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Supplement of

Impacts of secondary ice production on Arctic mixed-phase clouds based on ARM observations and CAM6 single-column model simulations

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The conservations of mass and number mixing ratios are ensured in the modified scheme. The tendencies of cloud hydrometeors are updated after we consider the SIP processes in the model. In the following equations, SIP related terms are in italic font and other processes are in the standard font:

For cloud ice:

\[
\begin{align*}
n_{\text{itend}} &= n_{\text{nuccd}} + n_{\text{nucct}} + n_{\text{nuccc}} + n_{\text{nudep}} + n_{\text{nsacwi}} + n_{\text{nsubi}} - n_{\text{prci}} - n_{\text{prai}} + n_{\text{nnuccri}} + nf_{1\text{mode}} + nf_{2\text{mode}} + nf_{isc} + nf_{ssc} + nf_{gisc} + nf_{ggc} \\
q_{\text{itend}} &= m_{\text{nuccd}} + m_{\text{nucct}} + m_{\text{nudep}} + m_{\text{msacwi}} - p_{\text{rci}} - p_{\text{rai}} + v_{\text{ap Dep}} + b_{\text{erg}} + \text{ice_sublim} + m_{\text{nuccd}} + m_{\text{nuccri}} + mf_{1\text{mode}} + mf_{2\text{mode}} + mf_{isc} + mf_{ssc} + mf_{gisc} + mf_{ggc}
\end{align*}
\]

For rain:

\[
\begin{align*}
n_{\text{rtend}} &= n_{\text{prc}} + (n_{\text{subr}} - n_{\text{pracs}} - n_{\text{nuccr}} - n_{\text{nuccri}} + n_{\text{nragg}} - nsipr) \\
q_{\text{rtend}} &= p_{\text{ra}} + p_{\text{rc}} + p_{\text{re}} - p_{\text{pracs}} - m_{\text{nuccr}} - m_{\text{nuccri}} - (mf_{1\text{mode}} + mf_{2\text{mode}} + mf_{big})
\end{align*}
\]

For snow:

\[
\begin{align*}
n_{\text{stend}} &= n_{\text{subs}} + n_{\text{nsagg}} + n_{\text{nuccr}} + n_{\text{prci}} + nf_{big} - nsips \\
q_{\text{stend}} &= p_{\text{rai}} + p_{\text{rci}} + p_{\text{saacws}} + b_{\text{ergs}} + p_{\text{rds}} + p_{\text{pracs}} + m_{\text{nuccr}} + mf_{big} - mf_{isc} - mf_{ssc} - mf_{gisc} - mf_{ggc}
\end{align*}
\]
in which the process names are listed as follows:

| Process Name | Description |
|--------------|-------------|
| nnuccd/mnuccd | homogeneous and heterogeneous nucleation from water vapor |
| nnucct/mnuct | contact freezing of cloud water |
| nnuccc/mnuccc | immersion freezing of cloud water |
| nnudep/mnudep | deposition nucleation in mixed-phase clouds |
| nsacwi/msacwi | H-M splintering |
| npcri/prci | autoconversion of cloud ice to snow |
| nprai/prai | accretion of cloud ice by snow |
| nnuccri/mnuccri | freezing of rain to form ice |
| vap_depl | deposition of cloud ice |
| ice_sublim/nsubi | sublimation of cloud ice |
| berg | WBF between cloud water and cloud ice |
| nprec/prc | autoconversion of cloud droplet to rain |
| nsubr/pre | evaporation of rain |
| npracs/pracs | collection of rain by snow |
| nnuccr/mnuccr | freezing of rain to form snow |
| nragg | self-collection of rain |
| pra | accretion of cloud water by rain |
| nsubs | sublimation of snow |
| nsagg | self-aggregation of snow |
| psacws | collection of droplets by snow |
| bergs | WBF between cloud water and snow |
| prds | sublimation of snow |
| nf_1mode/mf_1mode | SIP from the first mode of freezing rain break-up |
| nf_big/mf_big | SIP from the first mode of freezing rain break-up (big fragments) |
| nf_2mode/mf_2mode | SIP from the second mode of freezing rain break-up |
| nf_isc/mf_isc | SIP from cloud ice and snow collision |
| nf_ssc/mf_ssc | SIP from snow and snow collision |
| nf_gisc/mf_gisc | SIP from graupel and cloud ice/snow collision |
| nf_ggc/mf_ggc | SIP from graupel and graupel collision |
| nsipr | decrease of rain number due to SIP |
| nsips | decrease of snow number due to SIP |
Figure S1. Ice number concentrations as a function of normalized cloud height from cloud base from (a) observation, (b) CTL, (c) SIP_PHIL, and (d) CTL_no_HM. Black solid lines show the linear regression between ice number concentration and height. Only ice particles with diameters larger than 53 μm from observations and model simulations are included in the comparison, no anti-shattering tip is adopted in this Figure.
Figure S2. Ice number concentrations as a function of normalized cloud height from cloud base from (a) observation, (b) CTL, (c) SIP_PHIL, and (d) CTL_no_HM. Black solid lines show the linear regression between ice number concentration and height. Only ice particles with diameters larger than 100 µm from observations and model simulations are included in the comparison. A correction factor of 1/2 is applied to the observed ice number concentrations in (a).
Figure S3. The probability density function (PDF) of ice crystal number concentrations from observation (gray line), CTL (orange line), and SIP_PHIL simulations (green line). Only ice particles with diameters larger than 53 μm from observations and model simulations are included in the comparison, no anti-shattering tip is adopted in this Figure.
Figure S4. The probability density function (PDF) of ice crystal number concentrations from observation (gray line), CTL (orange line), and SIP_PHIL simulations (green line). Only ice particles with diameters larger than 100 μm from observations and model simulations are included in the comparison. A correction factor of 1/2 is applied to the observed ice number concentrations.
Figure S5. Bivariate joint probability density function of ice enhancement defined in terms of both temperature and ice enhancement. The ice enhancement is defined as \( \log_{10}(N_{\text{SIP\_PHIL}} / N_{\text{CTL}}) \).