Aerosol-cloud interactions in mixed-phase clouds and their role for climate

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What is a mixed-phase cloud?
Why mixed-phase clouds?
Southern Ocean bias and mixed-phase clouds

The ice fraction $f$ is given in CAM as:

- $f = 0$; for $T > T_{\text{ice}}$, $T_{\text{ice}} = 268$ K in the control experiment
- $T_{\text{ice}} = 253$ K in the sensitivity experiment
- $f$ increases linearly up to $f = 1$ for $T \leq 238.15$ K

Kay et al., 2016
Working principle of our holographic device

Lohmann et al., 2016
Classification of cloud droplets/ice crystals

Convolutional Neuronal Network

Input layer

Filter first layer: simple shapes

Filter higher layers: more complex shapes

“Black box”

Top layer

Output layer

Water droplet

1%

Ice particle

0%

Artifact

99%
Observation of mixed-phase clouds

Lohmann et al. 2016, GRL

Ice water fraction:

Ice water (IWC) / total water (TWC)

North-West (NW)

North-East (NE)

South-East (SE)

Jungfraujoch (JFJ)
Origin of cloud droplets – inferred from model results with COSMO

NW wind cases

SE wind cases

Lohmann et al., GRL, 2016
Origin of the ice crystals?

Beck et al., ACP, 2018
Origin of the ice crystals?

Expectations from surface-based processes:

- Mainly irregular ice crystals
- Decrease of ICNC with height

Beck et al., ACP, 2018
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- Mainly irregular ice crystals
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Beck et al., ACP, 2018
Mountain-top in-situ measurements are influenced by surface processes.

Measurement at Sonnblick observatory (SBO), Austria.
Origin of the ice crystals?

Beck et al., ACP, 2018
• Our holographic measurements provide information of the distribution of cloud particles on the mm-scale

• Ice nucleation and surface-based processes alone cannot explain the observed ice crystal number concentrations at Jungfraujoch

• Cloud droplets in orographic clouds are replenished in high updraft cases
Response of clouds to CO₂ doubling

- The net radiative feedback due to all cloud types is *likely* positive.

- Rising of the melting level causes more liquid instead of ice clouds → higher optical depth → negative cloud feedback.
The higher SLF (liquid/(liquid+ice)) in the current climate, the smaller the negative cloud phase feedback

→ larger ECS

Similar results in other models?

Tan et al., Science, 2016
### Sensitivity studies with ECHAM6-HAM2

<table>
<thead>
<tr>
<th>Sim.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF</td>
<td>Release version ECHAM6.3-HAM2.3</td>
</tr>
<tr>
<td>ALL_ICE</td>
<td>no supercooled liquid water at $T &lt; 0 , ^\circ \text{C}$</td>
</tr>
<tr>
<td>ALL_LIQ</td>
<td>only supercooled liquid water at $T &gt; -35 , ^\circ \text{C}$</td>
</tr>
</tbody>
</table>

Lohmann and Neubauer, ACP, 2018
Annual global mean cloud properties

Cloud water (mg/kg)

Cloud ice (mg/kg)

Cloud fraction (%)
ECHAM also underestimates SLF, but less than CESM
→ do we also underestimate ECS? And if so, by how much?

CESM Figure from Tan et al. (2016)
Components of the globally averaged cloud feedback parameters

\[ \lambda_c (\text{W/m}^2\text{K}^{-1}) \]
Equilibrium climate sensitivity

No ECS shift from cloud phase feedback between the reference simulation and ALL_LIQ in ECHAM6-HAM2 despite the smaller cloud phase feedback → why not?

CESM Figure from Tan et al. (2016)
ALL_ICE: larger shift from optically thin to optically thick low and mid-level clouds than in REF
ALL_LIQ: high level clouds become optically thicker than in REF
Why is the cloud phase feedback not important in ALL_LIQ?
Changes of tropical clouds (15°S – 15°N) in a warmer climate
Changes of cloud properties in a warmer climate

ΔCloud water (2xCO2-1xCO2)

ΔCloud ice (2xCO2-1xCO2)

ΔCloud fraction (2xCO2-1xCO2)
Changes in cloud radiative effects (CRE) in a warmer climate

CRE (radiative kernel method; only changes in clouds)

CRE (includes changes in water vapor, CO₂, surface temperature, albedo)
Impact of a new ice microphysics scheme

With our new ice microphysics scheme (Dietlicher et al., ACPD, 2018) the cloud optical depth feedback becomes positive and climate sensitivity increases to 3.8 °C (vs. 2.5 °C in REF)
The supercooled liquid fraction is not a good indicator for the cloud phase feedback because cloud phase matters most for clouds not shielded by higher clouds.

If cloud phase changes for optically thick clouds then changes in the shortwave and longwave compensate each other (consistent with the findings by Bodas-Salcedo, 2018).

ECS is significantly higher when using the new ice microphysics scheme (Dietlicher et al., ACPD, 2018) with 3.8 °C vs. 2.5 °C. The reasons for this require further analysis but could be linked to a smaller contribution of mixed-phase clouds in that scheme.
## Classification

### Train and test on same dataset (accuracy %)

<table>
<thead>
<tr>
<th>Simple approach</th>
<th>Normal tree</th>
<th>SVM</th>
<th>Deep Learning</th>
</tr>
</thead>
<tbody>
<tr>
<td>88.6 ± 3.3</td>
<td>95.3 ± 1.4</td>
<td>98.1 ± 0.7</td>
<td>97.4 ± 0.5</td>
</tr>
</tbody>
</table>

### Train on four datasets, test on unseen dataset (accuracy %)

<table>
<thead>
<tr>
<th>Year</th>
<th>Dataset</th>
<th>Simple approach</th>
<th>Normal tree</th>
<th>SVM</th>
<th>Deep Learning</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>iHOLIMO 3G</td>
<td>70.4</td>
<td>89.6</td>
<td>95.5</td>
<td>96.2 ± 0.2</td>
</tr>
<tr>
<td>2016</td>
<td>iHOLIMO 3M</td>
<td>61.7</td>
<td>94.7</td>
<td>96.3</td>
<td>98.0 ± 0.2</td>
</tr>
<tr>
<td>2016</td>
<td>JFJ 3G</td>
<td>72.0</td>
<td>90.4</td>
<td>95.0</td>
<td>96.8 ± 0.2</td>
</tr>
<tr>
<td>2016</td>
<td>SON 3G</td>
<td>71.8</td>
<td>81.1</td>
<td>75.7</td>
<td>91.1 ± 1.6</td>
</tr>
<tr>
<td>2017</td>
<td>SON 3G</td>
<td>87.1</td>
<td>90.5</td>
<td>82.6</td>
<td>97.0 ± 1.0</td>
</tr>
</tbody>
</table>
Annual-zonal mean cloud properties