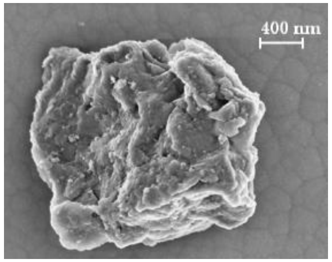
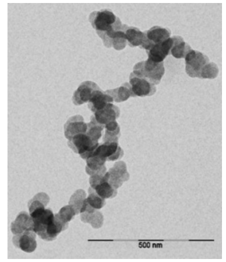
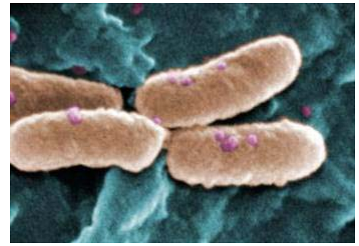
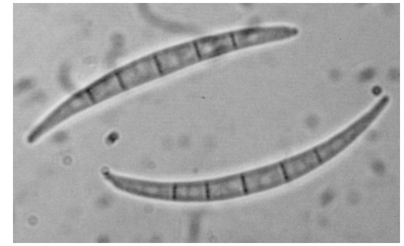
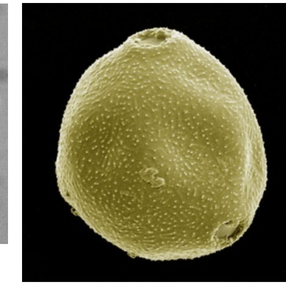


Montmorillonite (Welti et al , 2009)


Soot (M. Jargelius)


Pseudomonas aeruginosa (J. H. Carr)


Fusarium acuminatum (F. Lord)


Birch pollen (J. Derksen)

Ice nucleation by mineral dust, soot, bacteria, fungal spores and pollen: GCM studies with new freezing parameterizations

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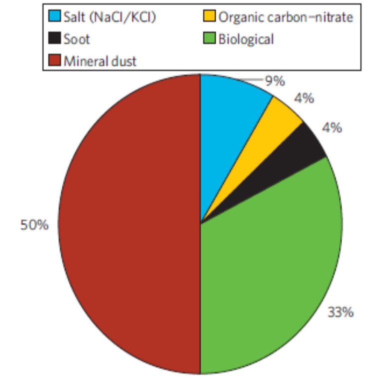
Motivation

- Bioaerosols are found to be highly efficient ice nuclei in lab experiments. First evidence of atmospheric relevance *(Christner et al 2008, Pratt et al. 2009, Prenni et al. 2009)*



- Ice nucleation parameterizations in GCMs are either only T-dependent or account for dust & soot influence on ice nucleation in simplified ways *(e.g. Lohmann & Diehl 2006, Hoose et al. 2008, Liu et al. 2009)*
- *Chen et al. (2008)*: derive parameters for classical nucleation theory from laboratory experiments
    - flexible parameterization
    - sound theoretical basis
    - matches lab data
    - can include all sorts of possible ice nuclei

Extension of CAM-Oslo

- Detailed aerosol scheme coupled to 2-moment warm & cold cloud microphysics *(Seland et al, 2008, Storelvmo et al, 2006 & 2008)*
- Include emission parameterizations for bacteria, fungal spores and pollen
- Replace empirical freezing parameterization after Lohmann & Diehl by classical nucleation theory (CNT) for -38°C<T<0°C, freezing parameters derived after *Chen et al. (2008):*
  - Dust, soot, bacteria, fungi and pollen immersion freezing
    
  - Dust and soot deposition nucleation
    
  - Dust and soot contact freezing
    

Bioaerosol emissions

- **Bacteria**: constant emission fluxes from different ecosystems (*Burrows et al., 2009)*

  d=1 µm

$$F_{\text{bacteria}} = \sum_{i=1}^{4} f_i F_i$$

- **Fungal spores**: estimated emission function based on *Heald & Spracklen (2009)*

  d=5 µm

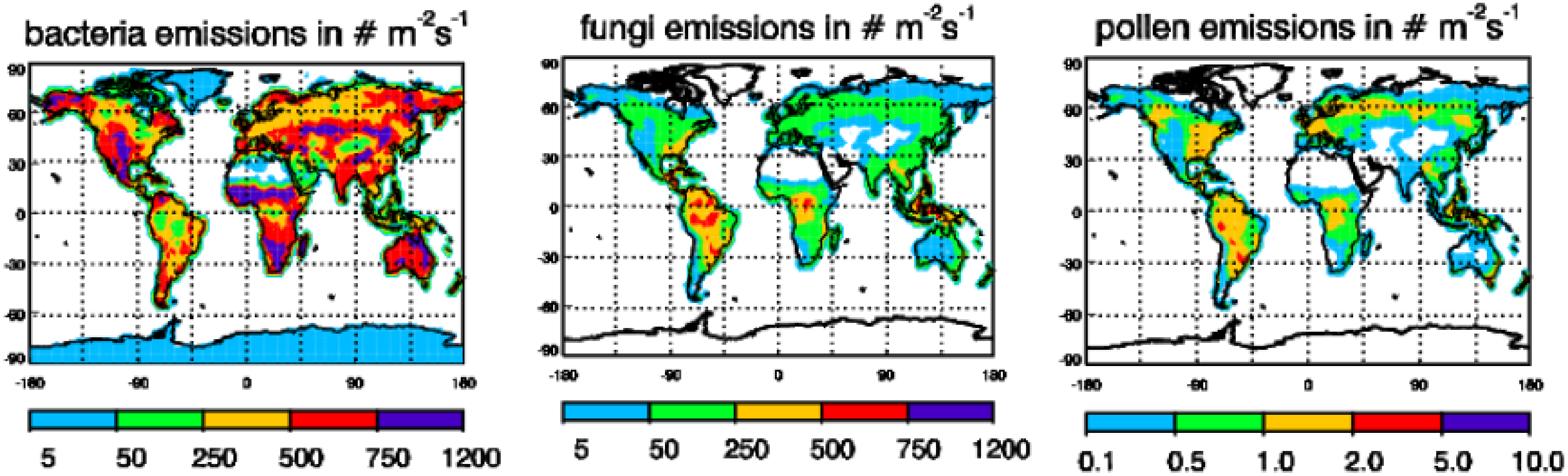
$$F_{\text{fungi}} = 500\,\text{m}^{-2}\text{s}^{-1} \times \frac{\text{LAI}}{3} \times \frac{q}{1.5 \cdot 10^{-2}\text{kg kg}^{-1}}$$

- **Pollen**: from *Jacobson & Streets (2009),* simplified

$$F_{\text{pollen}} = 0.5\,\text{m}^{-2}\text{s}^{-1} \times \text{LAI} \times R_{\text{month}}$$

  d=30 µm

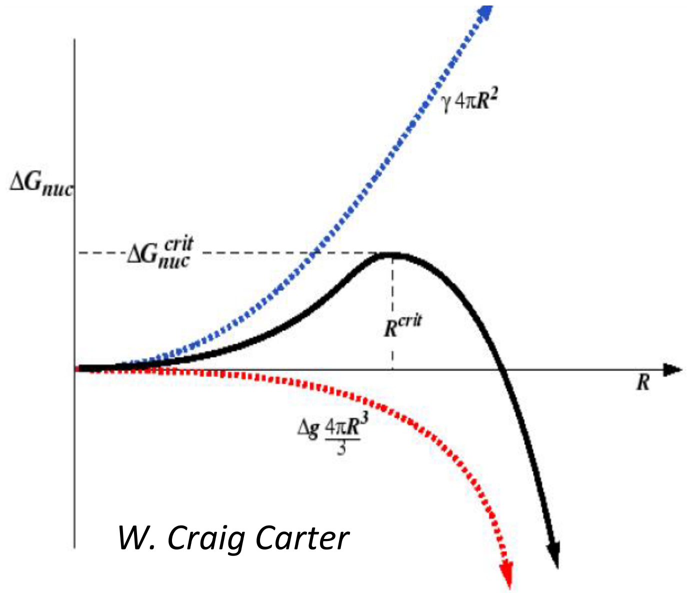
Global bioaerosol emissions



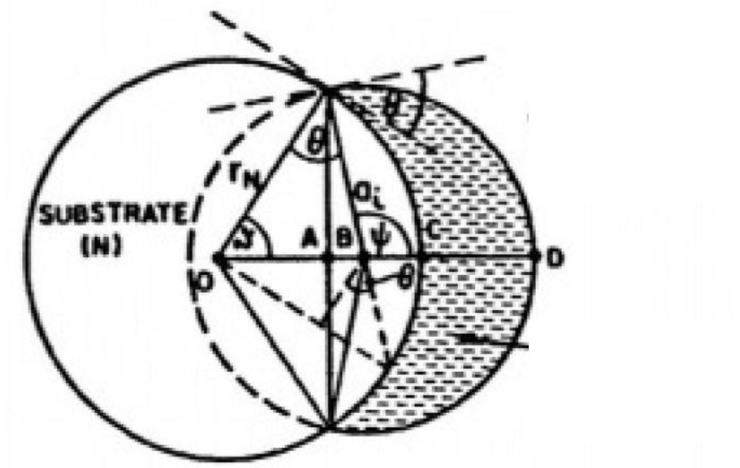
	Global emissions [Tg/yr]	Literature values	Global burden [Gg]	Literature values
Bacteria	**1.4**	0.6[a], 28[b]	**7.0**	6.6[a]
Fungi	**53**	28[c], 50[d], 186[b]	**158**	180[c]
Pollen	**48**	85[b]	**22**	
Total PBAP	**102**	<10[e], 186[f], 296[b]	**187**	

(2007), [e]Winiwarter et al. (2009), [f]Mahowald et al. (2008)

Classical nucleation theory



W. Craig Carter

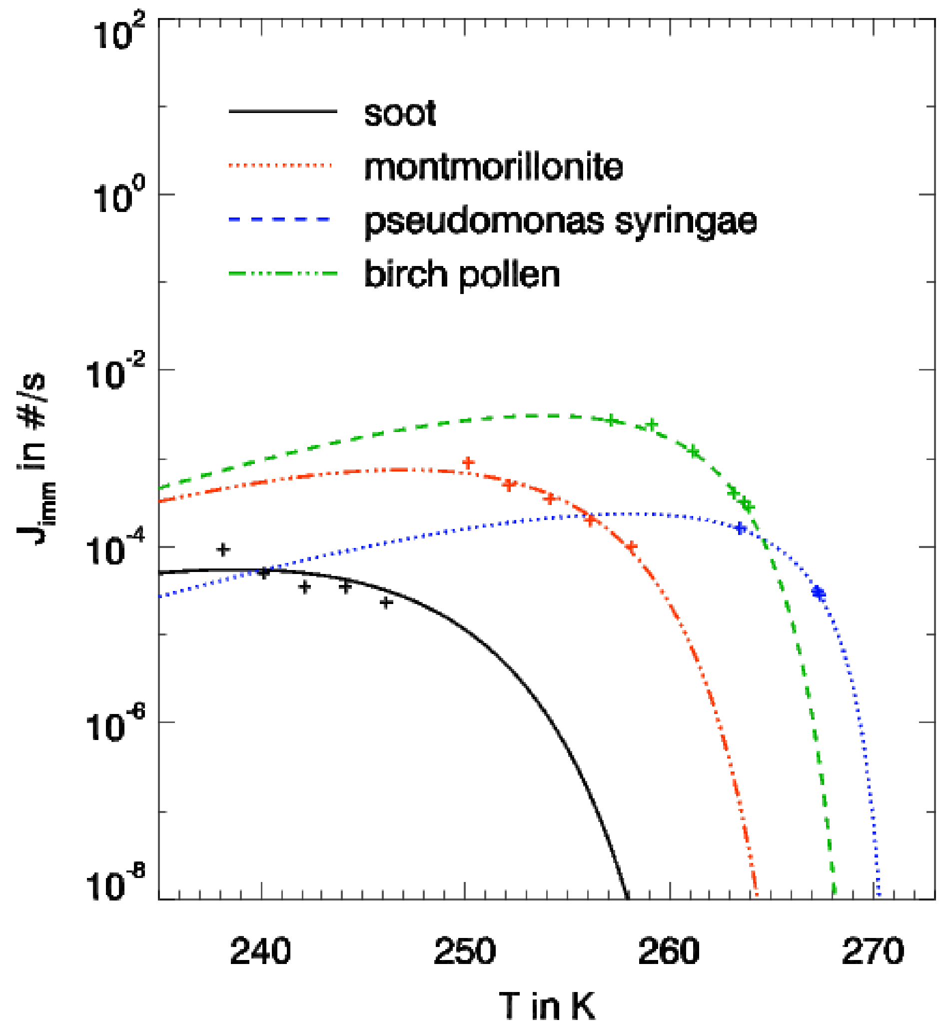


Pruppacher & Klett (1997)

- Energy barrier for germ formation (surface vs. volume term)
- Nucleation (=growth of germ to a critical size) is a **stochastic** process
- IN surface lowers the energy barrier (IN-specific **contact angles** and **activation energies**)

Immersion nucleation

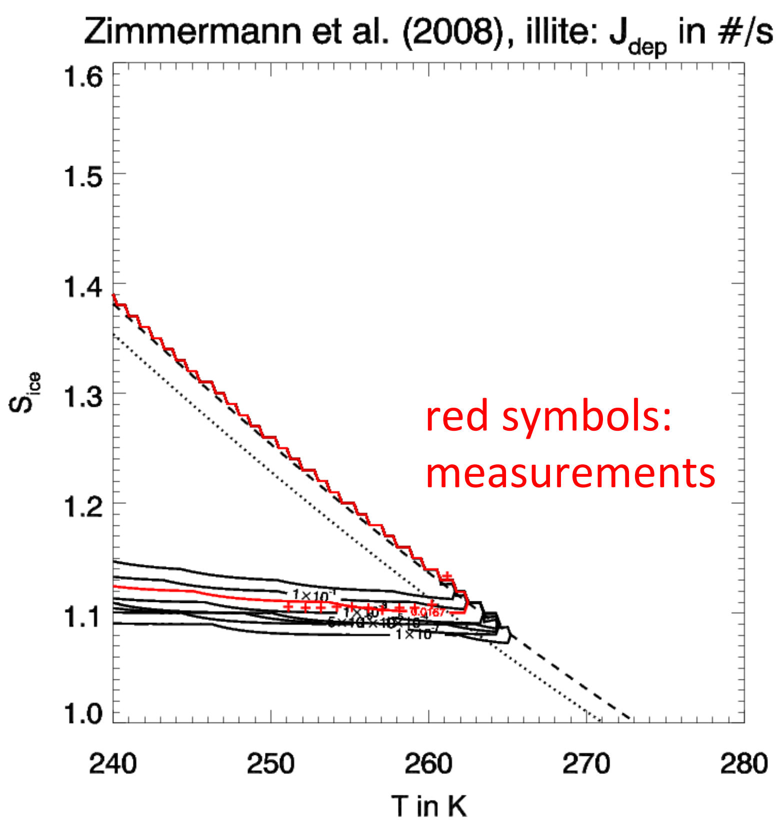
- Nucleation rates derived by applying classical theory to observations *(Chen et al, 2008)*
- Fungi: assume the same parameters as for pseudomonas syringae (cf. *Pouleur et al, 1992*)
- Limit to 1% of soot, 0.1% of INA bacteria and fungi

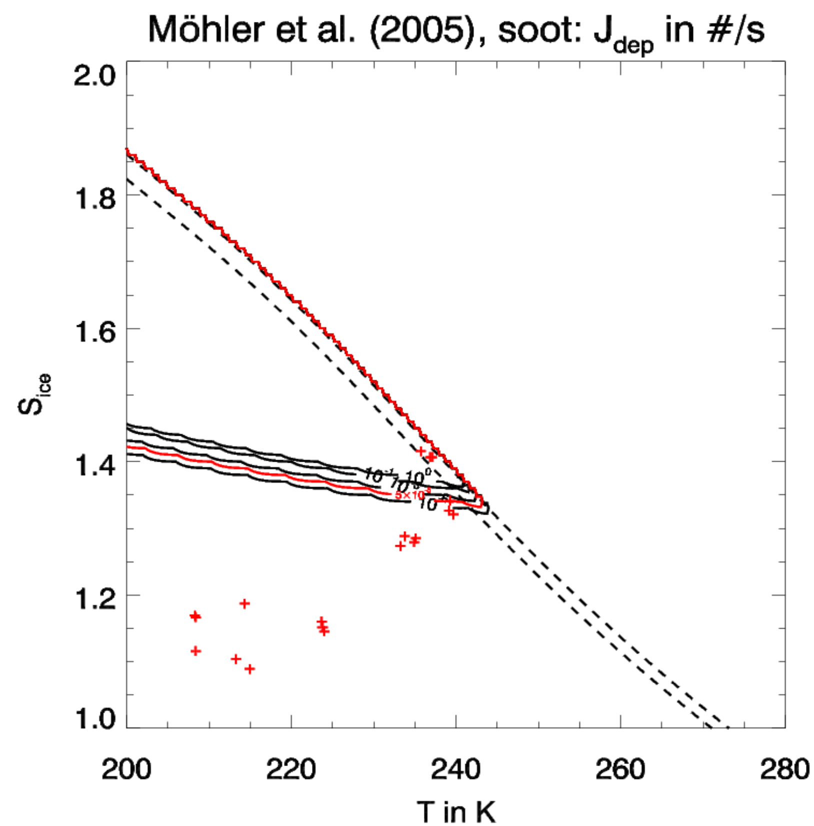


Observations by *DeMott, 1990* (soot); *Pitter & Pruppacher, 1973* (montmorillonite); *Diehl et al, 2002* (birch pollen); *Möhler et al, 2008* (pseudomonas syringae)

Deposition nucleation

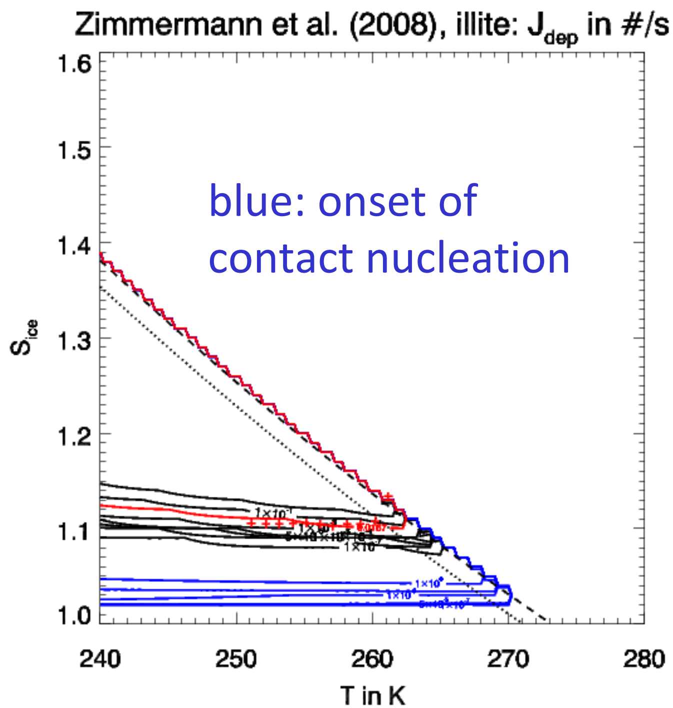
- Function of S_{ice} and T
- Evaluate at 98% RH_w (typical value in mixed-phase clouds, according to *Korolev & Isaac, JAS 2006*)
- Allow only for interstitial, uncoated particles

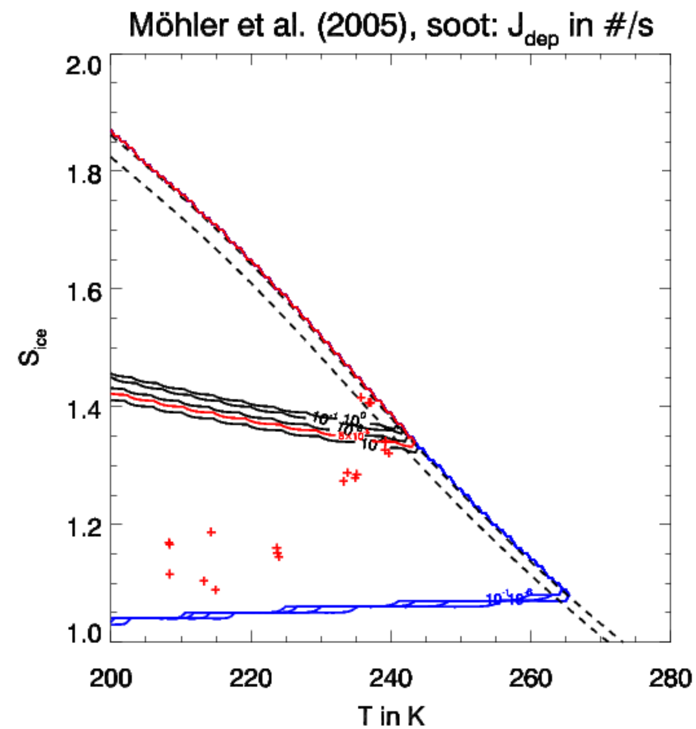




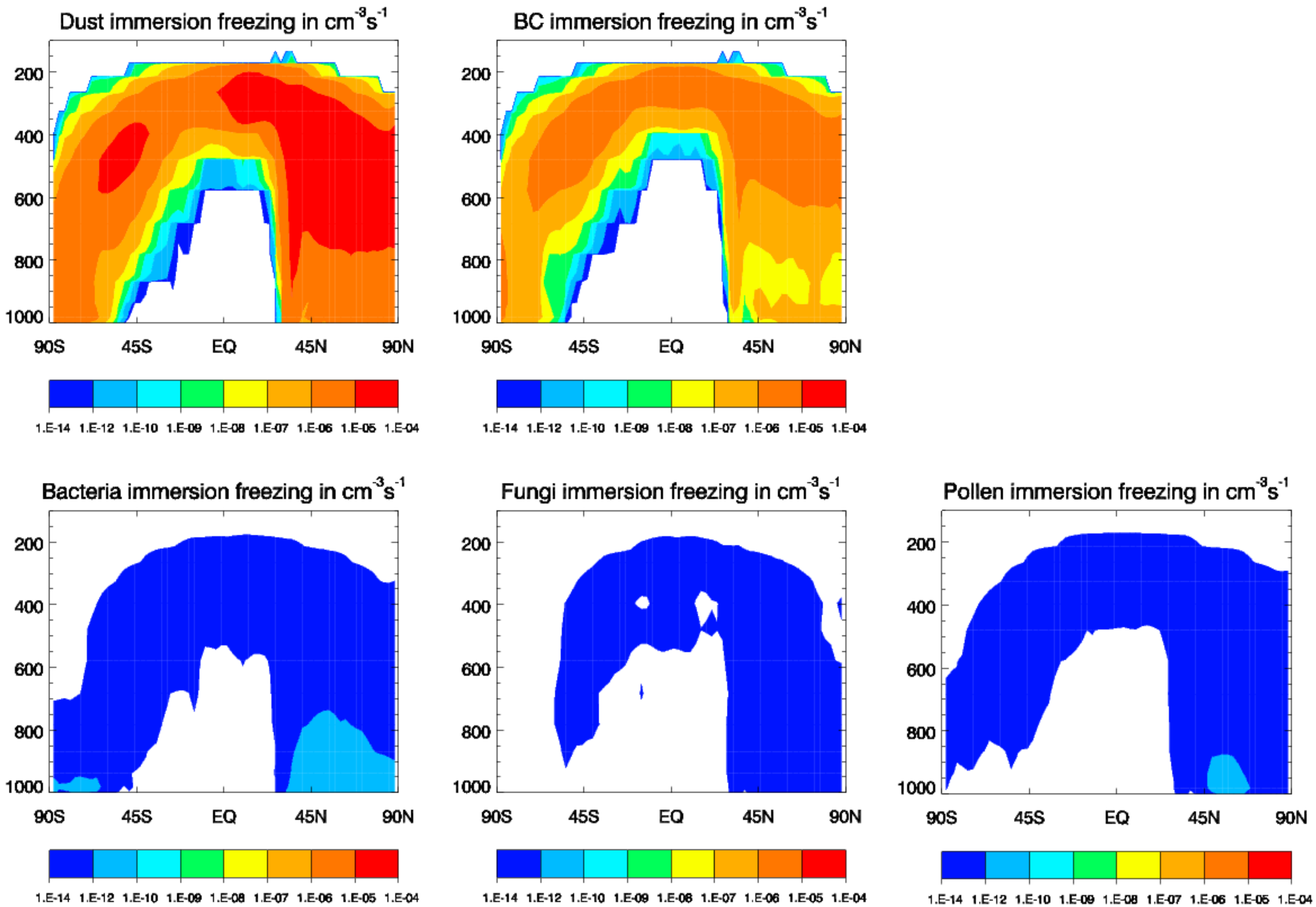
Contact nucleation

- Derive contact freezing rates from Cooper's (1974) hypothesis, i.e., take deposition nucleation parameters but critical size of immersion freezing germs
- allow only for interstitial, uncoated particles
- calculate collision probability

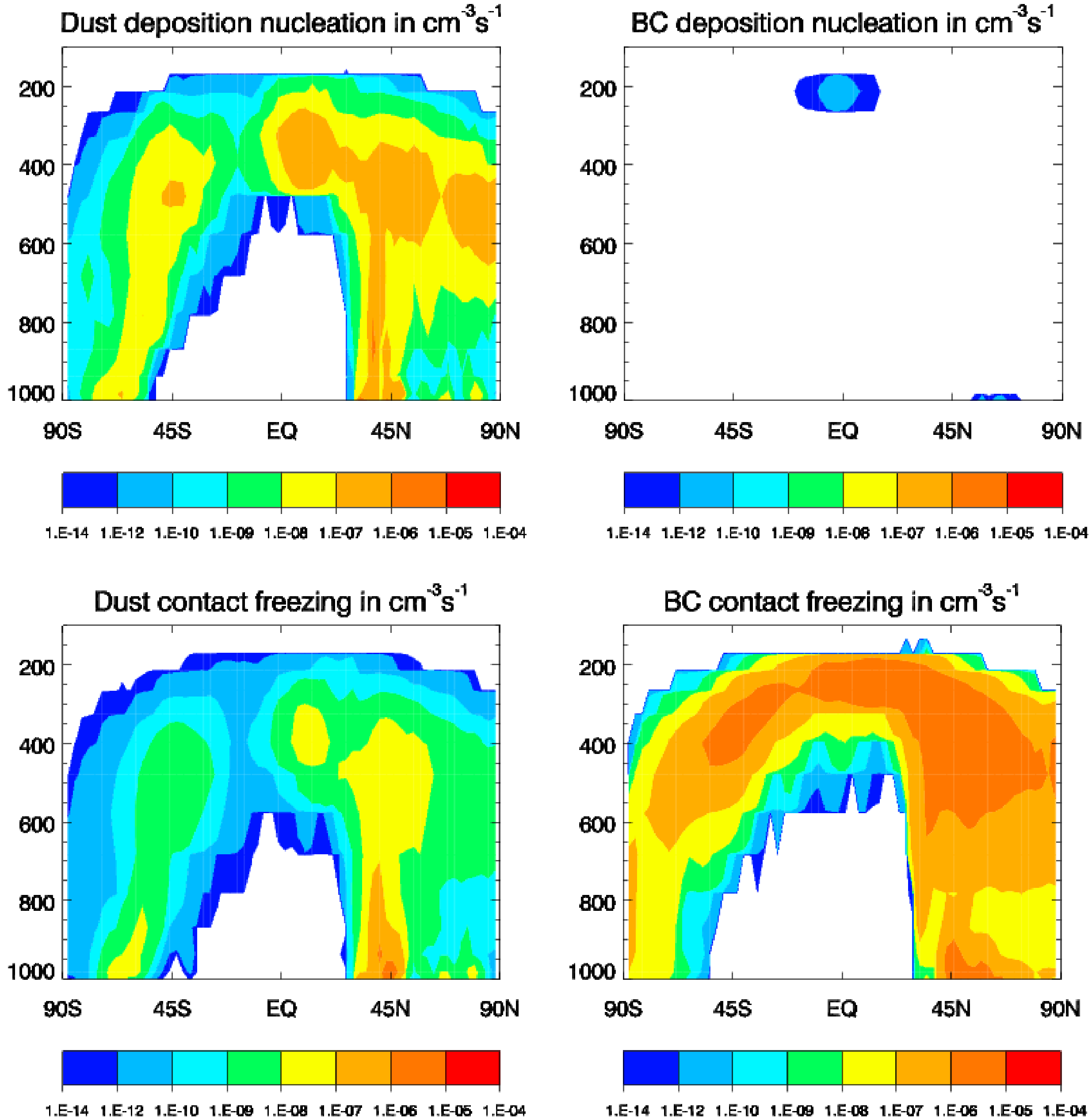




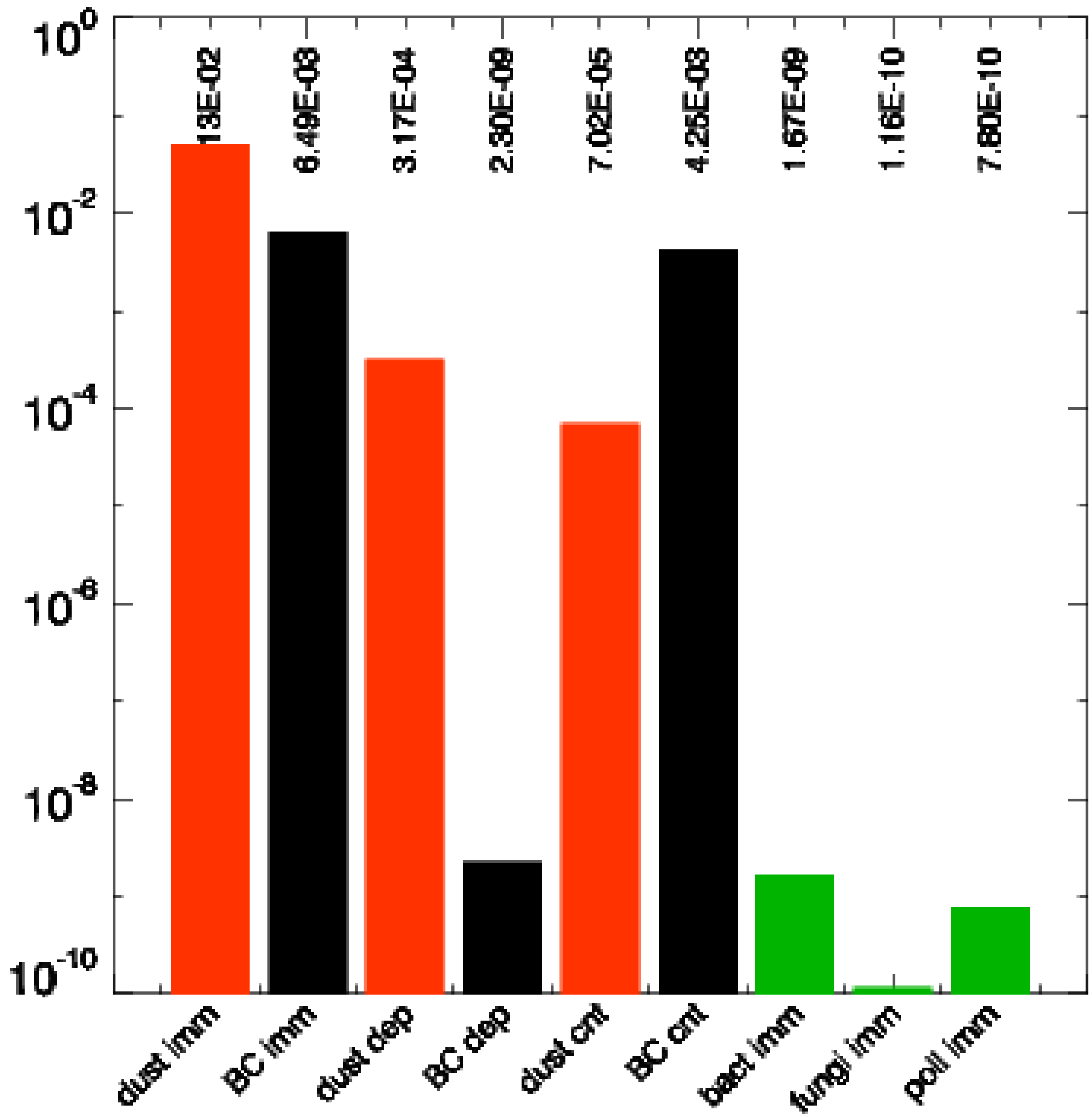
Immersion freezing rates [$cm^{-3}\ s^{-1}$]



Deposition and contact nucleation rates [$cm^{-3}\ s^{-1}$]

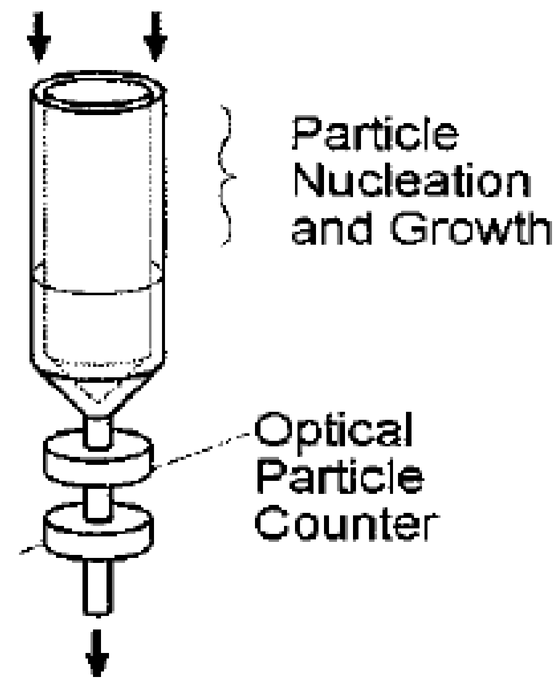


Global integrated freezing rates [$m^{-2}\ s^{-1}$]



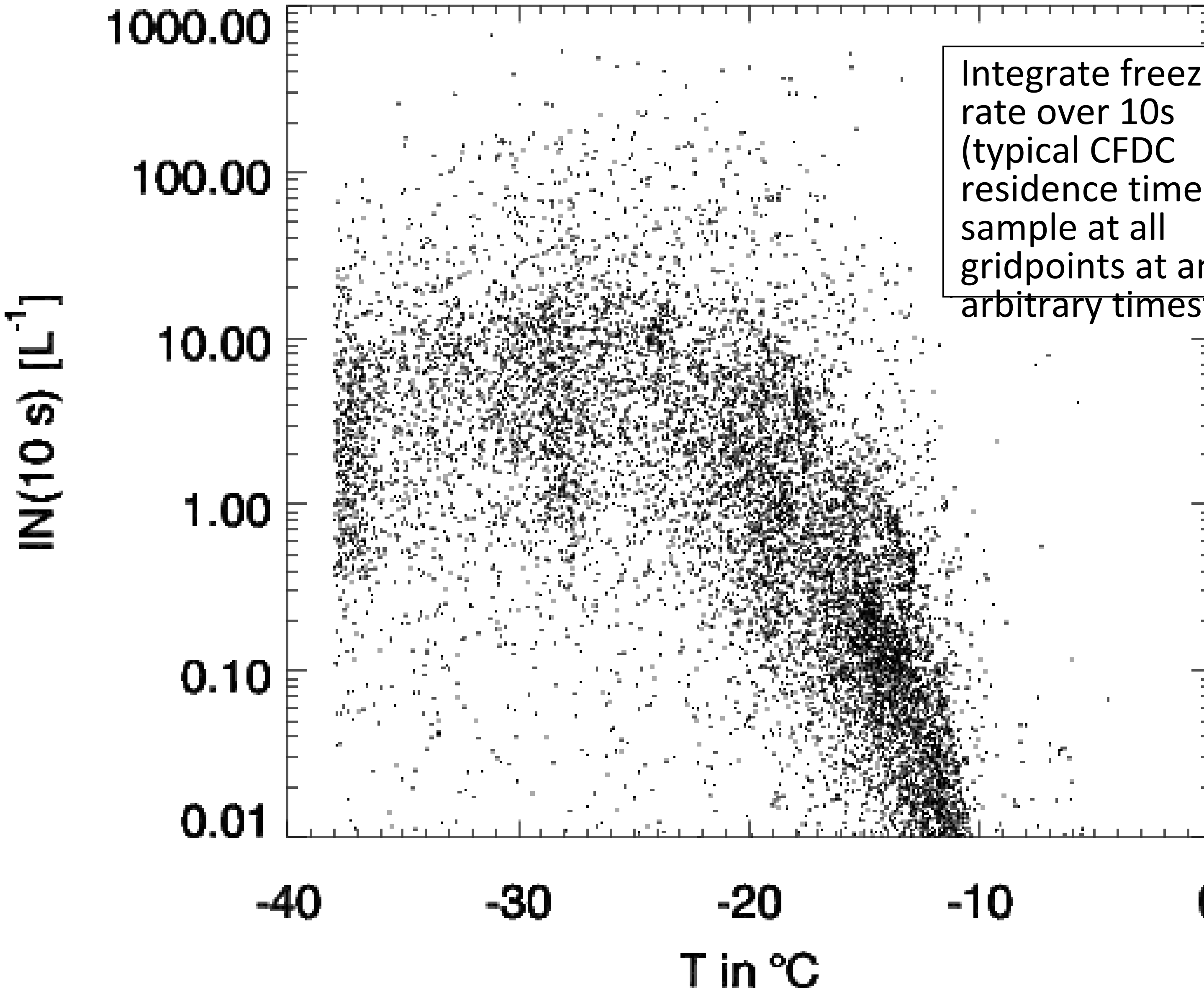
Comparison to CFDC data

- Continuous flow diffusion chamber (CFDC): expose aerosol to a chosen T and S_i, for about 10s
- measures deposition and condensation/ immersion IN
- Compare to
  - Concentration of all aerosol particles which can be IN?
  - Ice crystal concentration?
  - Integrated freezing rate?



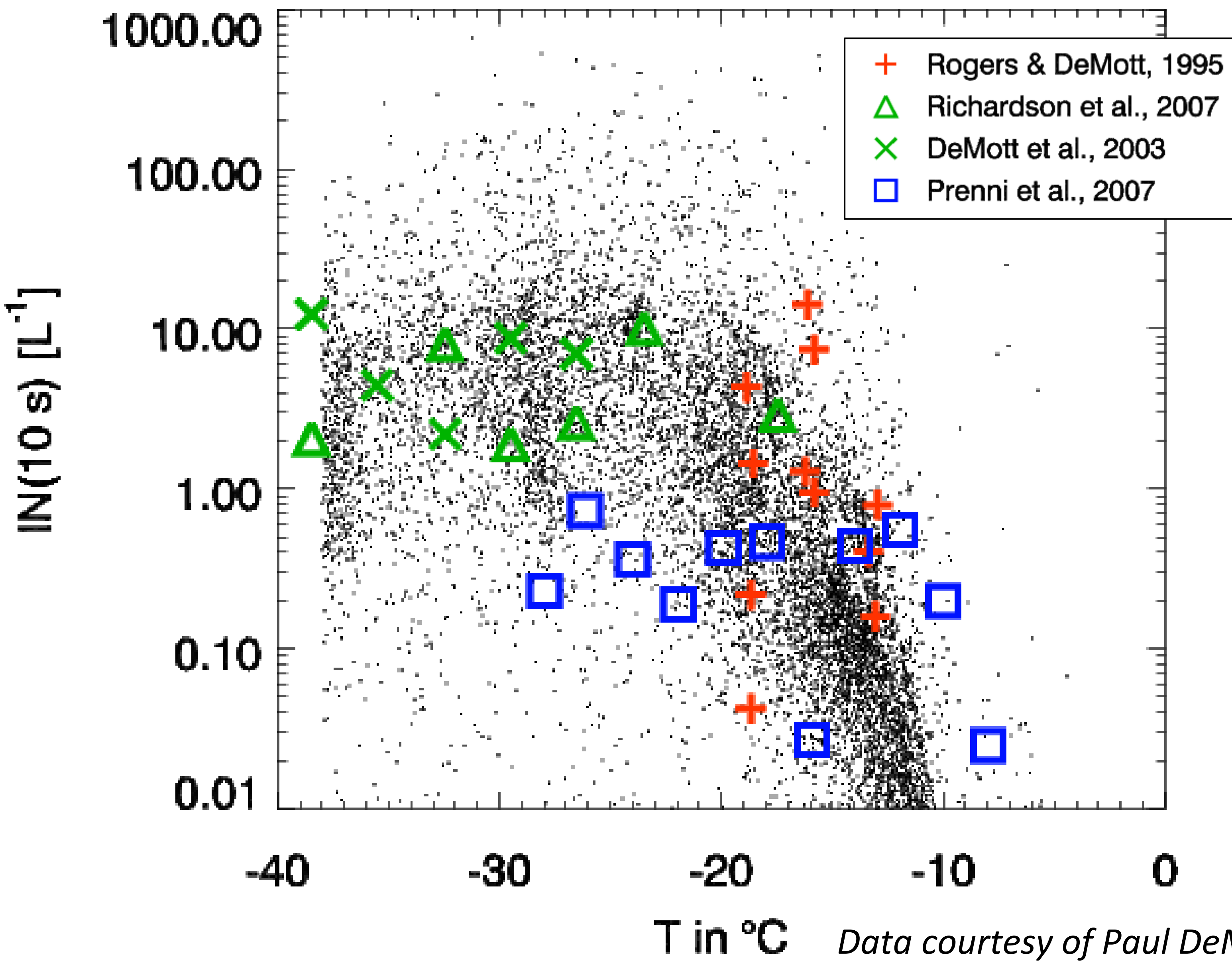
Rogers et al (2001)

Comparison to CFDC data (I)



Integrate freezing rate over 10s (typical CFDC residence time), sample at all gridpoints at an arbitrary timestep

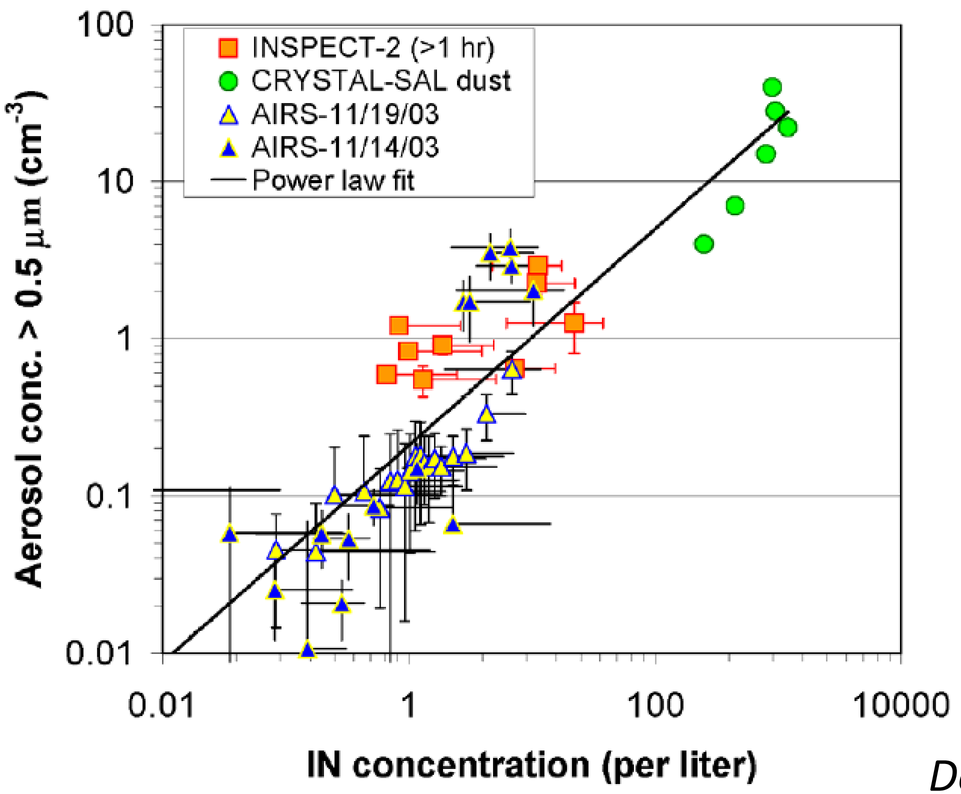
Comparison to CFDC data (I)



Data courtesy of Paul DeMott

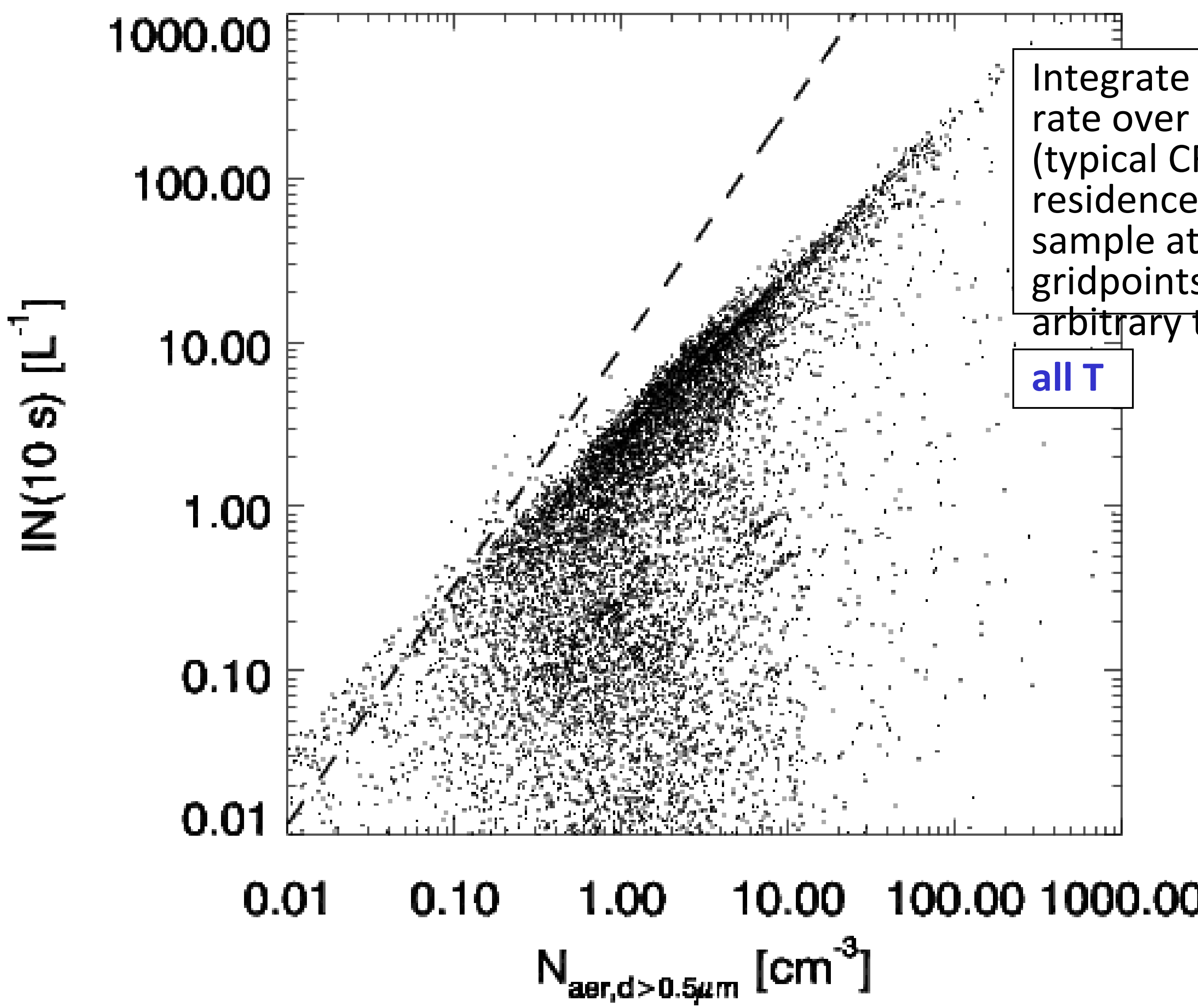
Comparison to CFDC data (II)

- CFDC IN concentrations correlate with coarse mode particle concentrations (not with total particle concentrations)



DeMott et al (2006)

Comparison to CFDC data (II)

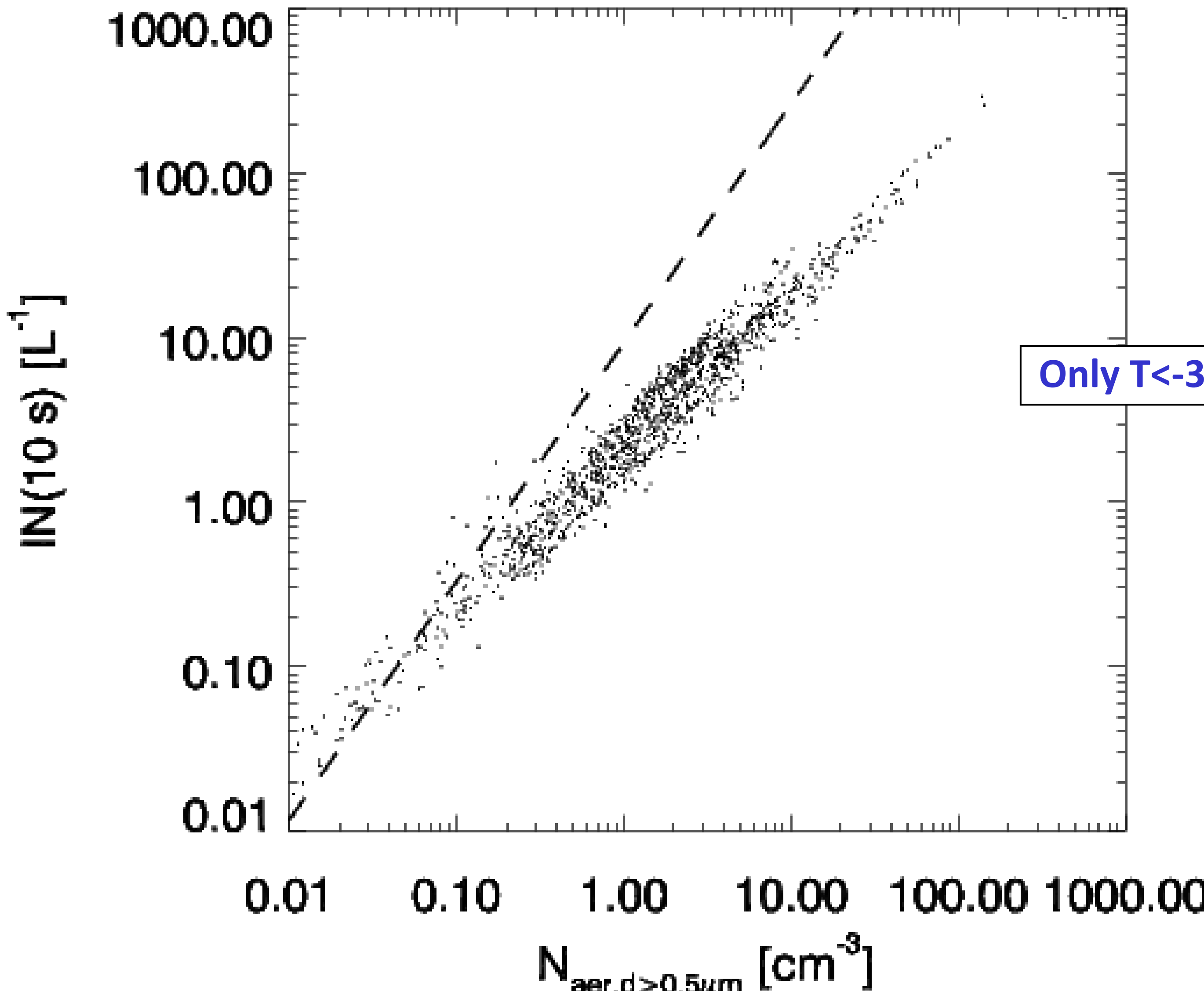


Integrate freezing rate over 10s (typical CFDC residence time), sample at all gridpoints at an arbitrary timestep

all T

--- *DeMott et al (2006)*

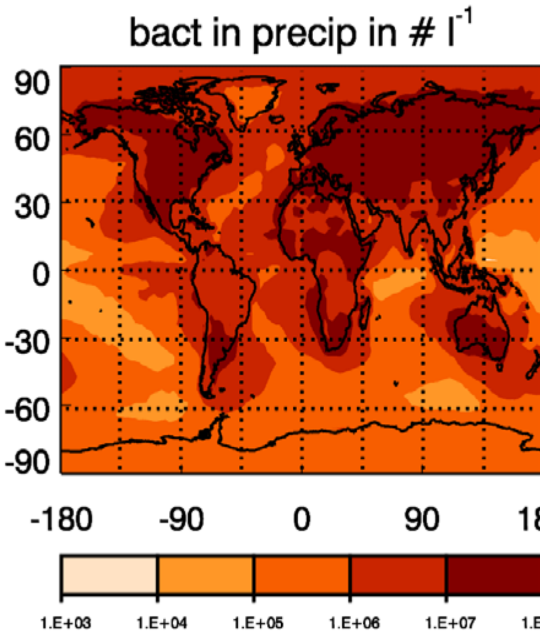
Comparison to CFDC data (II)



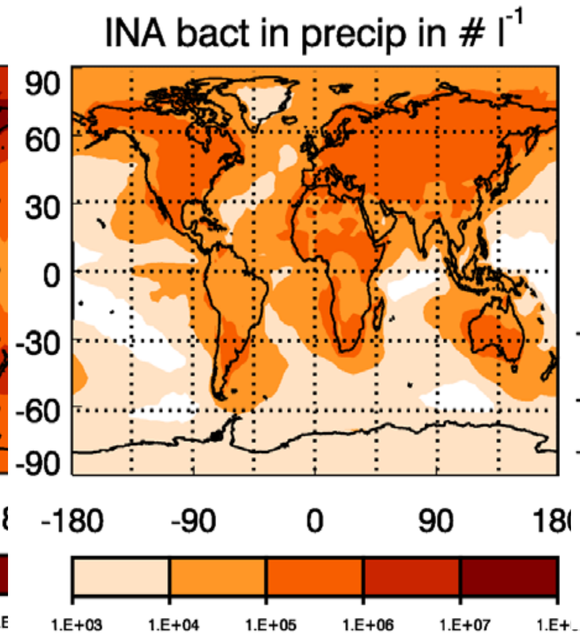
Only T<-32°C

--- *DeMott et al (2006)*

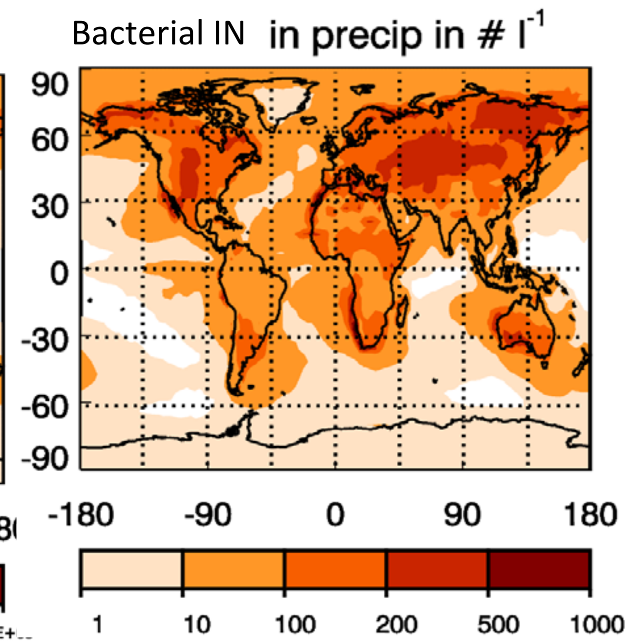
Bacteria in rain and snow



- Assume in-cloud scavenging coefficient of 100%, below-cloud 50% (same as coarse mode sea salt)

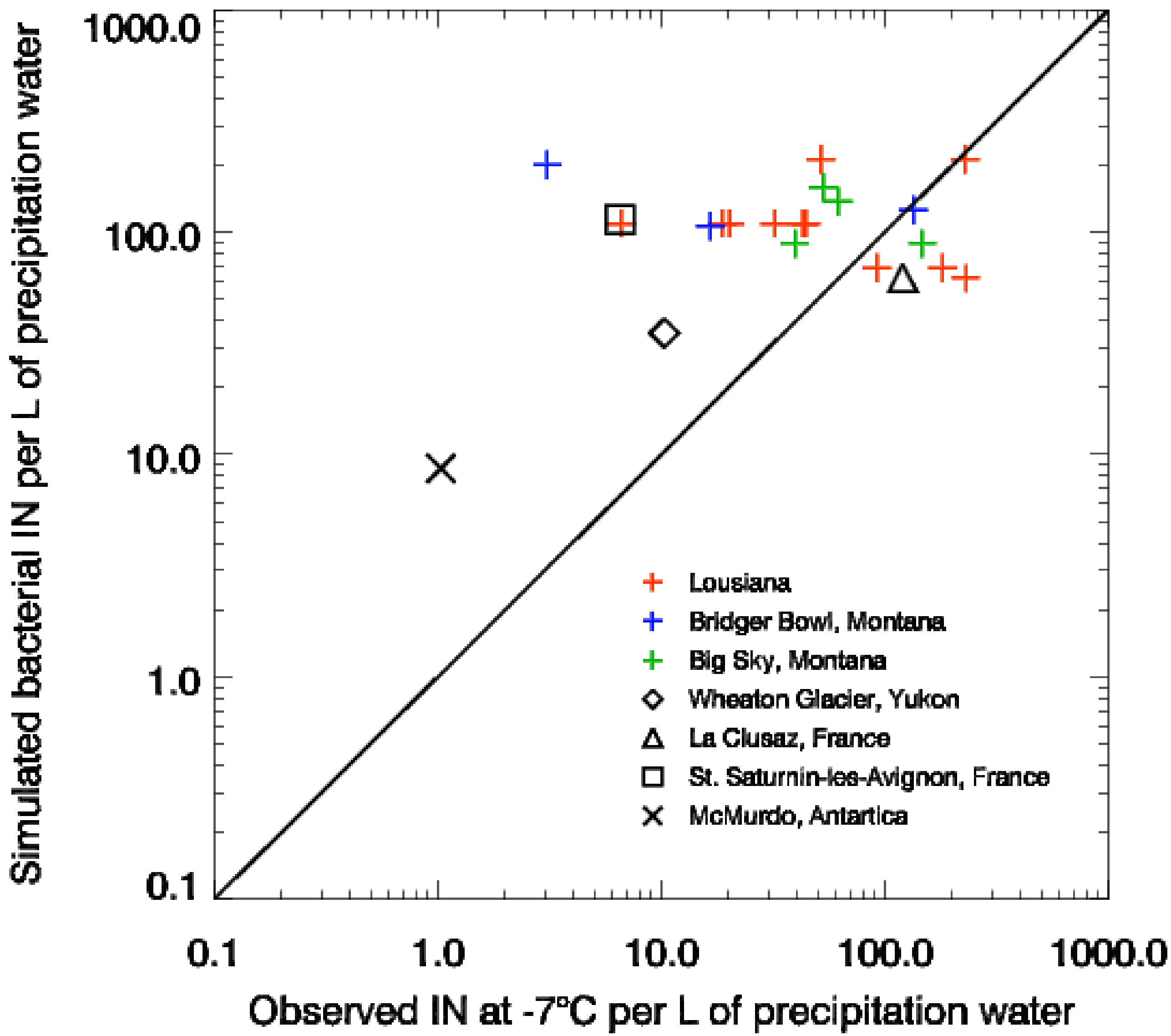


- Assume 1% of all bacteria belong to ice-nucleation active species (INA) *(Lindemann et al, 1982, Phillips et al, 2009)*



- Assume active at -7°C: 0.1% of all INA bacteria

Bacteria in rain and snow



Observations by Christner et al (2008)

Conclusions

- **Immersion freezing on mineral dust** is the most important ice nuclation process. Deposition nucleation can be a relevant process for uncoated dust.
- **Soot** contributes significantly, although ice nucleation is limited to 1%.
- Contact nucleation: most uncertain.
- **Bioaerosols: efficient, but play a minor role**, because their number concentrations are so low. Uncertain: how many airborne bacteria belong to INA species?
- Good agreement with IN measurements. Valid comparison?
- The observed concentrations of INA bacteria in snow can be explained from our simulations, without assuming preferential role in precipitation formation.

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Thank you!

Many thanks to the CAM-Oslo developers Trond Iversen, Alf Kirkevåg, Øyvind Seland and Trude Storelvmo.