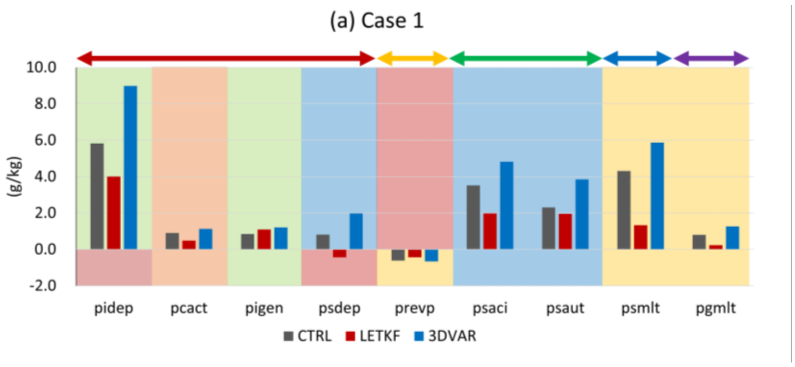
Appendix A.: Microphysical process budgets

The figure below shows the vertically integrated microphysical process budgets of CTRL, LETKF, and 3DVAR in the blue region (Pyeong-Chang area) during the forecast period. Among the 39 microphysical processes, the top 10 processes are selected from each experimental group, and only the most common processes are shown. The color of the arrow at the top of the figure indicates from which hydrometeor it grew, and the background color indicates what kind of hydrometeor has grown. Red represents water vapor, yellow represents rain, orange represents cloud, green represents ice, blue represents snow, and purple represents graupel. In Case 1, the pidep process, in which water vapor is deposited into ice, was the most dominant in the three experimental groups, and the main precipitation formation process was the process of ice produced through the previous process growing into snow through the psaci and psaut processes and then melting with rain (psmlt) to form precipitation. In Case 2, the temperature was higher than in Case 1, so the process of condensing water vapor into clouds and accretion as rain was added to the main process shown in Case 1, and it appeared as a major precipitation formation process. In both Cases 1 and 2, the amount of pidep in 3DVAR was approximately twice that of pidep in LETKF. In both cases, the snow mixing ratio of LETFK was higher than 3DVAR in the analysis field of the last data assimilation time, but the amount of psmlt converted from snow to rain was the smallest among the three experimental groups, and the amount was 4.53 g/kg and 2.63 g/kg less than 3DVAR. The amount of microphysical processes growing from water vapor to other hydrometeors, including pidep, was the largest in 3DVAR, where the highest water vapor mixing ratio was calculated at the analysis field, and other formation processes also showed the largest value in 3DVAR. That is, the factor that had the greatest influence on the formation of precipitation during the 12-hour forecast period is the water vapor mixing ratio, and the assimilation of the water vapor mixing ratio is important.



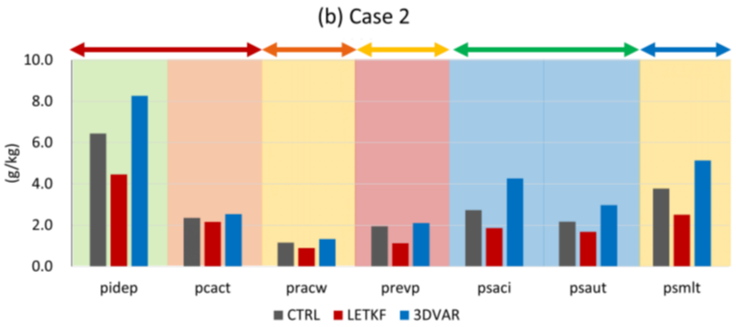


Figure A.1 Common main microphysical processes of (a) CTRL(black bar), (b) LETKF(red bar) and (c)3DVAR for (a) Case 1, (b) Case 2, the forecast period averaged over blue area (red shading: water vapor formation, yellow shading: cloud water formation, green shading: cloud ice formation, blue shading:snow formation; red arrow: from water vapor, yellow arrow: from cloud water, green arrow: from cloud ice, blue arrow: from snow, purple arrow: from graupel).

The figure below are pie charts showing the proportion of microphysical processes in each experiment group. In all of the experiments and cases, the growth process from water vapor to other hydrometeors showed the largest percentage (red shading) and are similar among two DA methods. This is due to the fact that the activation of hydrometeors are dependent on the microphysical scheme employed in the experiment. However, it can be seen that for Case 1, the process of converting snow and hail into rain (blue and purple shading), which are relatively large hydrometeors, accounted for 22% in 3DVAR, but in LETKF, where the amount of water vapor growing into large hydrometeors was small, the process of converting large snow and hail into rain was 12%.

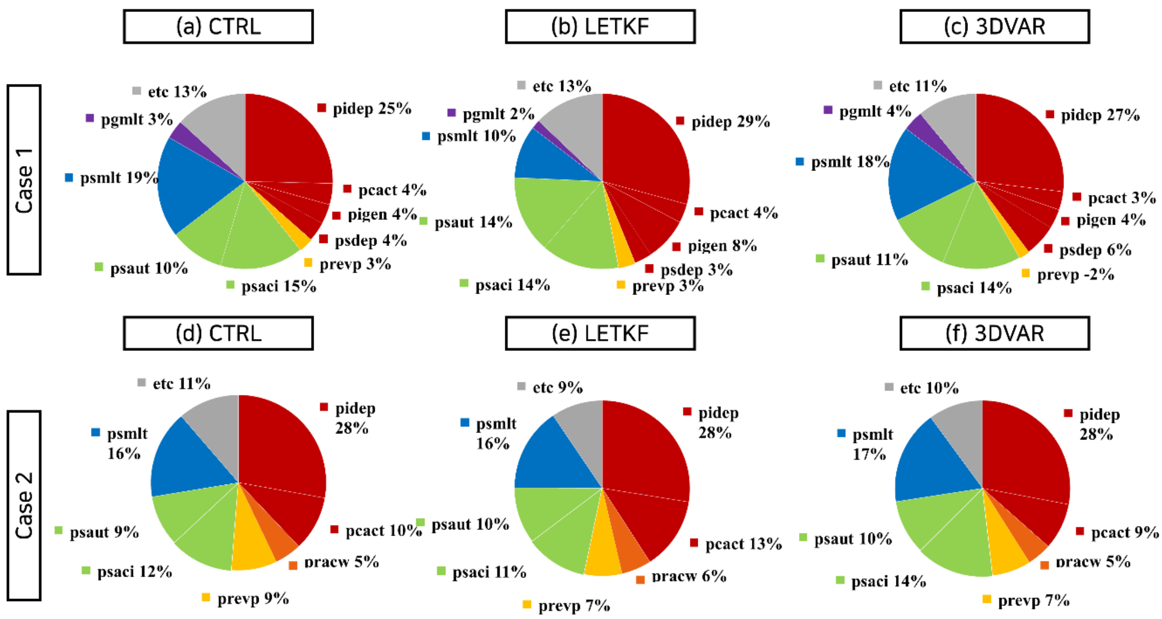


Figure A.2 Microphysical process pie chart (a) and (d) CTRL and (b) and (e) LETKF and (c) and(f) 3DVAR for (a)–(c) Case 1, and (d)–(f) Case 2, i.e., the forecast period averaged over blue area (red:

from water vapor, yellow: from cloud water, green: from cloud ice, blue: from snow, purple: from graupel).

Table A.1 List of cloud microphysical processes for calculating mixing ratios WDM6 scheme.

Abbreviation	Description
Pcact	Production rate for activation of cloud condensation nuclei
Pgmlt	Production rate for melting of graupel to form rain
Pidep	Production rate for (+) deposition/(−) sublimation rate of ice
Pigen	Production rate for generation (nucleation) of ice from vapor
Pracw	Production rate for accretion of cloud water by rain
Prevp	Production rate for (+) condensation/(−) evaporation rate of rain
Psaci	Production rate for v of cloud ice by snow
Psaut	Production rate for autoconversion of cloud ice to form snow
Psdep	Production rate for (+) deposition/(−) sublimation rate of snow
Psmlt	Production rate for melting of snow to form cloud water
Pgmlt	Production rate for melting of graupel to form cloud water

Appendix B.: Reflectivity operator

A) The reflectivity operator used in the LETKF.

While the WRF-LETKF performs, the model output data must be converted into the observational variables such as radial wind and reflectivity. And the operator of reflectivity is refer to Jung et al.2008, 2010. T-matrix based and considering the Rayleigh scattering, a power-law scattering amplitude functions are fitted for S-band radar. Beside the operator also consider the effect of tumbling and tilting while the ice-phase meteors fallen. Also, near the melting layer, the mixing-phase meteors are also considered, which could simulated the bright band effect. The equation demonstrated below is the calculation of reflectivity for rain.

$$Z_{h,r} = \frac{4\lambda^4 {\alpha_{ra}}^2 N_{0r}}{\pi^4 |K_w|^2} {\Lambda_r}^{-(2\beta_{ra}+1)} \Gamma(2\beta_{ra}+1)(mm^6 m^{-3}) \quad (1)$$

The α_{ra} and β_{ra} are the coefficients of the scattering amplitude function. λ is the s-band radar lenghth. K_w is for the dieletric variables. Λ_r and N_{0r} are derived by the mixing ratio and total number concentration. The reflectivity of snow and graupel could also be calculated by the similar equation above. Finally, sum up the reflectivity contributed by all the meteors, than the total reflectivity could be converted.

B) The reflectivity operator used in the 3DVAR.

The radar reflectivity was partitioned into the reflectivity of each hydrometeor type based on the model background temperature by using the hydrometeor classification method and then converted to the hydrometeor mixing ratio.

The observed reflectivity (Z_o) was converted from dBZ to $mm^6 \cdot m^{-3}$, which is the unit for input reflectance (Z_e) and is expressed as

$$Z_o = 10 \log_{10} Z_e. \quad (2)$$

Z_e can be expressed as

$$Z_e = Z_r + Z_{ds} + Z_{ws} + Z_g, \quad (3)$$

because it is a volume average that is observed by several hydrometeors, such as rain (r), dry snow (ds), wet snow (ws), and graupel (g) [27–29].

For the precipitation echo data assimilation ($Z_o > -15$ dBZ), Wang et al. (2013) classified hydrometeors by using the model's temperature field (T (K)). Rain exists in a grid with a temperature of $T \geq 5$ °C, and a grid temperature of $-5°C < T < 5$ °C assumes that rain, wet snow, hail, and dry snow can coexist (Equations (4)–(7)). The α in Equations (5)–(6) represents a value of zero at −5 °C with $\alpha = 1$ at 5 °C, and it varies linearly between zero and one with the model temperature (Equation (8)).

$$Z_e = Z_r \ (5 \text{ °C} \leq T).$$

$$Z_e = \alpha Z_r + (1 - \alpha)[Z_{ws} + Z_g] \ (0 \text{ °C} < T < 5 \text{ °C}).$$

$$Z_e = \alpha Z_r + (1 - \alpha)[Z_{ds} + Z_g] \ (-5\ °C < T \leq 0\ °C).$$

$$Z_e = Z_{ds} + Z_g \ (T \leq -5\ °C).$$

$$\alpha = \frac{T + 5°C}{10°C} \quad (-5\ °C < T \leq 5\ °C).$$

The reflectivity of the hydrometeors was converted into the mixing ratio ($kg \cdot kg^{-1}$) of each hydrometeor by using the equation of the reflectivity–mixing ratio relationship. The hydrometeor mixing ratio was then used as an indirect assimilation method to assimilate reflectivity into the model [30].

$$q_r = [Z_r (\rho_a \times (3.63 \times 10^9)^{-1}]^{0.57}, \tag{9}$$

$$q_{ws} = [Z_{ws} (\rho_a \times (4.26 \times 10^{11})^{-1}]^{0.57}, \tag{10}$$

$$q_{ds} = [Z_{ds} (\rho_a \times (9.80 \times 10^8)^{-1}]^{0.57}, \tag{11}$$

$$q_g = [Z_g (\rho_a \times (4.33 \times 10^8)^{-1}]^{0.57}, \tag{12}$$

where ρ_a is the density ($kg \cdot m^{-3}$) of air. To create an environment in which convective clouds are actively maintained, the water vapor mixing ratio was nudged as the saturated water vapor mixing ratio when the observed reflectivity was greater than 30 dBZ. The saturated water vapor mixing ratio was calculated by using the Clausius–Clapeyron equation (e (hPa)) for water, and the water vapor saturation mixing ratio (q_s) was calculated as follows:

$$e = 6.112 \times \exp\left[\frac{L}{R_v}\left(\frac{1}{273.15} - \frac{1}{T}\right)\right], \tag{13}$$

$$q_s = \frac{\epsilon e}{p - (1-\epsilon)e}, \tag{14}$$

where L is $2.5 \times 10^6\ J \cdot kg^{-1}$ by heat of evaporation, R_v represents the gas constant of water vapor ($461.51\ J \cdot kg^{-1} \cdot K^{-1}$), ϵ is the ratio of the gas constant of dry air to the gas constant of water vapor, and P (hPa) is the pressure of the model.