IMPACT OF BLACK CARBON AEROSOLS ON GLOBAL WARMING

ULRIKE LOHMANN

ETH Zurich
Institute for Atmospheric and Climate Science, Zurich, Switzerland

INTRODUCTION

Black carbon and other absorbing aerosols can absorb solar radiation and with that cause a local warming. This reduces the amount of solar radiation that reaches the Earth's surface and causes a positive radiative forcing at the top-of-the-atmosphere. The local warming associated with black carbon can change the stability of the atmosphere and with that either enhance or suppress convection. Menon et al. (2002) suggested that the black carbon aerosols in China and India could have contributed to the increased summer floods in south China as well as to the increased drought in North China in recent decades.

Black carbon aerosols also lead to a reduced relative humidity, which can cause a cloud to evaporate. This effect is called semi-direct aerosol effect (Ackerman et al., 2000). The magnitude and the sign of the semi-direct effect depend on the altitude of the black carbon aerosols relative to the cloud and on the cloud type (Koch and Del Genio, 2010).

Black carbon aerosols never occur in isolation, but are always mixed with organic substances. These organic aerosols may scatter solar radiation, which offsets part of the warming associated with black carbon. In addition these mixed particles act as centers for cloud formation, so-called cloud condensation nuclei (CCN) and may also act as ice nuclei (IN). For a constant cloud water content, an increase in CCN leads to an increase in the cloud albedo and with that causes a cooling (Twomey effect). An increase in IN would counteract this cooling because more IN would cause supercooled liquid clouds to freeze more readily. Then the ice crystals would grow at the expense of cloud droplets because of the difference in water vapor pressure over liquid water and ice (glaciation effect; (Lohmann, 2002)). This would cause the cloud to precipitate, to reduce the total cloud cover and to absorb more solar radiation. This glaciation effect is, however, rather uncertain as a coating of black carbon aerosols may inhibit or reduce their ability to act as IN (de-activation effect; (Hoose et al., 008b; Storelvmo et al., 2008)), which would work in the opposite direction. If the glaciation or de-activation effect dominates is not known yet.

The effect of realistic black and organic carbon mitigation scenarios has been investigated by Chen et al. (2010). The authors reduced the primary emissions of black and organic carbon mass and number emissions from either only fossil fuel combustion or from all primary carbonaceous sources (fossil fuel, domestic fuel, and biomass burning). The direct effect causes a cooling of about 0.1 W m^{-2} in both scenarios. This cooling is, however, compensated by the reduction of the number of CCN. Depending on the scenario, this causes the clouds to reflect 0.13 to 0.31 W m^{-2} less radiation back to space. Thus, the net effect of these realistic combined black/organic carbon scenarios is a positive forcing of 0.1-0.2 W m^{-2}.

Koch et al. (2011) analyzed the effect of reducing black and organic carbon from biofuels on liquid clouds in a multi-model comparison. They found that this led to a positive cloud radiative response of 0.11 W m^{-2} which is comparable in size but of opposite sign to the respective direct effect. Reducing diesel soot (black and organic carbon) leads to even smaller radiative effects.

A summary of the radiative forcing of different aerosols and aerosol precursors in the year 2005 as compared to 1750 is shown in Figure 1. It shows that anthropogenic black carbon caused a positive radiative forcing of 0.34 W m^{-2} in 2005 as compared to pre-industrial times whereas organic carbon caused a negative forcing of 0.19 W m^{-2}. In addition the cloud albedo effect to which black and organic carbon also contribute has caused a negative forcing of 0.7 W m^{-2}.

In conclusion, the net radiative effect of realistic reductions of black and organic carbon on climate is small.

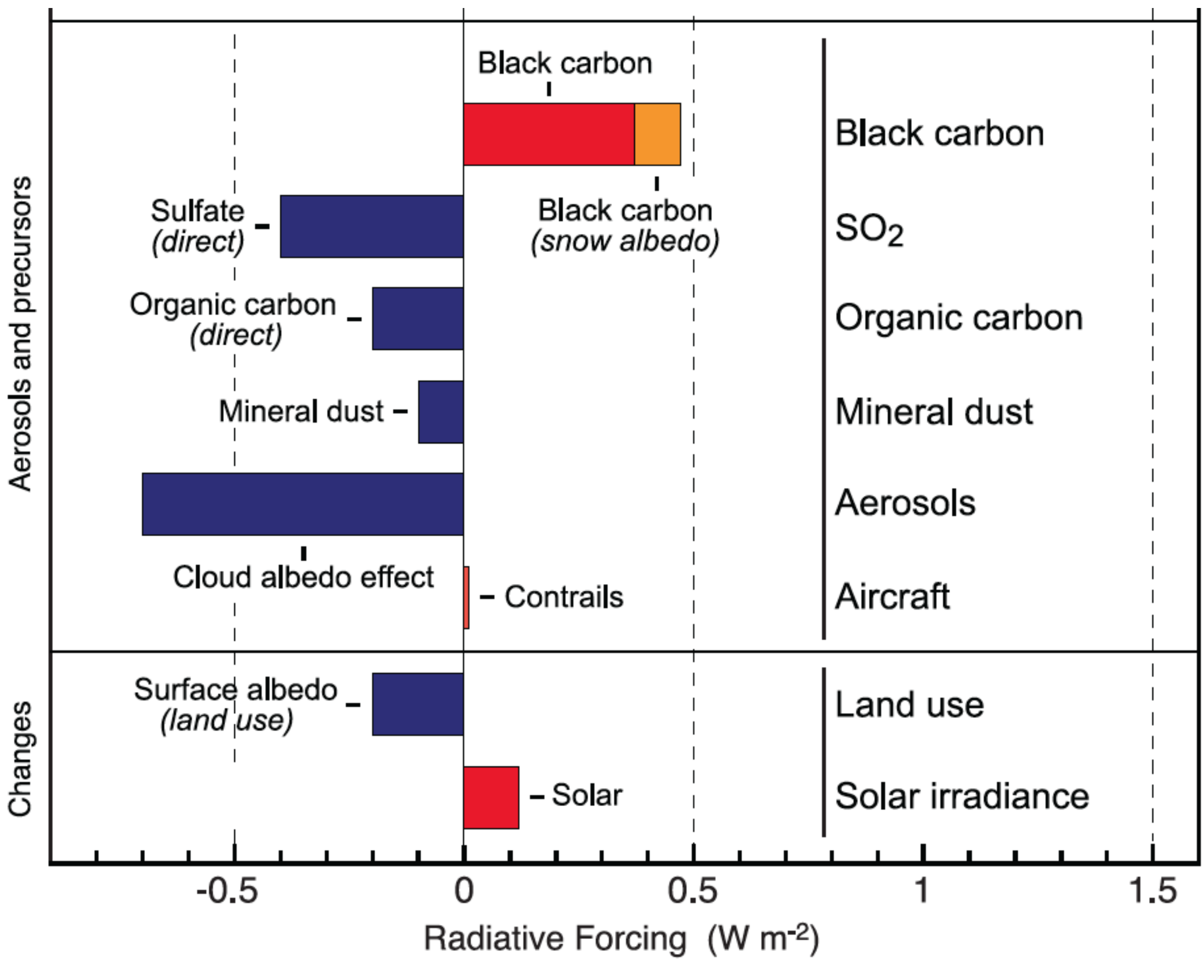


Fig. 1. Components of the radiative forcing for emissions of aerosols and aerosol precursors and other changes. Values represent radiative forcing in 2005 due to emissions and changes since 1750. Modified from Forster et al. (2007)

Partly, this is because black carbon is always found in combination with organic carbon which scatters solar radiation. In addition internally mixed black and organic carbon particles act as cloud condensation nuclei, a reduction of which causes the clouds to become darker, i.e. to reflect less solar radiation back to space.

REFERENCES

Ackerman, A. S., Toon, O. B., Stevens, D. E., Heymsfield, A. J., Ramanathan, V. and Welton, E. J. 2000. Reduction of tropical cloudiness by soot. *Science* **288**, 1042–1047.

Chen, W. T., Lee, Y. H., Adams, P. J., Nenes, A. and Seinfeld, J. H. 2010. Will black carbon mitigation dampen aerosol indirect forcing? *Geophys. Res. Lett.* **37**.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W., Haywood, J., Lean, J., Lowe, D. C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M. and Van Dorland, R. 2007. Radiative forcing of climate change. In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, eds., *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge Univ. Press, Cambridge, United Kingdom and New York, NY, USA. 129–234.

Hoose, C., Lohmann, U., Erdin, R. and Tegen, I. 2008b. Global influence of dust mineralogical composition on heterogeneous ice nucleation in mixed-phase clouds. *Environ. Res. Lett.* **3**, doi:10.1088/1748–9326/3/2/025,003. 025003.

Koch, D., Balkanski, Y., Bauer, S. E., Easter, R. C., Ferrachat, S., Ghan, S. J., Hoose, C., Iversen, T., Kirkevag, A., Kristjansson, J. E., Liu, X., Lohmann, U., Menon, S., Quaas, J., Schulz, M., Seland, O., Takemura, T. and Yan, N. 2011. Soot microphysical effects on liquid clouds, a multi-model investigation. *Atmos. Chem. Phys.* **11**, 1051–1064.

Koch, D. and Del Genio, A. D. 2010. Black carbon semi-direct effects on cloud cover: review and synthesis. *Atmos. Chem. Phys.* **10**, 7685–7696.

Lohmann, U. 2002. A glaciation indirect aerosol effect caused by soot aerosols. *Geophys. Res. Lett.* **29**, doi: 10.1029/2001GL014,357.

Menon, S., Hansen, J., Nazarenko, L. and Luo, Y. 2002. Climate effects of black carbon aerosols in China and India. *Science* **297**, 2250–2253.

Storelvmo, T., Kristjánsson, J.-E. and Lohmann, U. 2008. Aerosol influence on mixed-phase clouds in CAM-Oslo. *J. Atmos. Sci.* **65**, 3214–3230.

Impact of black carbon aerosols on global warming

Ulrike Lohmann

ETH Zurich
Institute for Atmospheric
and Climate Science

Acknowledgements:
S. Ferrachat, O. Stetzer

Schematic of aerosol and cloud processes

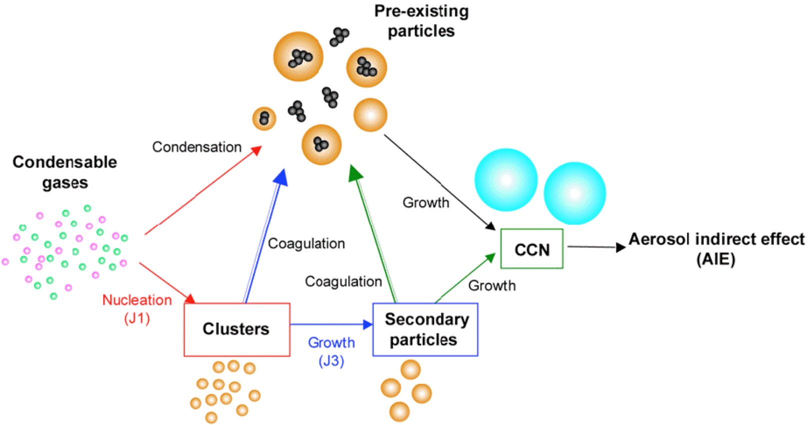


Figure from IPCC AR5

Aerosol radiative forcing

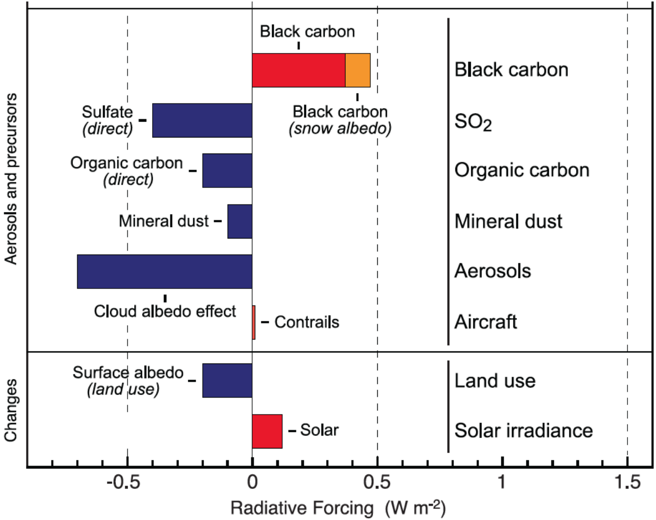
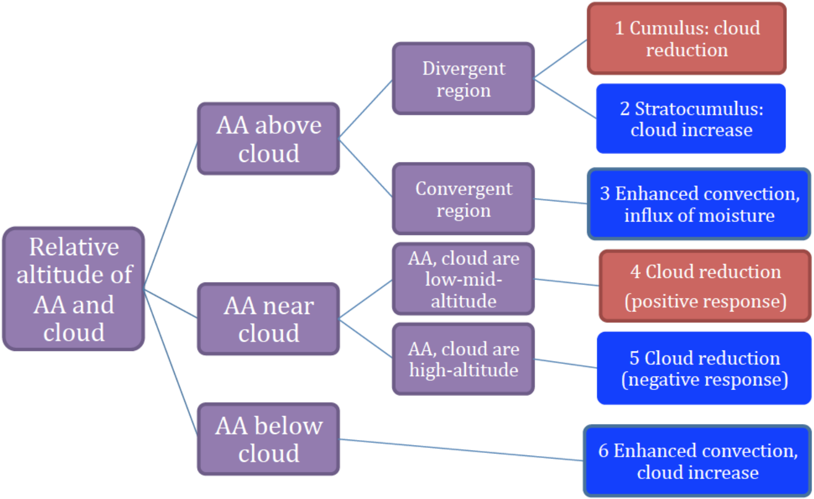


Fig. 2.21 (IPCC, 2007)

Effects of absorbing aerosols (AA) on cloud cover



Koch and DelGenio, ACP, 2010

Aerosols and floods in South East Asia

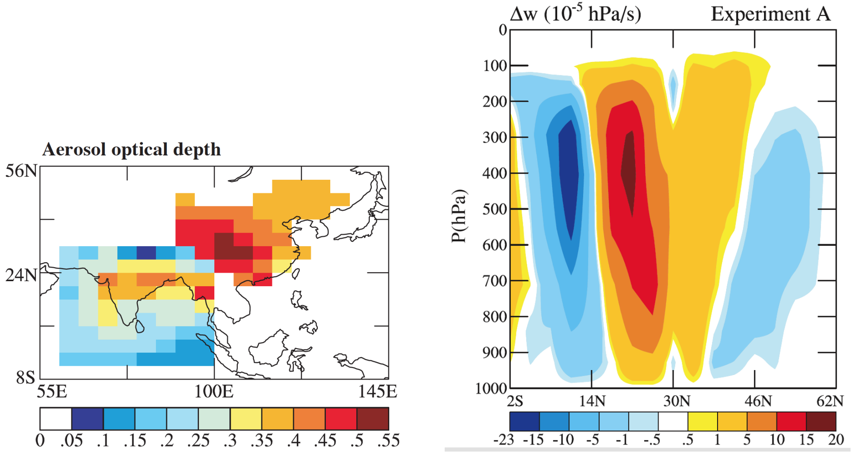
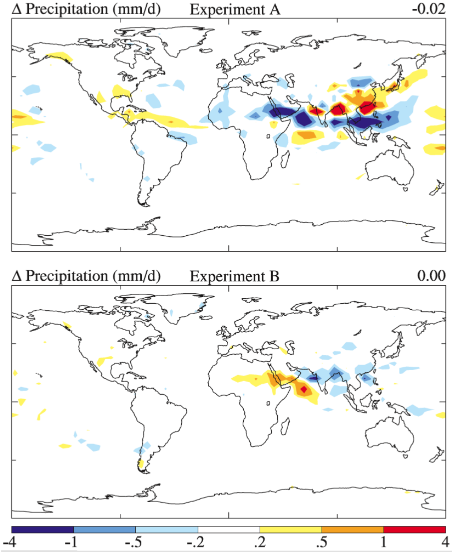


Figure: Observed aerosol optical depth in South East Asia in the 1990s and simulated JJA vertical velocity anomaly [Menon et al., Science, 2002]

JJA precip response to absorbing (exp A) and scattering aerosols (exp B)



Menon et al., Science, 2002

BC mitigation: direct + indirect effect

2 scenarios:

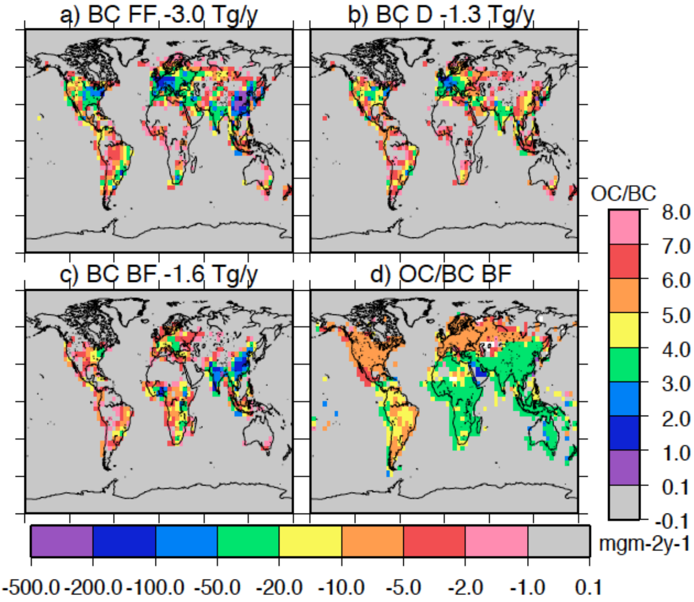
- 50% reduction of primary BC/OC mass and number emissions from fossil fuel combustion (termed HF),
- 50% reduction of primary BC/OC mass and number emissions from all primary carbonaceous sources (fossil fuel, domestic biofuel, and biomass burning) (termed HC).

Global annual mean change in the top-of-the-atmosphere (TOA) radiation:

	Direct Effect	Indirect Effect	Net Effect [W m^{-2}]
HF	-0.07	+0.13	+0.06
HC	-0.12	+0.31	+0.19

I.e. reducing BC leads to a warming!

Chen et al., GRL, 2010



Koch et al., ACP, 2011

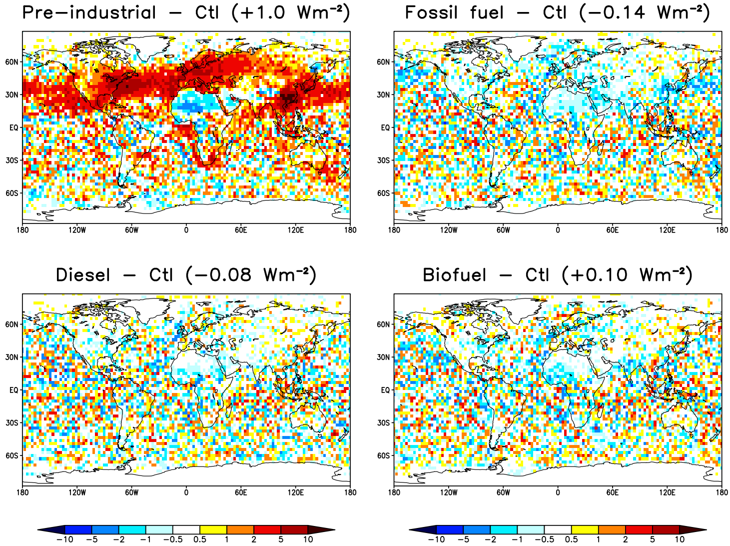
Description	BC Emission $Tg\,yr^{-1}$	OC Emission $Tg\,yr^{-1}$	OC/BC
Fossil fuel (reduced in FF)	3.0	0.	0
Biofuel (reduced in BF)	1.6	6.4	4
Diesel (reduced in D)	1.3	0.5	0.4
Biomass burning in 2000	3.1	24	7.7
Biomass burning in 1750	1.0	9	9
Year 2000 total particulate (PD)	7.7	32.9	6.1
Year 1750 total particulate (PI)	1.4	9.7	17

Global annual mean effect [$W\ m^{-2}$]:

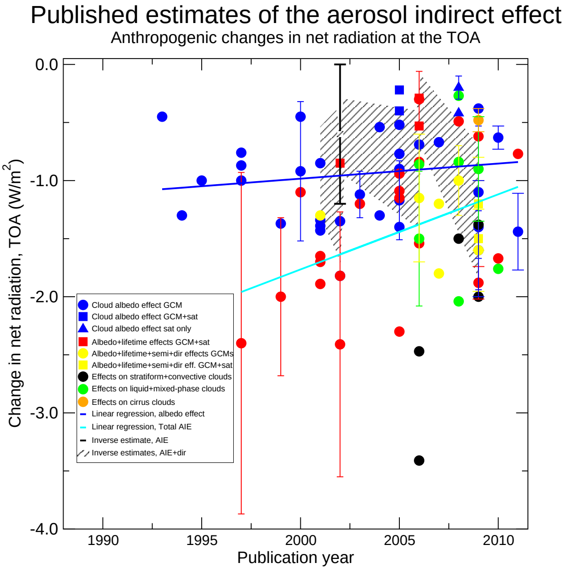
Simulation	Net
Fossil fuel - reference	-0.1
Diesel - reference	-0.01
Biofuel - reference	+0.06
Pre-industrial - reference	+1.18

Koch et al., ACP, 2011

Radiative effects of BC



Koch et al., ACP, 2011



Cloud albedo effect: -0.9 W m^{-2}; (Updated from Lohmann et al., ACP, 2010)

Heterogeneous freezing

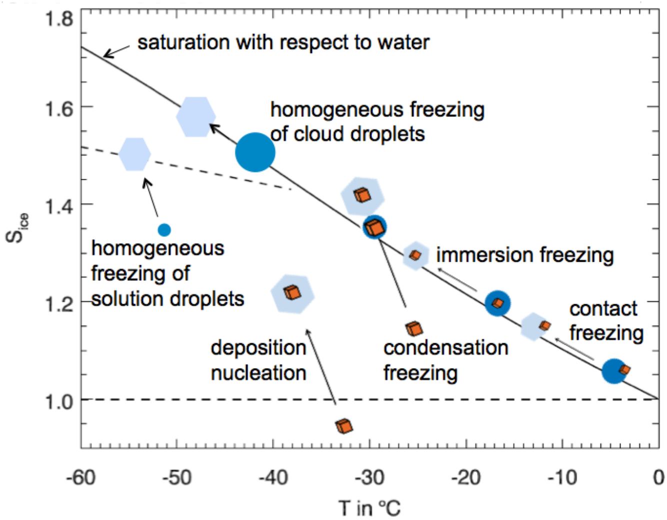


Figure courtesy of Corinna Hoose

Compilation of freezing data on soot

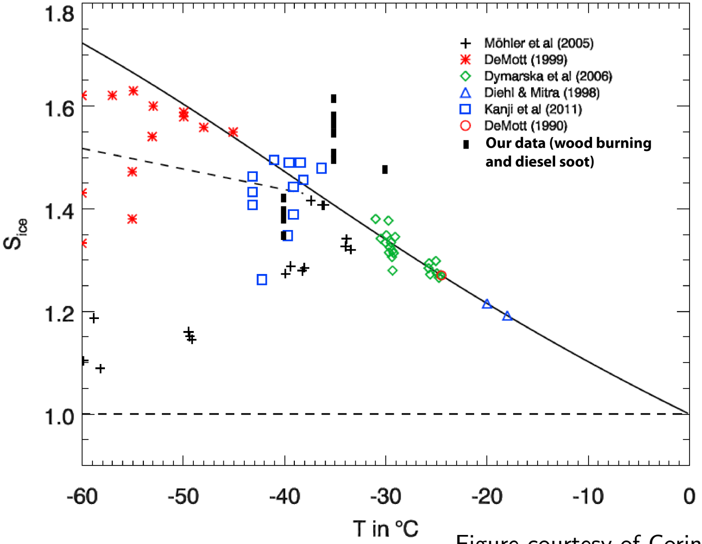


Figure courtesy of Corinna Hoose

Compilation of all freezing data (imm./dep.)

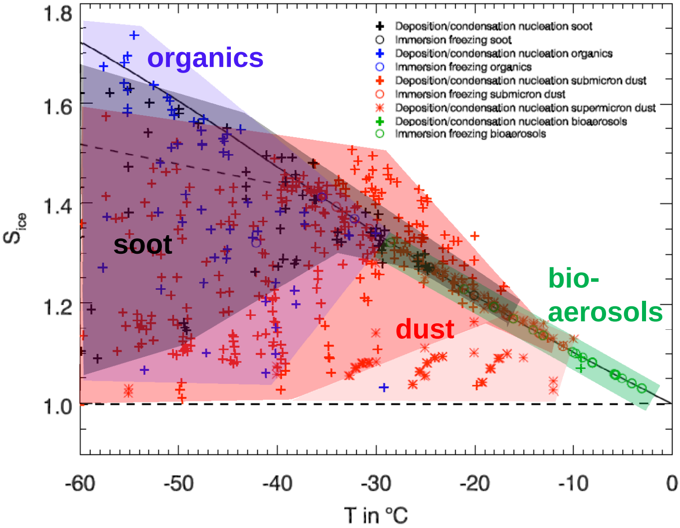
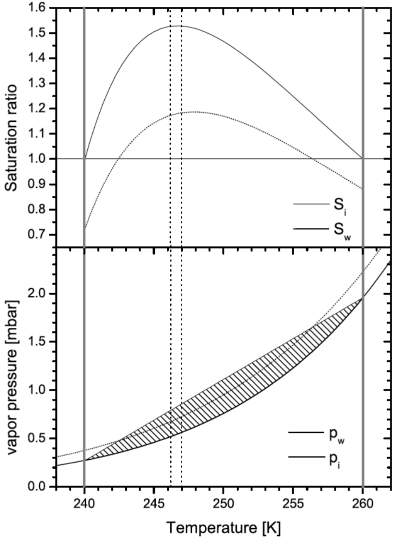
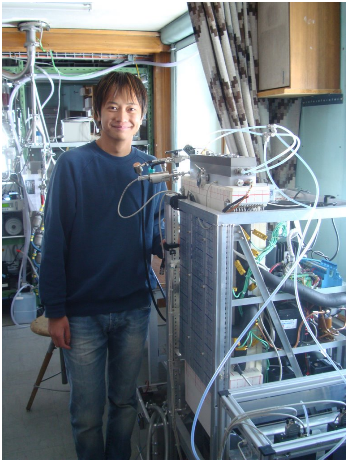


Figure courtesy of Corinna Hoose

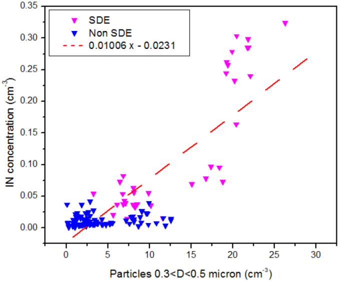
Zurich Ice Nucleation Chamber

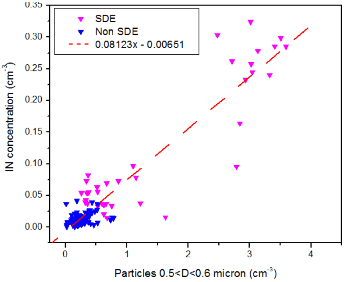


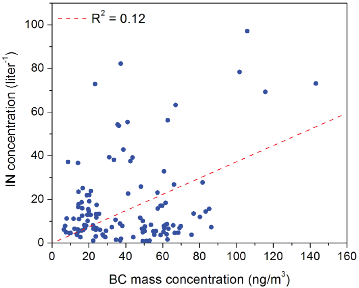


Stetzer et al., AST, 2007; Chou et al., ACP, 2011

Correlation of IN with Sahara dust and BC

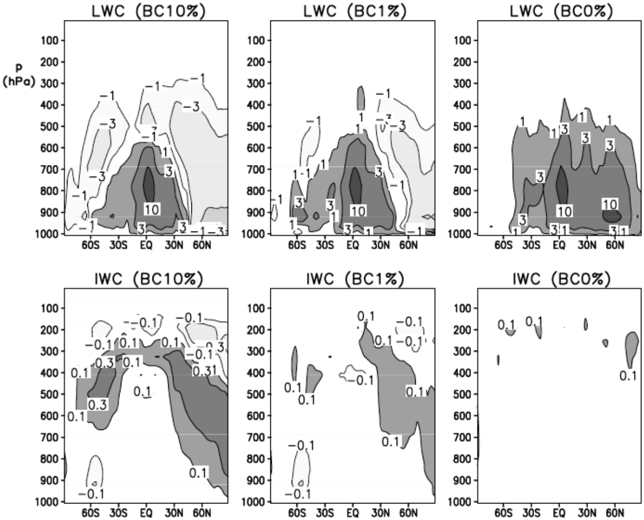






Chou et al., ACP, 2011

Is black carbon a good IN?



Lohmann, GRL, 2002

Conclusions

- The radiative effect of BC on climate is small
- The effect of BC on clouds counteracts its direct radiative effect
- If BC is important as an ice nucleus is still an open question