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

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Outline

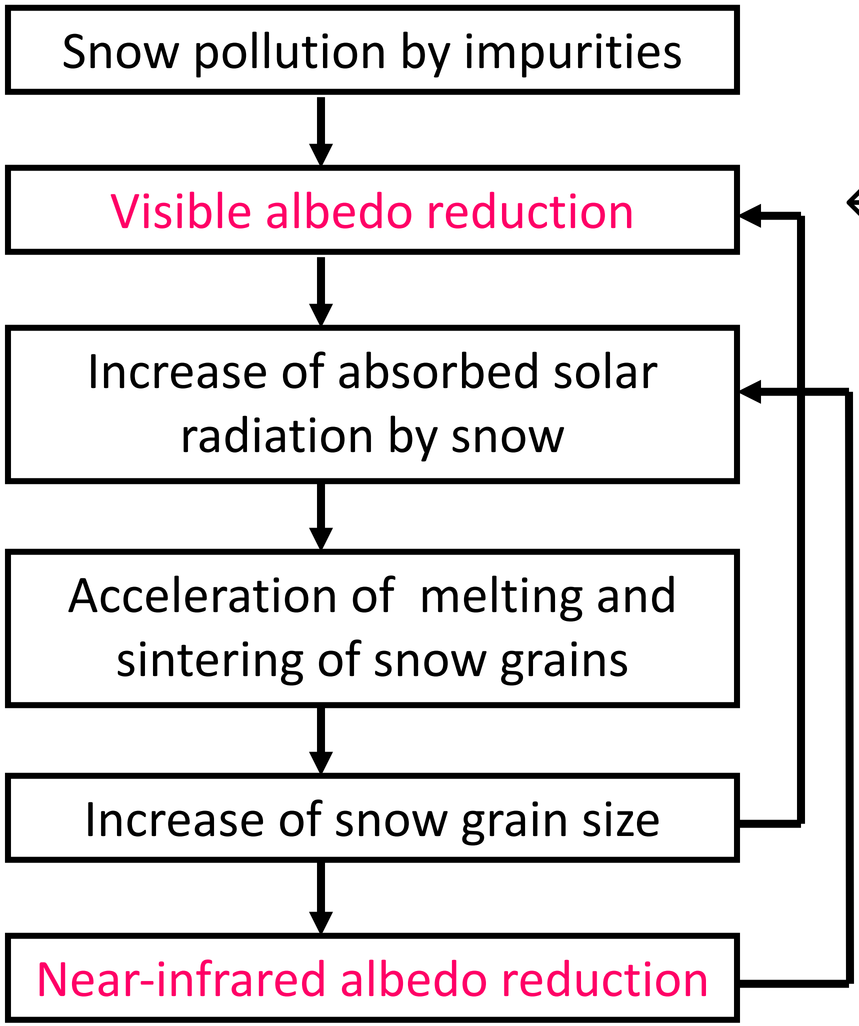
- ✓ Based on the black carbon (BC) concentrations measured at various sites over the world, the possible albedo reductions are estimated using a physically-based snow albedo model.
- ✓ Characteristics of the albedo reduction by BC are discussed in terms of the measurement region and measurement technique.
- ✓ 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.

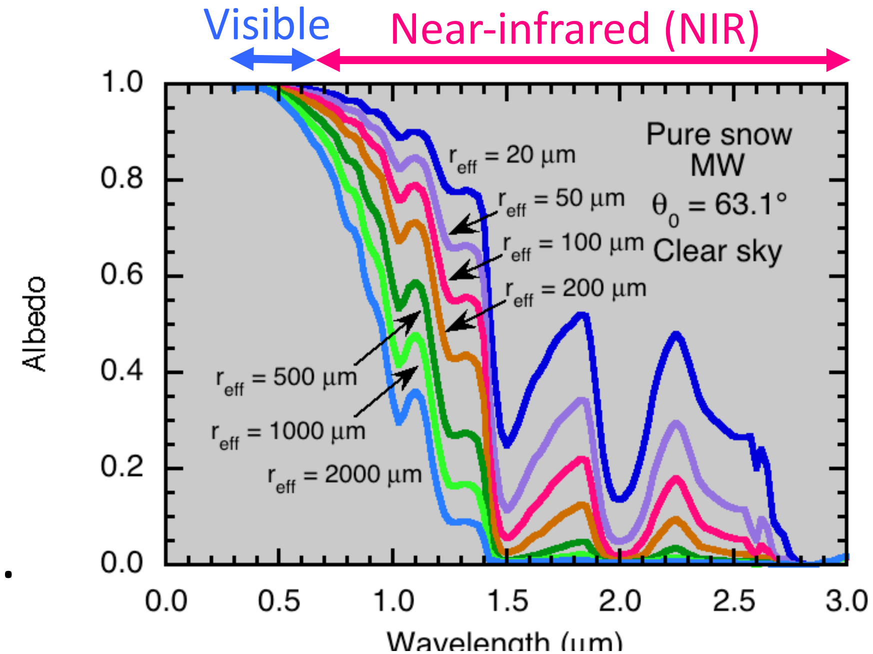
Feedback effect of snow albedo reduction

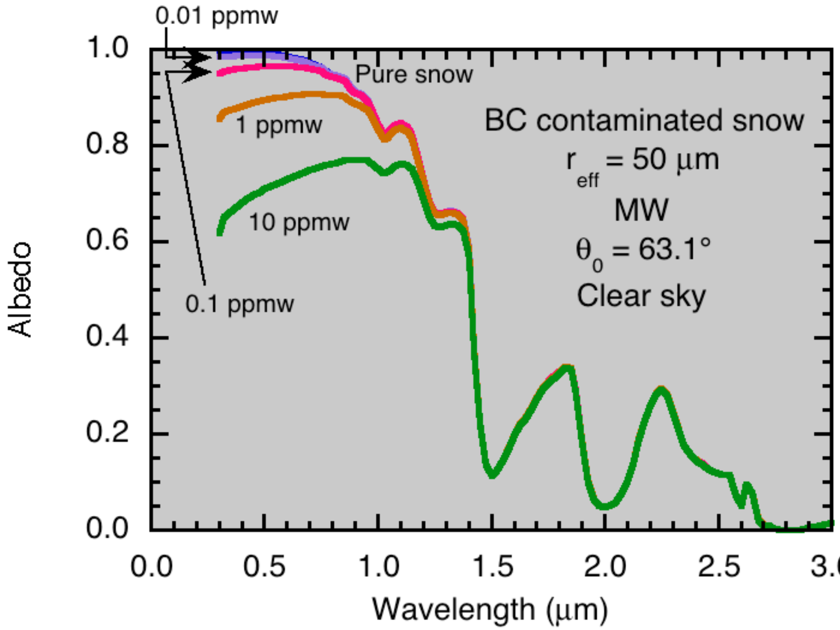
✓ Albedo of snow strongly depends on snow grain size and impurity concentration.

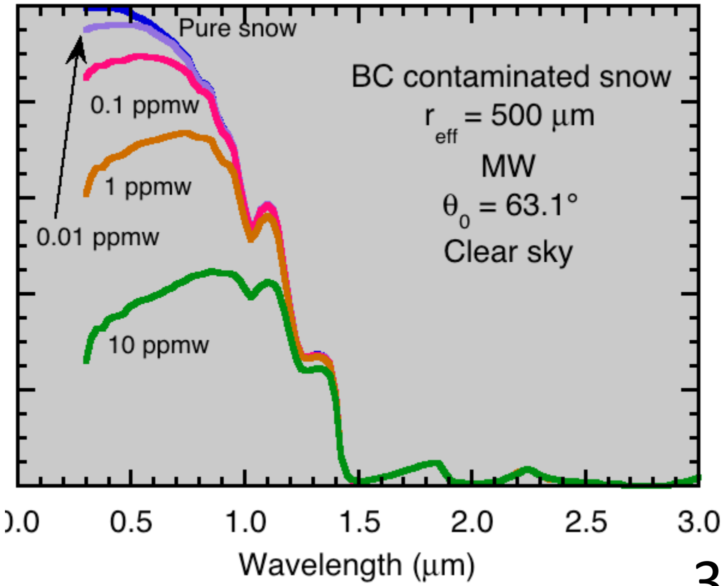
✓ Albedo reduction rate by impurities also depends on snow grain size as well.

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





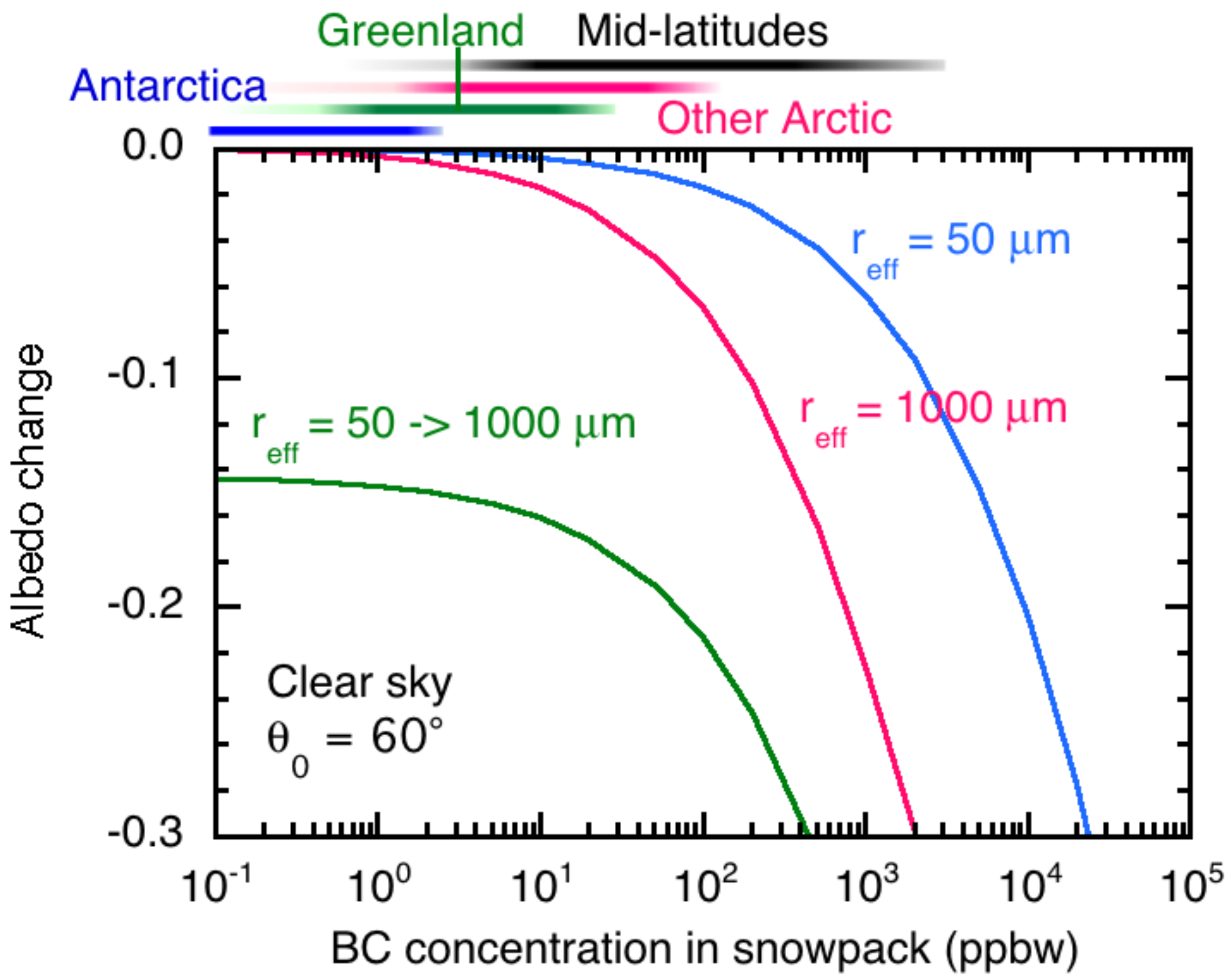




BC concentrations measured over the world

Area	BC conc.: median or mean (range) [ppbw]	References Red letters: SP2measurements
Antarctica	0.25 (0.1-2.5) 0.07-0.29 (0.04-2.69)	Chýlek + (1987) , Warren and Clarke (1990), Grenfell + (1994), Bisiaux + (2012a-b), Casey + (2017), Khan + (2018), Marquetto + (2019), Kinese + (2020)
Greenland ice sheet (GrIS)	0.55-20 (0.03-30.1) 0.65-2.3 (0.52-5)	Clarke and Noone (1985), Chýlek + (1987), Chýlek + (1995), Slater + (2002), Hegg + (2009), Hagler + (2007), McConnell + (2007), Forsström + (2009) , Carmagnola + (2013), Doherty + (2010), Doherty + (2013), Aoki + (2014), Mori + (2019)
Arctic other than GrIS	1.0-87.6 (0.0-150.9) 0.97-3.71 (0.7-7.16)	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)
Mid-latitudes other than Tibet and Himalaya	4-1220 (0.8-3707) No median data (1.4-50)	Grenfell + (1981), Clarke and Noone (1985), Chýlek + (1987), Sergent + (1993), Fily + (1997), Sergent + (1998), Lavanchy + (1999), Chýlek + (1999), Hadley + (2008), Doherty + (2014), Ye + (2012) , Wang + (2013), Kuchiki + (2015), Kaspari + (2014), Delaney + (2015)

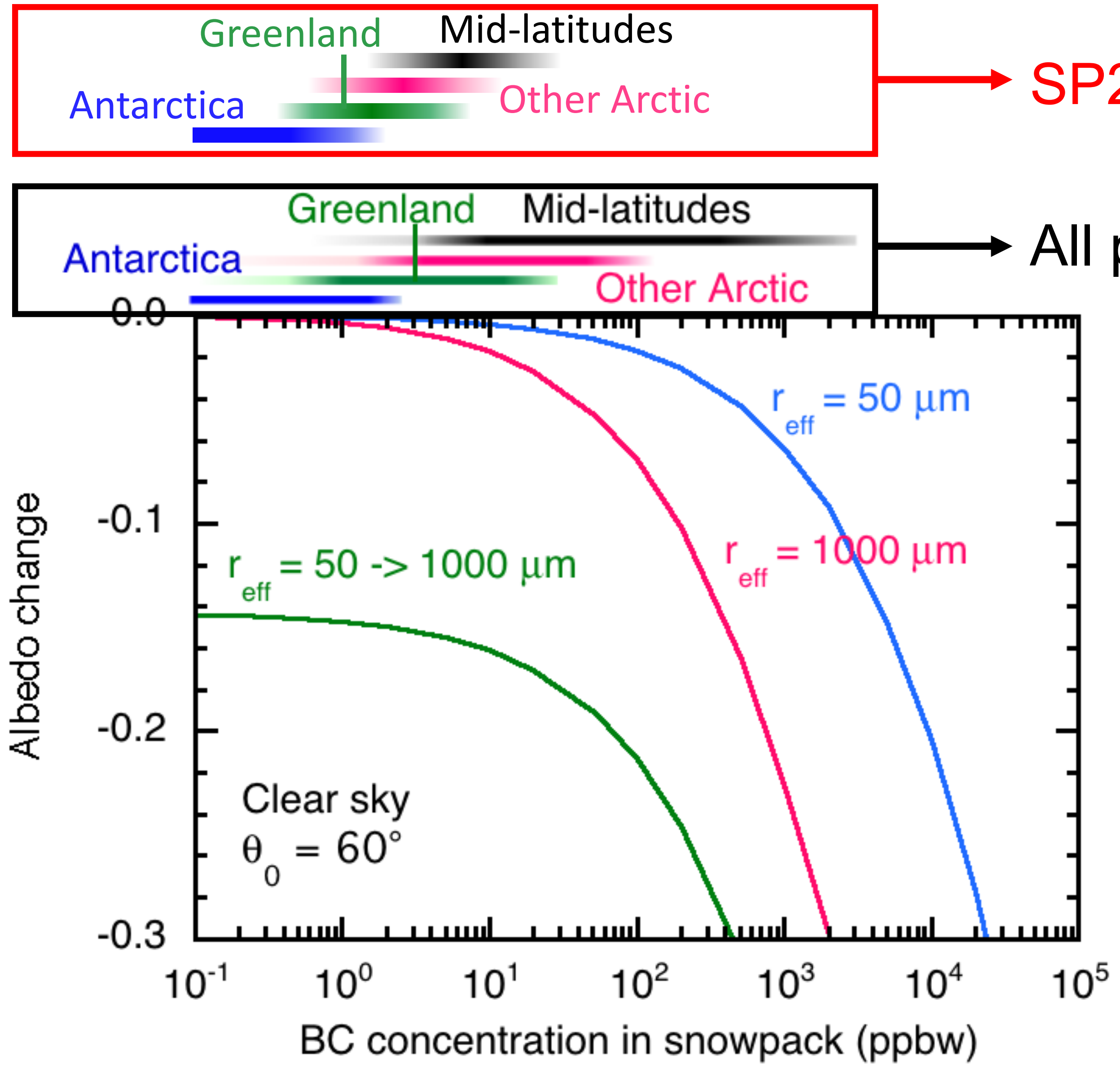
Albedo reduction due to snow impurities and snow grain growth



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_{eff}).

- ✓ Albedo reduction by snow grain growth from r_{eff} = 50 μm to 1000 μm 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_{eff} = 50 μm (new snow) and 0.026 for r_{eff} = 1000 μm (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_{eff} = 50 μm (1000 μm) is 0.015 (0.064) in the Arctic except GrIS and 0.070 (0.24) for r_{eff} = 50 μm (1000 μm) in mid-latitudes.

Uncertainties of BC 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).

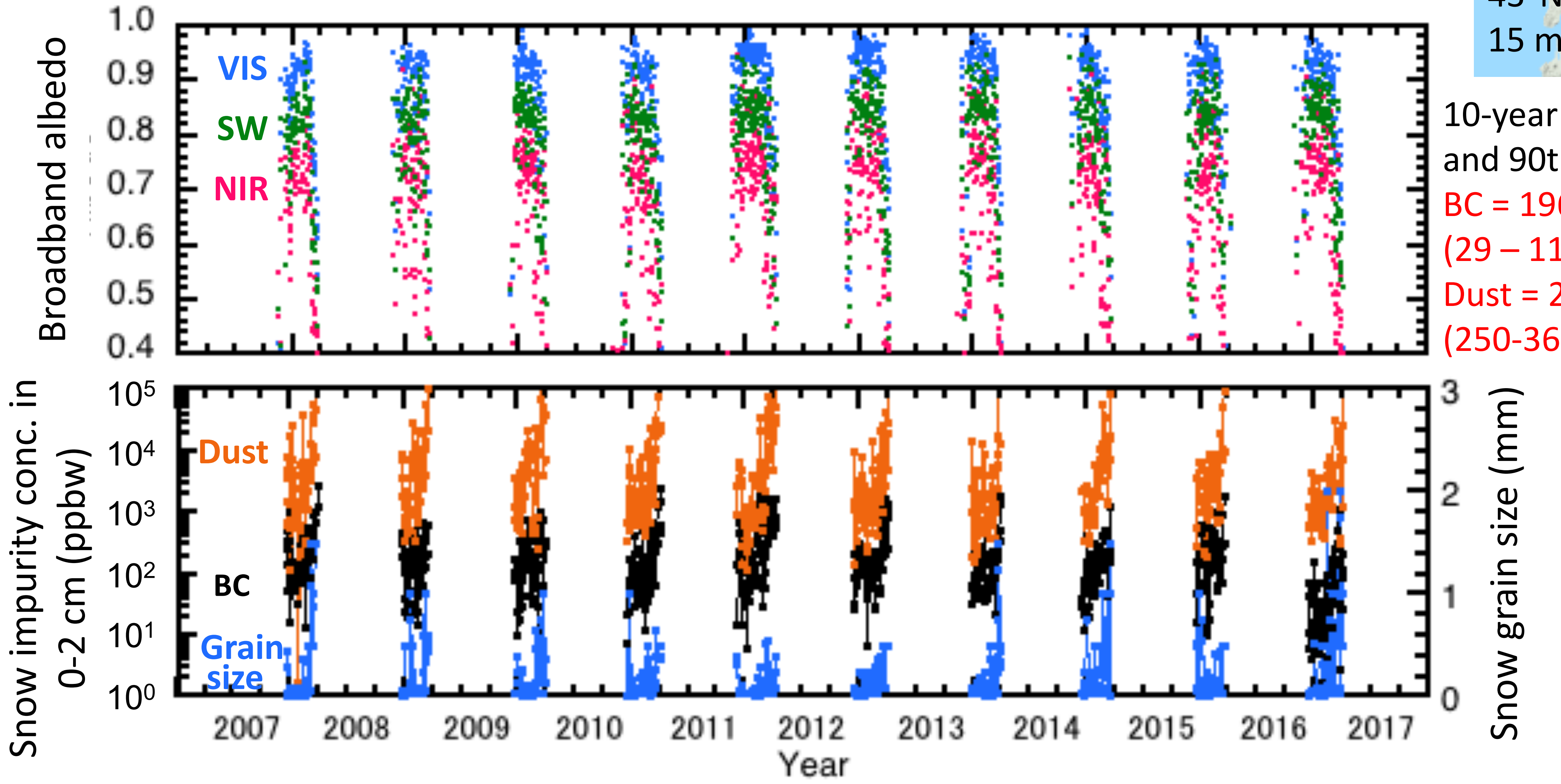
↓

- 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



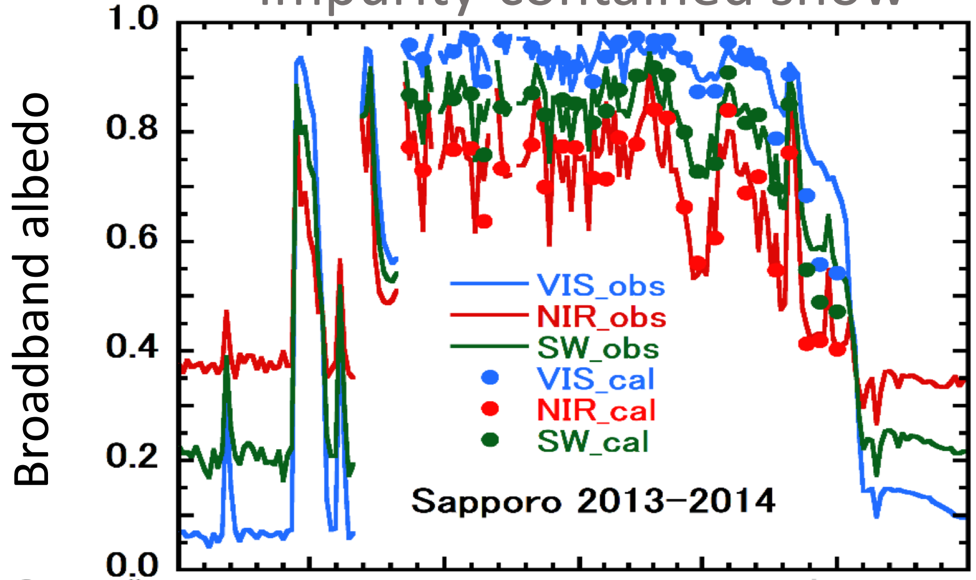
10-year median (10th and 90th percentiles)

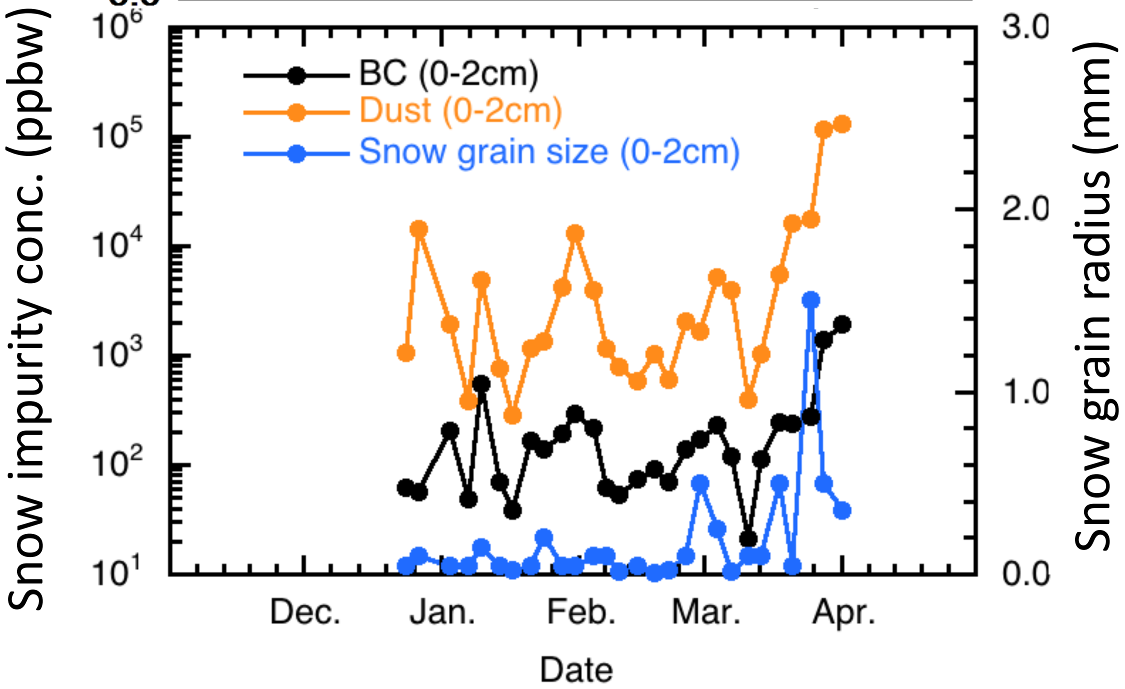
BC = 196 ppbw (29 – 1138 ppbw)

Dust = 2,700 ppbw (250-36,557 ppbw)

Albedo reduction ($\Delta\alpha$) and radiative forcing (RF) by snow impurities

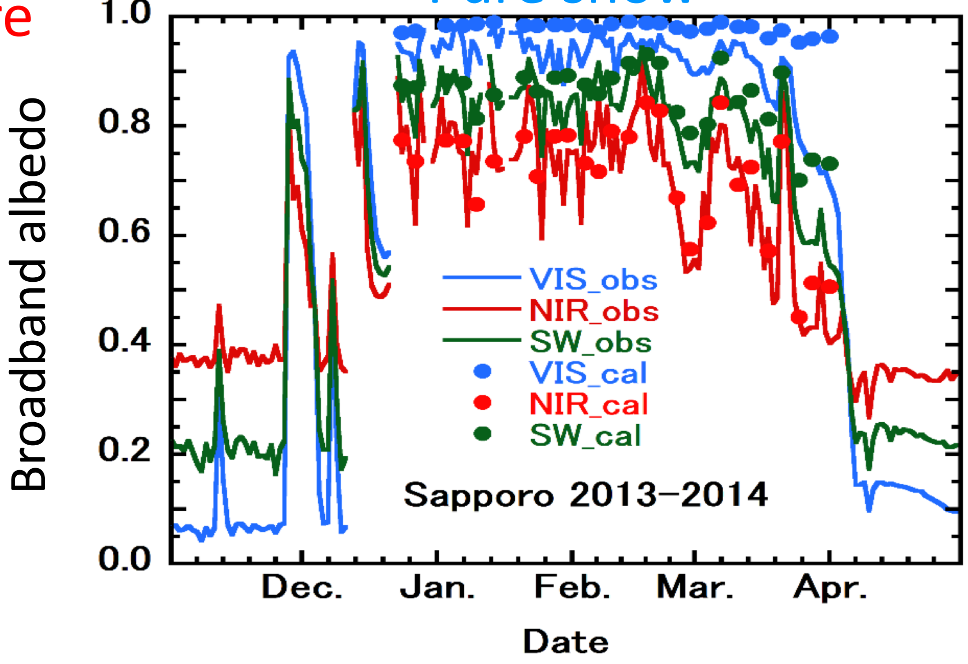
Impurity-contained snow





Impure and pure snow albedos are calculated with PBSAM.

Pure snow



$F^{\downarrow}$: Downward flux = observed value

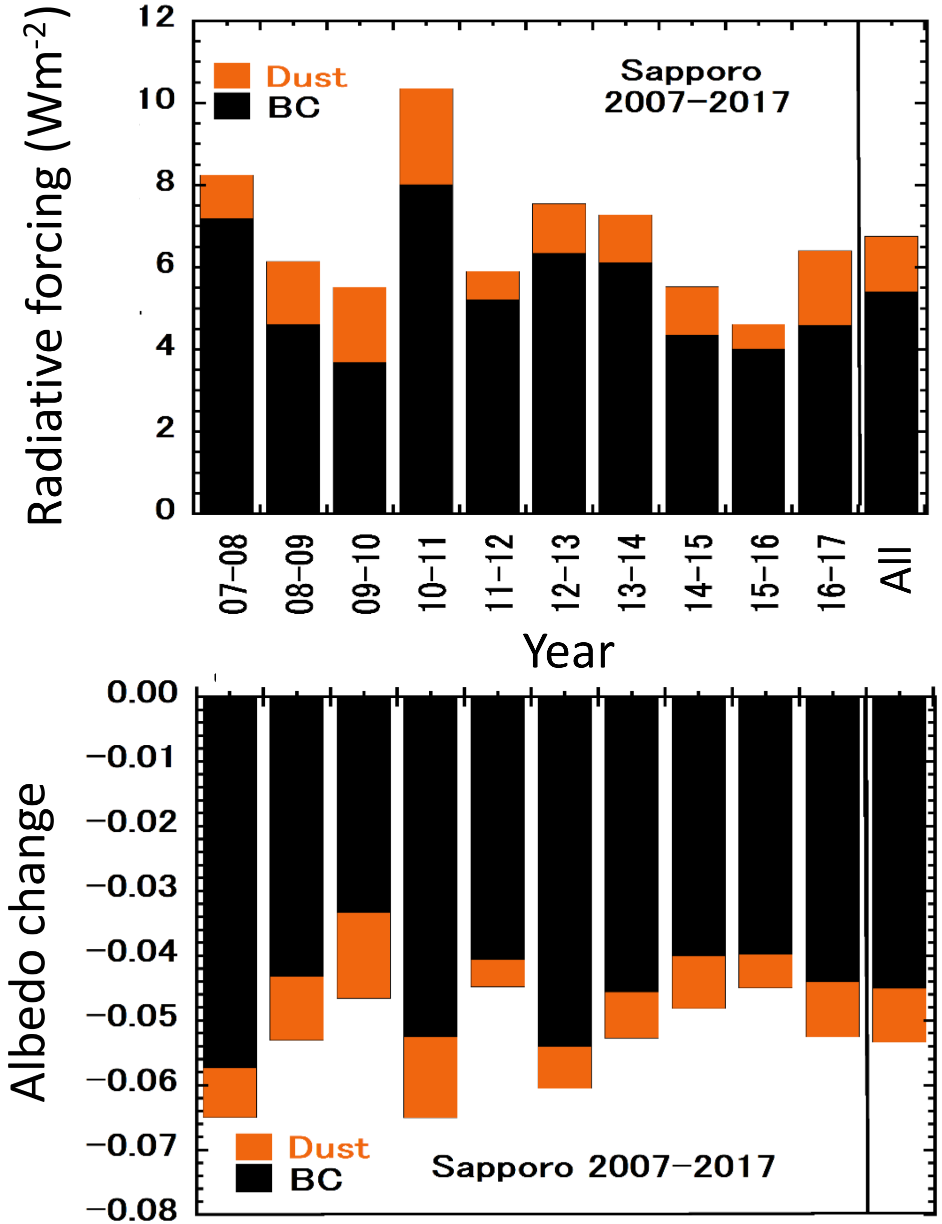
Albedo change:

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

Radiative forcing:

$$RF = F^{\downarrow-\uparrow}{}_{impure} - F^{\downarrow-\uparrow}{}_{pure}$$
$$= F^{\downarrow}(\alpha_{pure} - \alpha_{impure})$$
$$= F^{\downarrow}(-\Delta\alpha)$$

Albedo reduction (Δα) and radiative forcing (*RF*) by snow impurities



Snow impurity radiative forcing

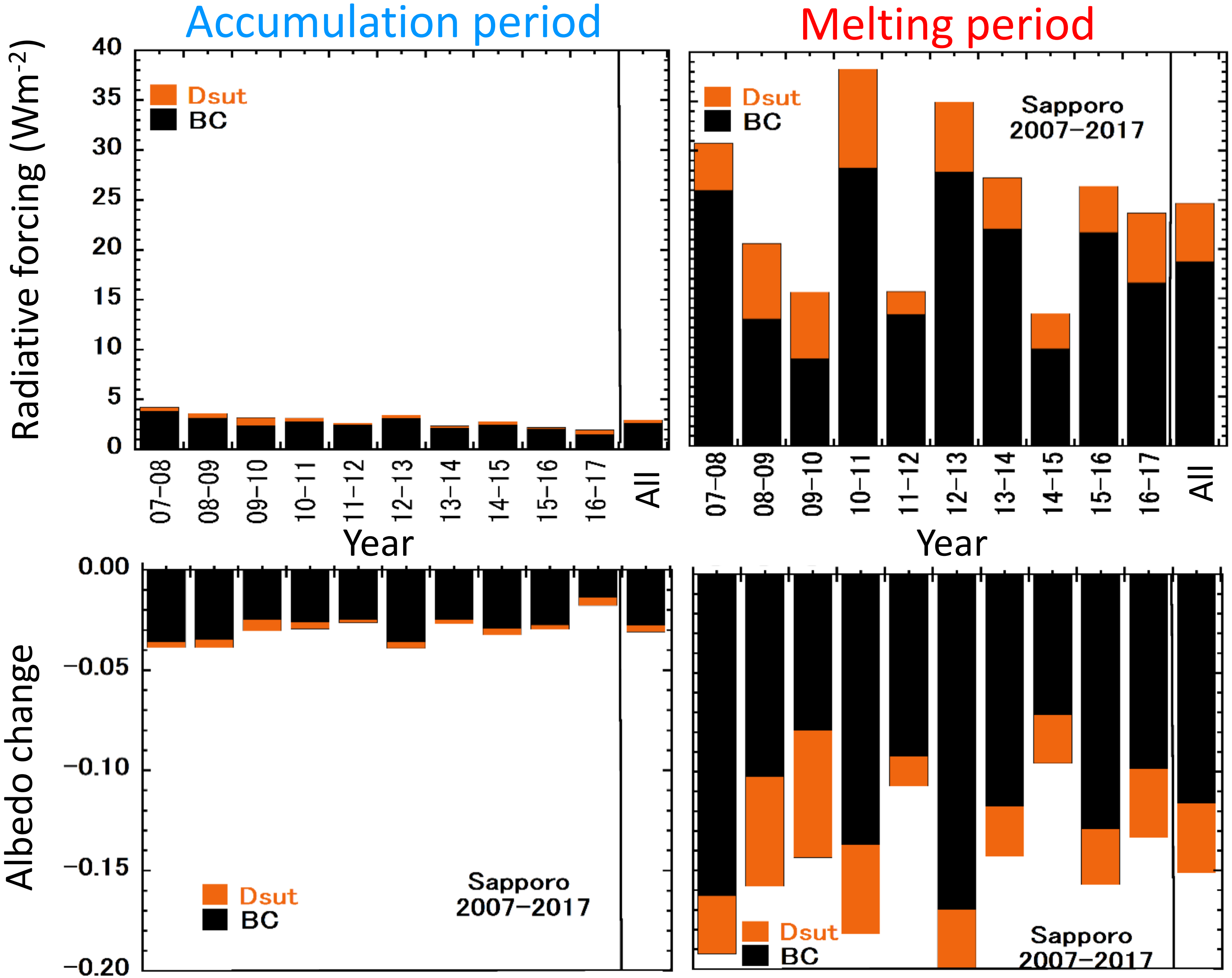
$$\boldsymbol{RF} = \boldsymbol{F}^{\downarrow}(-\Delta\boldsymbol{\alpha})$$

Albedo change and radiative forcing averaged for 10 winters

Snow impurity	Δα	*RF* (Wm^{-2})
BC+Dust	-0.053	+6.7
BC	-0.045	+5.4
Dust	-0.008	+1.3

✓ BC effects for both Δα and *RF* are several times higher than those for dust.

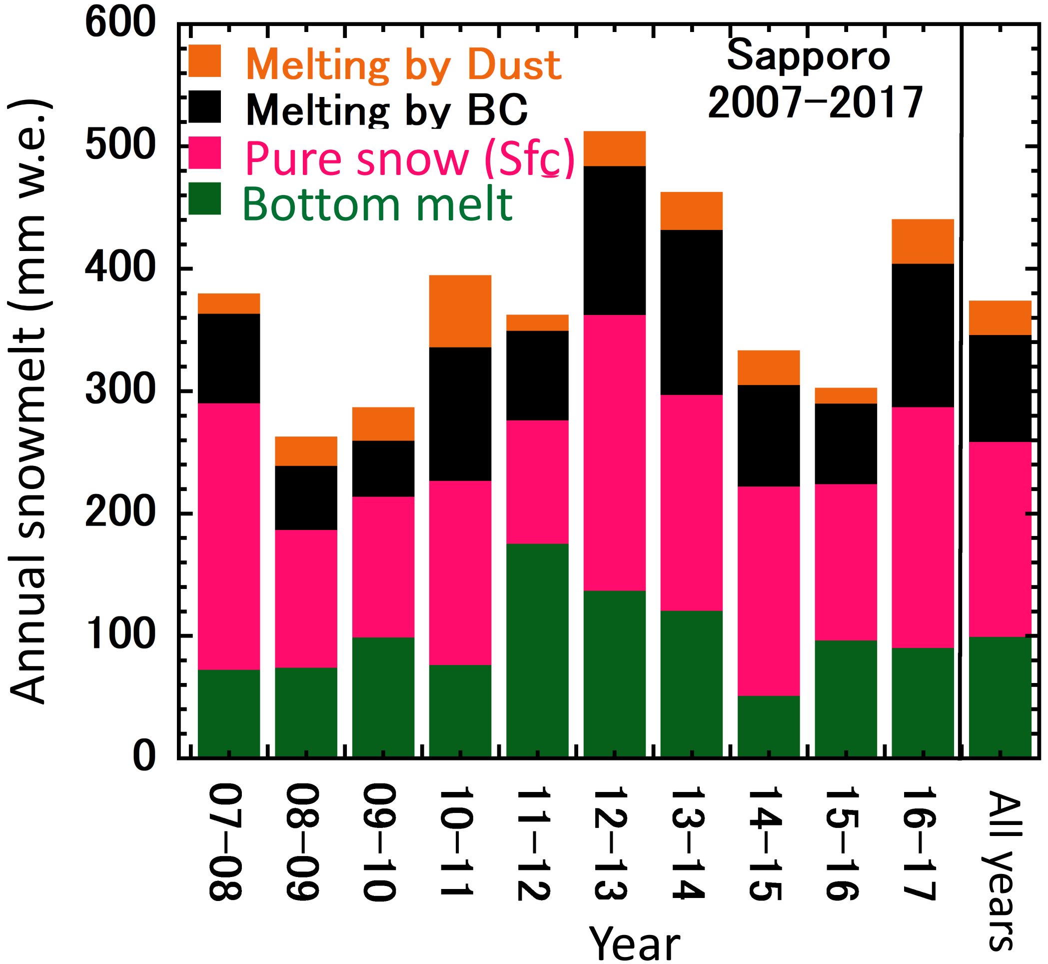
Difference in Δα and *RF* between accumulation and melting periods

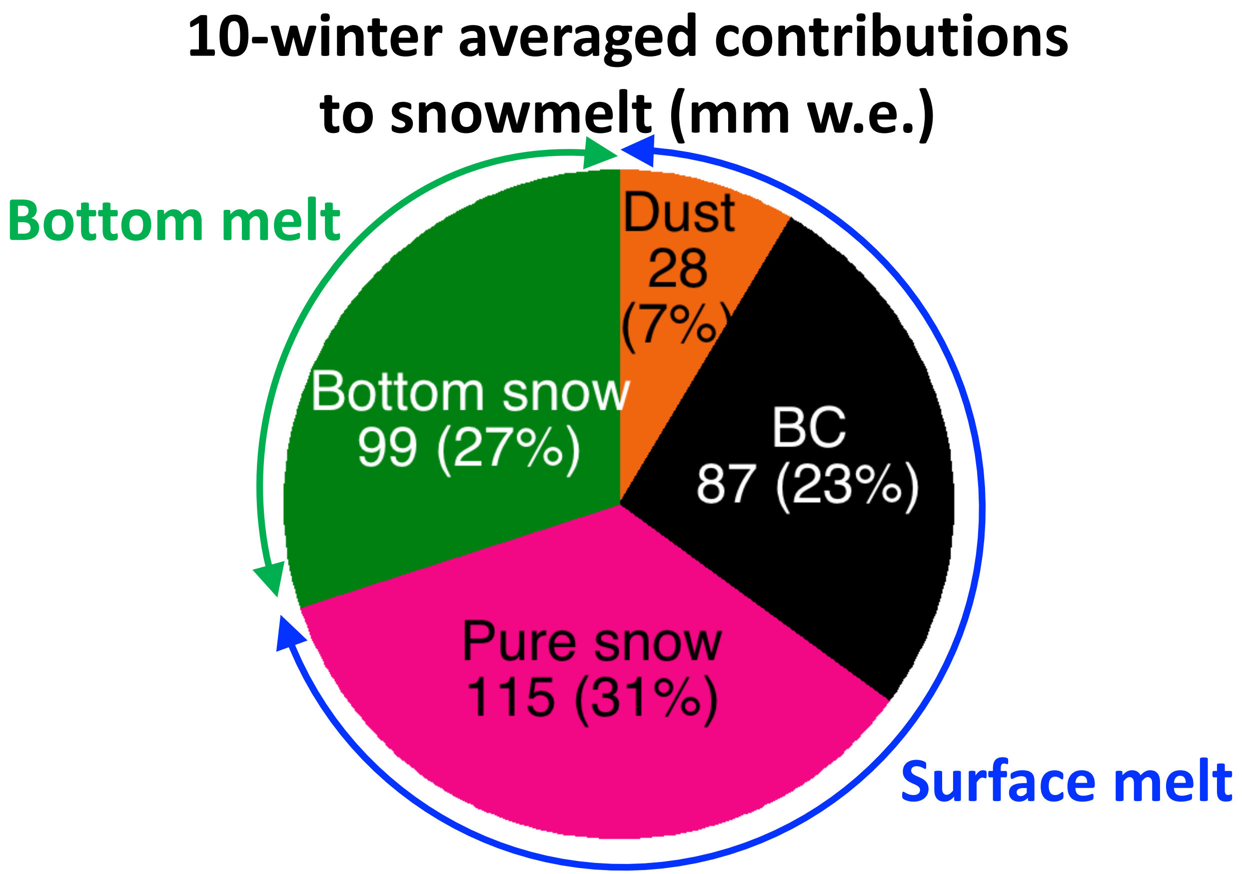


- ✓ Albedo reduction and radiative forcing by snow impurities in the melting season are much higher than those in accumulation season.

Period	Snow impurity	Δα	RF (Wm^{-2})
Acc.	BC+Dust	-0.031	+3.0
	BC	89%	88%
	Dust	11%	12%
Melt	BC+Dust	-0.151	+25.0
	BC	77%	76%
	Dust	23%	24%

Contribution of snow impurities to snowmelt





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.).