Secondary ice production in NorESM2 climate model: quantifying the impact on Arctic clouds

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Well-known Secondary Ice Production (SIP) Mechanisms

- Climate models include only one SIP mechanism: the Hallet-Mossop process (active only between -8°C and -3°C)

- In NorESM2, rime-splintering (Hallet-Mossop) occurs only after collisions of cloud droplets with snow (contribution from raindrops is not accounted)

Korolev et al. 2020
### Implementation of missing SIP processes in NorESM2

<table>
<thead>
<tr>
<th>Sensitivity simulation</th>
<th>Set-up</th>
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<tr>
<td>CNTRL</td>
<td>Standard NorESM2 (SIP only through Hallet-Mossop &amp; after cloud drop – snow collisions)</td>
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<tr>
<td>HMrain</td>
<td>Hallet-Mossop is also activated after raindrop-snow collisions</td>
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<tr>
<td>DSH</td>
<td>Drop-Shattering is the only active SIP mechanism. It occurs after rain – snow &amp; rain – cloud ice collisions, &amp; after immersion freezing. Description follows Phillips et al. 2018</td>
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<tr>
<td>BRphil</td>
<td>Collisional break-up is the only active SIP mechanism. It occurs after cloud ice – snow and snow – snow collisions. Description follows Phillips et al. 2017</td>
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<tr>
<td>BRtak</td>
<td>Collisional break-up the only active SIP mechanism. Description follows Takahashi et al. 1995, but scaled for size as in Sotiropoulou et al. 2021</td>
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</tbody>
</table>
Simulations of Arctic clouds observed at Ny-Alesund (06/2016-12/2017)

- Ice multiplication is most pronounced in HMrain and BRtak at temperatures above -20°C, increasing median ICNCs (ice crystal number concentrations) by a factor of ~5

- IWC enhancement is very weak; IWC (ice water content) remains substantially underestimated in all simulations
Impact of aggregation on collisional break-up efficiency

- Ice aggregation has no impact when collisional break-up is deactivated.
- Ice aggregation limits the efficiency of collisional break-up.
- BRtak without ice aggregation is the only simulation that reproduces observed IWC; it produces 50 times larger median ICNCs at temperatures below -20°C.
Activation of all SIP mechanisms simultaneously

- Only the simulation with BR following Takahashi et al. (1995) (but scaled) and deactivated aggregation compares relatively well to observations. This gives very similar results to BR_tak (suggesting negligible contribution from other mechanisms)

Solid lines: 10% of ice-ice collisions result in aggregation
Dashed lines: no aggregation
Ice multiplication effects on Liquid Water Path (LWP)

- The simulation (panel d) with more realistic IWC and ice effective radius also gives more realistic LWP
- Simulations with larger ICNCs also produce larger LWP (likely due to enhanced sublimation of the smaller precipitation particles)

**ALL SIP simulations are performed with Takahashi et al. 1995 scaled BR parameterization**
Ice multiplication effects on surface net radiation

- Activating all SIP mechanisms in NorESM2 has hardly any impact on surface radiation (panel a), due to the fact that the 5-fold enhancement in ICNCs has little effect on ice and liquid macrophysical properties.

- Activation of SIP in combination with deactivated aggregation (panel b) can alter the net radiation budget by up to -5 – -10 Wm\(^{-2}\) in several Arctic regions. This is the simulation that best conforms with observations.
Conclusions:

- Activation of all SIP mechanisms in NorESM2 results in a ~5-fold ICNC enhancement at temperature above -20°C, compared to CNTRL. This has a weak enhancing impact on IWC and LWP, and thus hardly any impact on surface radiation.

- Deactivation of ice-ice aggregation enhances the efficiency of collisional break-up (BR) by almost a factor of 10 at warm subzero temperatures, thus this process eventually dominates ice multiplication.

- The simulation with Takahashi et al. (1995) scaled BR parameterization and deactivated aggregation results in best agreement with IWC and LWP observations. This set-up enhances median ICNCs by a factor of 50 compared to CNTRL at Temp>-20°C, and alters surface net radiation budget by ~ -10 to -5 W m⁻² in several Arctic regions.


