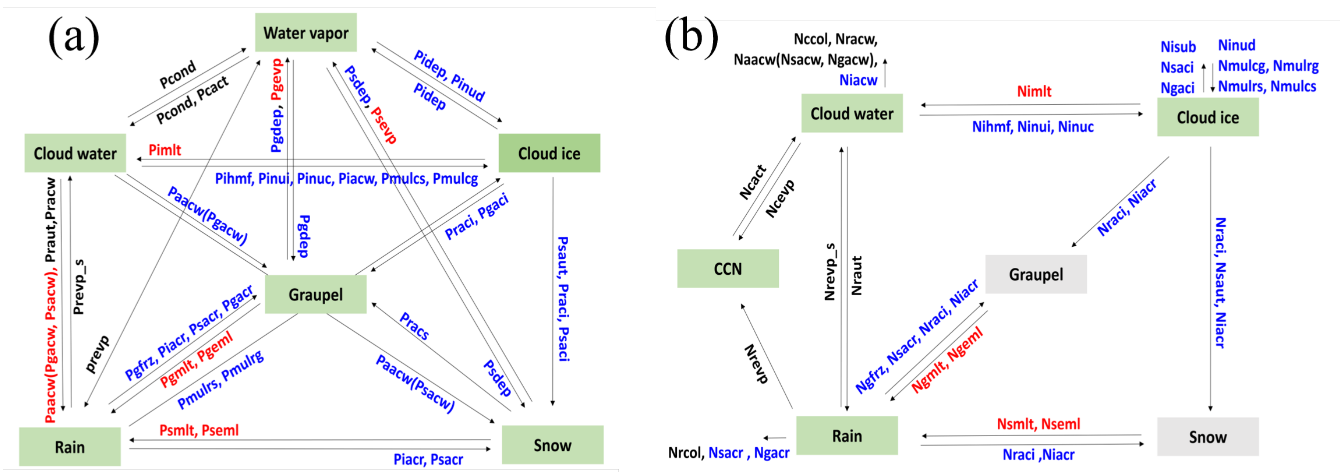
$$\frac{\partial q_x}{\partial t} = -\vec{V} \cdot \nabla_3 q_x - \frac{1}{\rho_a}\frac{\partial}{\partial z}\left(\rho_a q_x V_{q_x}\right) + S_{q_x}, \quad (A5)$$

$$\frac{\partial N_x}{\partial t} = -\vec{V} \cdot \nabla_3 N_x - \frac{1}{\rho_a}\frac{\partial}{\partial z}\left(\rho_a N_x V_{N_x}\right) + S_{N_x}, \quad (A6)$$

where the first and second terms on the right-hand side of Eq. (A5) represent the 3D advection and sedimentation for q_x, respectively. The third term represents the source and sink of q_x. $\vec{V}$ and V_{q_x} represent the three-dimensional 3D wind fields and the q_x-weighted mean terminal velocities of X, respectively; ρ_a is the air density. Eq. (A6) is identical to Eq. (A5) but for the number concentration.

The production terms (S_{q_x} and S_{N_x}) for each hydrometeor category are composed of several microphysical processes including melting, accretion, and nucleation, as shown in Figure A1. One of the accretion processes, Psacr, represents the accretion between snow and rain particles, which primarily contributes to the formation of graupel or snow. When the mass mixing ratios of both rain and snow are greater (smaller) than 1.e-4 kg kg^{-1}, it contributes to the formation of graupel (snow). This process acts as a source process for the graupel or snow mass mixing ratio and as a sink process for the rain mass mixing ratio (Fig. A1a). Detailed descriptions and parameterization equations of these microphysical processes are available in previous studies by Park and Lim (2023) and Lim and Hong (2010).

Figure A1. Flowcharts of microphysical processes for predicting (a) mass mixing ratio (S_{q_x}) and (b) number concentration (S_{N_x}) of hydrometeors in WDM6 scheme. The number concentrations of hydrometeors in the green boxes are predicted only (e.g., cloud water, cloud ice, rain, and cloud condensation nuclei (CCN)). Microphysical terms drawn with red (blue) are activated when the temperature is above (below) 0°C. Terms drawn in black are activated regardless of temperature.



Supplementary material:

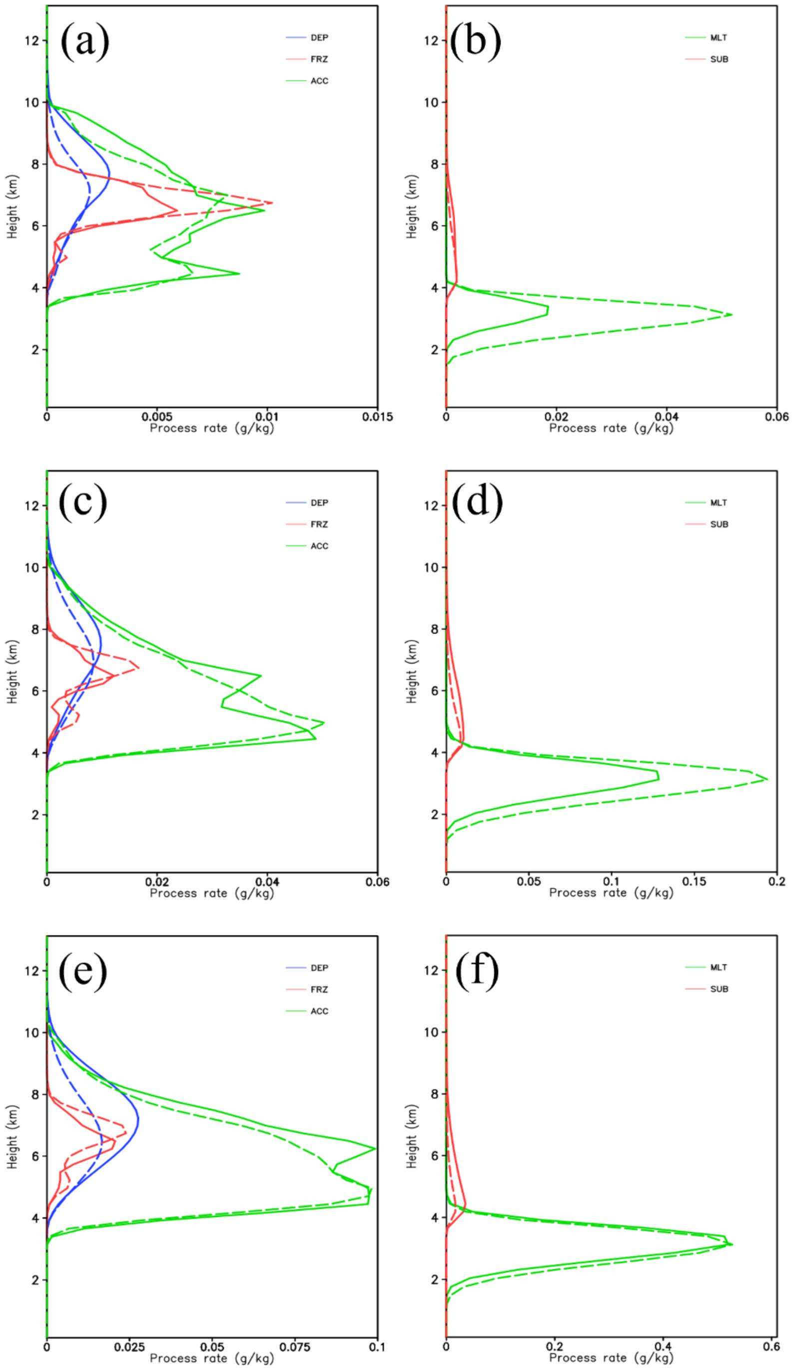


Figure S1: Vertical profiles for the domain-averaged (a) sources and (b) sinks of graupel mass mixing ratio in WDM6_FD (Solid line) and WDM6_PD (dashed line) at 1 hour (a and b), 2 hour (c and d), and 4 hour (e and f). The main source processes, namely, deposition (Pgdep; DEP), accretion (mean of Paacw, Psacr and Pgacr; ACC) and freezing (Pgfrz; FRZ) are plotted with the major sink processes, namely, sublimation (Pgsub; SUB) and melting (Pgmlt; MLT).

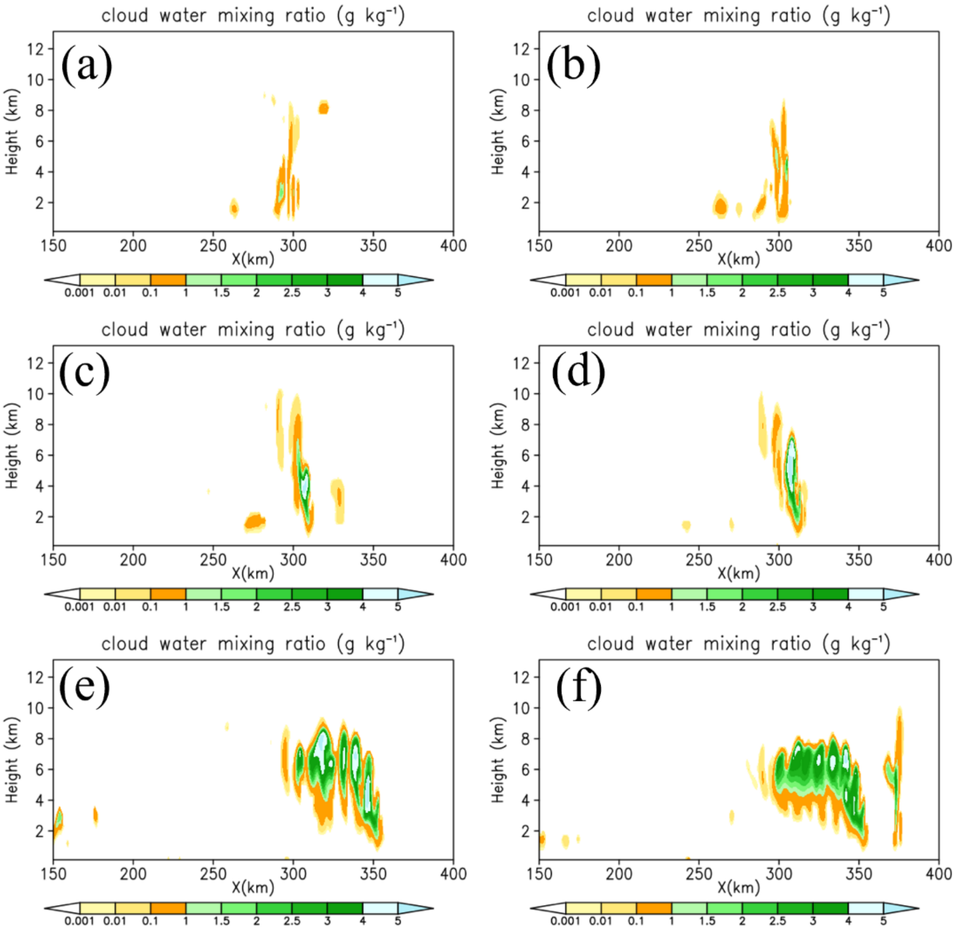


Figure S2: Spatial distribution of cloud water mass mixing ratio (g kg^{-1}) in WDM6_FD (a, c, and e) and WDM6_PD (b, d, and f) at 1 hour (a and b), 2 hour (c and d), and 4 hour (e and f).

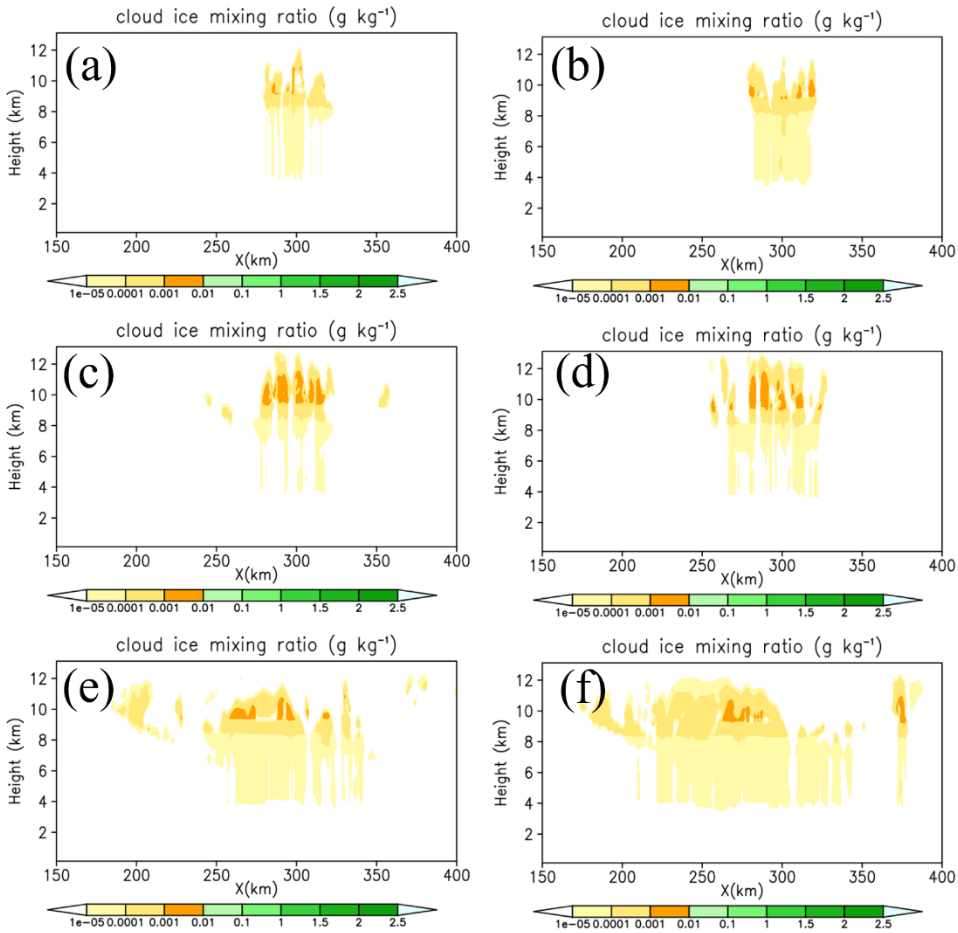


Figure S3: Same as Figure 1, but for cloud ice.

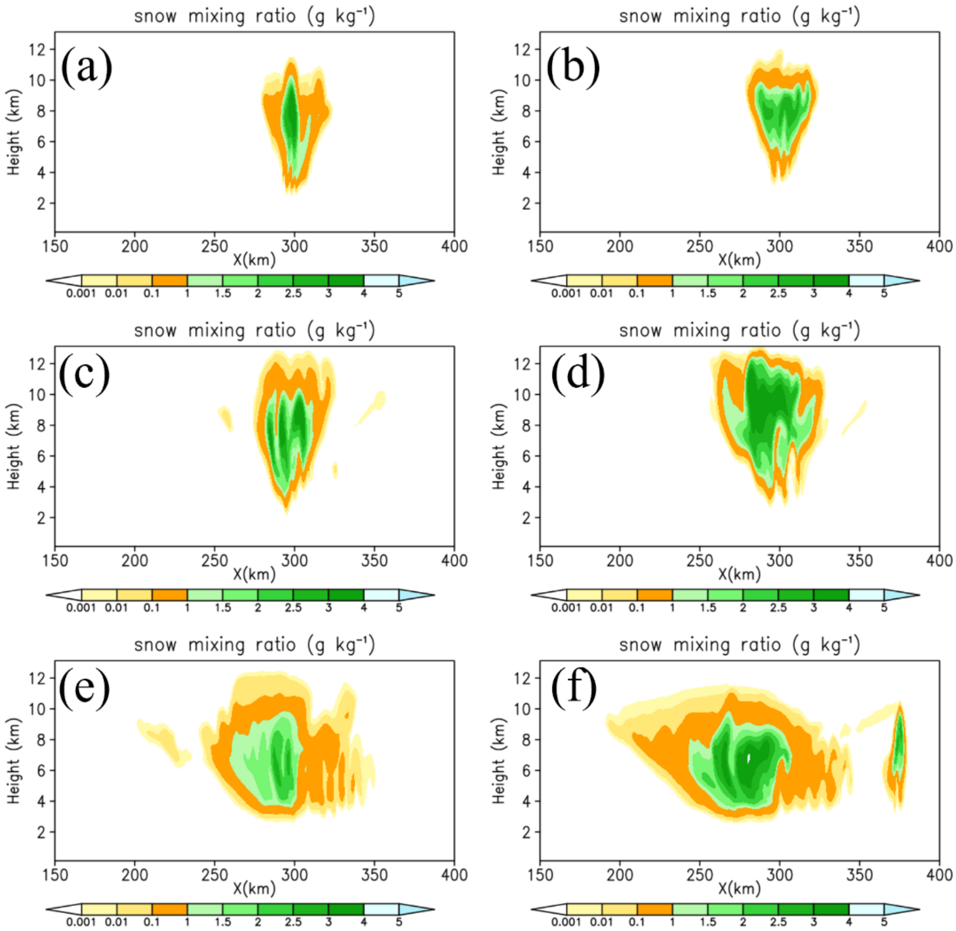


Figure S4: Same as Figure 1, but for snow.

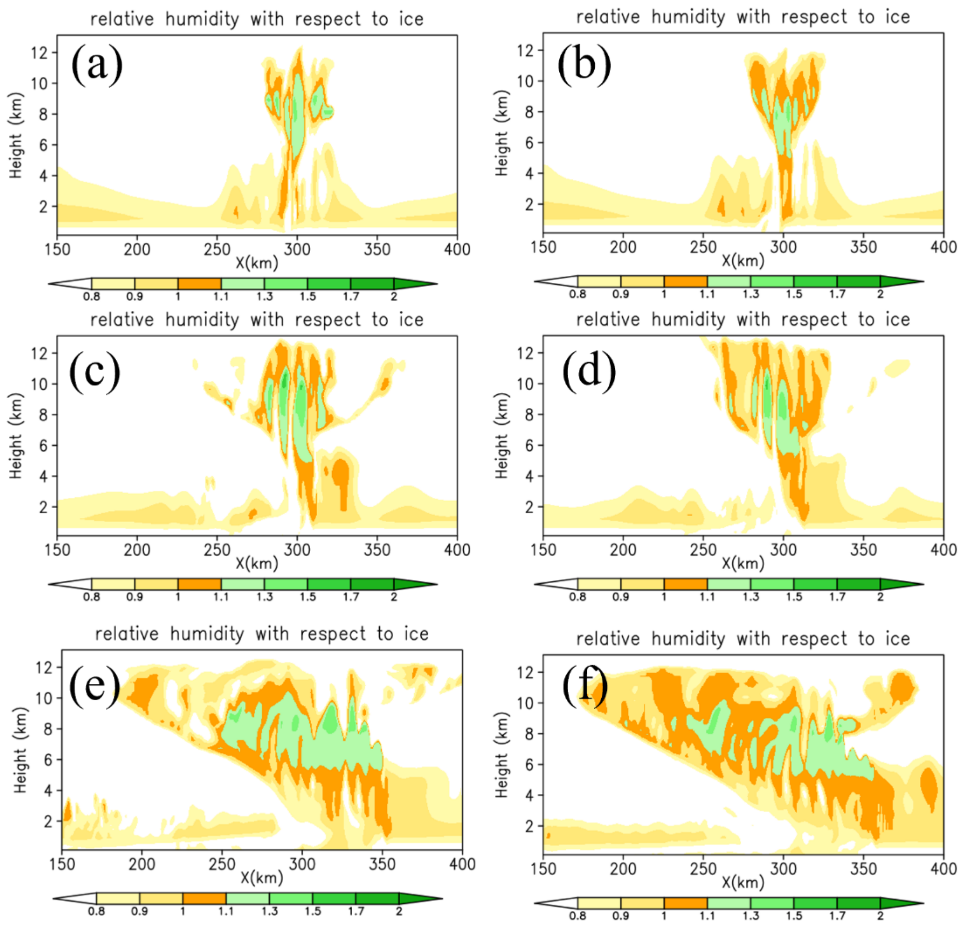


Figure S5: Same as Figure 1, but for relative humidity with respect to ice.

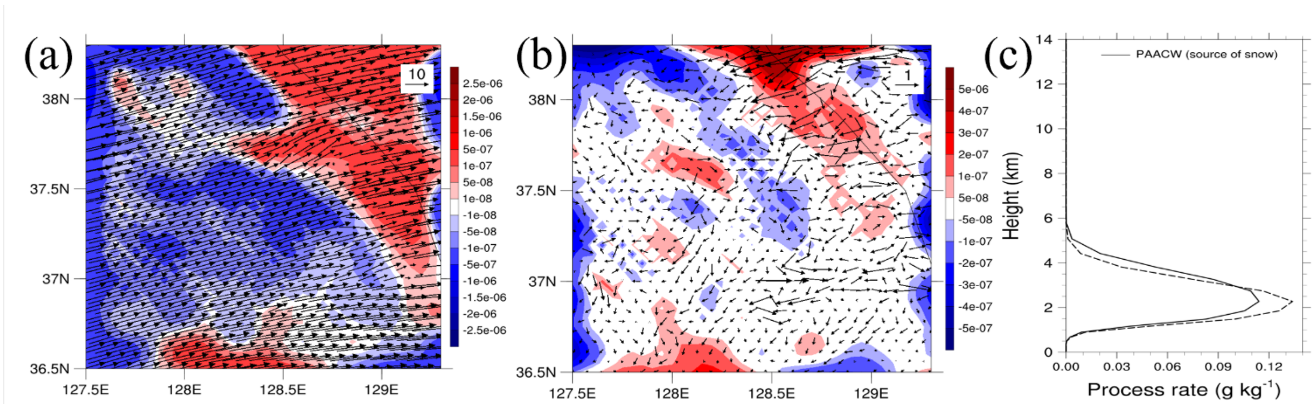


Figure S6: Snow advection (g kg^{-1} s^{-1}) and wind vector (m s^{-1}) at 850hPa for CL case from (a) WDM6_FD, and (b) the difference between WDM6_PD and WDM6_FD (WDM6_PD minus WDM6_FD). The vertical profiles of the time-domain-averaged Paacw process for C1 case are shown in (c). The solid (dashed) line represents WDM6_FD (WDM6_PD).