Possible albedo reduction due to light absorbing impurities in snowpack observed at various sites

SIGMA-A in Greenland

SIGMA-II

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Outline

✓ By reviewing the black carbon (BC) concentrations measured at various sites over the world, the possible albedo reductions are estimated using a physically-based snow albedo model.

✓ Characteristics of the albedo reduction by BC are discussed in terms of the measurement region and measurement technique.

✓ The albedo reductions, radiative forcing, and snowmelt due to BC and dust at Sapporo, Japan, highly polluted mid-latitudinal region, are calculated from the 10-year snow and meteorological data.
Feedback effect of snow albedo reduction

✓ Albedo of snow strongly depends on snow grain size and impurity concentration.

✓ Albedo reduction rate by impurities also depends on snow grain size as well.

← Feedback works on snow albedo through grain size and impurity concentration.

Snow pollution by impurities

Visible albedo reduction

Increase of absorbed solar radiation by snow

Acceleration of melting and sintering of snow grains

Increase of snow grain size

Near-infrared albedo reduction

Visible Near-infrared (NIR)

UV Albedo of snow strongly depends on snow grain size and impurity concentration.

Albedo reduction rate by impurities also depends on snow grain size as well.

Feedback works on snow albedo through grain size and impurity concentration.
### BC concentrations measured over the world

<table>
<thead>
<tr>
<th>Area</th>
<th>BC conc.: median or mean (range) [ppbw]</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antarctica</td>
<td>0.25 (0.1-2.5) 0.07-0.29 (0.04-2.69)</td>
<td>Chýlek + (1987) , Warren and Clarke (1990), Grenfell + (1994), Bisiaux + (2012a-b), Casey + (2017), Khan + (2018), Marquetto + (2019), Kinese + (2020)</td>
</tr>
<tr>
<td>Arctic other than GrIS</td>
<td>1.0-87.6 (0.0-150.9) 0.97-3.71 (0.7-7.16)</td>
<td>Clarke and Noone (1985), Grenfell + (2002), Hegg + (2009), Perovich + (2009), Doherty + (2010), Forsström + (2009), Forsström + (2013), Meinander + (2013), Svensson + (2013), Pedersen at al. (2014), Mori + (2019)</td>
</tr>
</tbody>
</table>
Albedo reduction due to snow impurities and snow grain growth

- Albedo reduction by snow grain growth from $r_{\text{eff}} = 50 \, \mu\text{m}$ to $1000 \, \mu\text{m}$ is larger (0.14) than that by very high concentration BC.
- Albedo in Antarctic snow is not affected by BC in any case of snow grain size.
- GrIS albedo reduction due to BC is small around 0.006 for $r_{\text{eff}} = 50 \, \mu\text{m}$ (new snow) and 0.026 for $r_{\text{eff}} = 1000 \, \mu\text{m}$ (melting snow), suggesting a few percent of albedo reduction could occur under warmer climate condition due to enhanced snow metamorphism.
- The maximum albedo reduction for $r_{\text{eff}} = 50 \, \mu\text{m}$ (1000 $\mu\text{m}$) is 0.015 (0.064) in the Arctic except GrIS and 0.070 (0.24) for $r_{\text{eff}} = 50 \, \mu\text{m}$ (1000 $\mu\text{m}$) in mid-latitudes.

Albedo reduction calculated with a physically based snow albedo model (PBSAM: Aoki et al., 2011) as a function of BC concentration for two typical snow grain radii ($r_{\text{eff}}$).
Uncertainties of BC measurements

SP2 measurements

All previous measurements

- BC concentrations measured with SP2 are, in general, lower than the previous measurements, as described by Schwarz et al. (2011) and Mori et al. (2019).
- BC pollution in snow improved.
- Previous measurements underestimate.
- Inter-comparison of BC measurement techniques (ISSW, TOT, TOR, and SP2) is needed for various snow types mixed with the other impurities.
Albedos and snow impurity concentrations measured at Sapporo, Japan during 10 winters from 2007 to 2017

Sapporo
43°N, 141°E, 15 m a.s.l.

10-year median (10th and 90th percentiles)
BC = 196 ppbw
(29 – 1138 ppbw)
Dust = 2,700 ppbw
(250-36,557 ppbw)
Albedo reduction ($\Delta\alpha$) and radiative forcing ($RF$) by snow impurities

Impure and pure snow albedos are calculated with PBSAM.

Snow impurity conc. (ppbw)

Snow grain radius (mm)

Broadband albedo

Albedo change:

$\Delta\alpha_{BC+Dust} = \alpha_{BC+Dust} - \alpha_{pure}$

$\Delta\alpha_{BC} = \alpha_{BC+Dust} - \alpha_{Dust}$

$\Delta\alpha_{Dust} = \alpha_{BC+Dust} - \alpha_{BC}$

Radiative forcing:

$RF = F_{\downarrow \uparrow}^{\text{impure}} - F_{\downarrow \uparrow}^{\text{pure}}$

$F_{\downarrow}$: Downward flux

= observed value

$= F_{\downarrow}^{\text{impure}} (\alpha_{pure} - \alpha_{impure})$

$= F_{\downarrow}^{\text{impure}} (-\Delta\alpha)$
Albedo reduction ($\Delta \alpha$) and radiative forcing ($RF$) by snow impurities

Snow impurity radiative forcing

$$RF = F_{\downarrow}(-\Delta \alpha)$$

Albedo change and radiative forcing averaged for 10 winters

<table>
<thead>
<tr>
<th>Snow impurity</th>
<th>$\Delta \alpha$</th>
<th>$RF$ (Wm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC+Dust</td>
<td>-0.053</td>
<td>+6.7</td>
</tr>
<tr>
<td>BC</td>
<td>-0.045</td>
<td>+5.4</td>
</tr>
<tr>
<td>Dust</td>
<td>-0.008</td>
<td>+1.3</td>
</tr>
</tbody>
</table>

✓ BC effects for both $\Delta \alpha$ and $RF$ are several times higher than those for dust.
Difference in $\Delta \alpha$ and RF between accumulation and melting periods

- Albedo reduction and radiative forcing by snow impurities in the melting season are much higher than those in accumulation season.

<table>
<thead>
<tr>
<th>Period</th>
<th>Snow impurity</th>
<th>$\Delta \alpha$</th>
<th>RF (Wm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acc.</td>
<td>BC+Dust</td>
<td>-0.031</td>
<td>+3.0</td>
</tr>
<tr>
<td></td>
<td>BC</td>
<td>89%</td>
<td>88%</td>
</tr>
<tr>
<td></td>
<td>Dust</td>
<td>11%</td>
<td>12%</td>
</tr>
<tr>
<td>Melt</td>
<td>BC+Dust</td>
<td>-0.151</td>
<td>+25.0</td>
</tr>
<tr>
<td></td>
<td>BC</td>
<td>77%</td>
<td>76%</td>
</tr>
<tr>
<td></td>
<td>Dust</td>
<td>23%</td>
<td>24%</td>
</tr>
</tbody>
</table>
Contribution of snow impurities to snowmelt

10-winter averaged contributions to snowmelt (mm w.e.)

- **Pure snow (Sfc)**
- **Bottom melt**
- **Dust 28 (7%)**
- **BC 87 (23%)**
- **Bottom snow 99 (27%)**
- **Total snowmelt = 393 mm w.e.**

Snowmelt was calculated from the energy budget at snow surface and bottom.

Melting energy by snow impurity-induced albedo reduction is equivalent to 30% of total snowmelt, which is larger than the bottom melt (27%).

Contributions from dust and BC to total snowmelt are 7% and 23%, respectively.
Summary

✓ For areas where snow is weakly contaminated by BC such as Greenland Ice Sheet the albedo reduction due to the present level of BC is small for small grain size snow, but a few percent of albedo reduction could occur due to enhanced snow metamorphism under future warmer climate conditions.

✓ Since there might be some uncertainties in the previous BC measurements, inter-comparison of BC measurement techniques is needed for various snow types mixed with the other impurities.

✓ Albedo reduction in highly polluted area such as mid-latitudes including Sapporo cannot be ignored even in case of new snow and is more serious for melting snow.

✓ At Sapporo, the albedo reduction due to snow impurities (BC+dust) averaged during 10 winters from 2007 was 5.3% and the radiative forcing +6.7 Wm$^{-2}$, and the melting energy due to snow impurity-induced albedo reduction is equivalent to 30% (23% by BC and 7% by dust) of the total snowmelt (393 mm w.e.).