Towards an improved representation of IN particle sources in models: adding the missing pieces

July 27, 2020

Susannah M. Burrows

1st virtual INP colloquium

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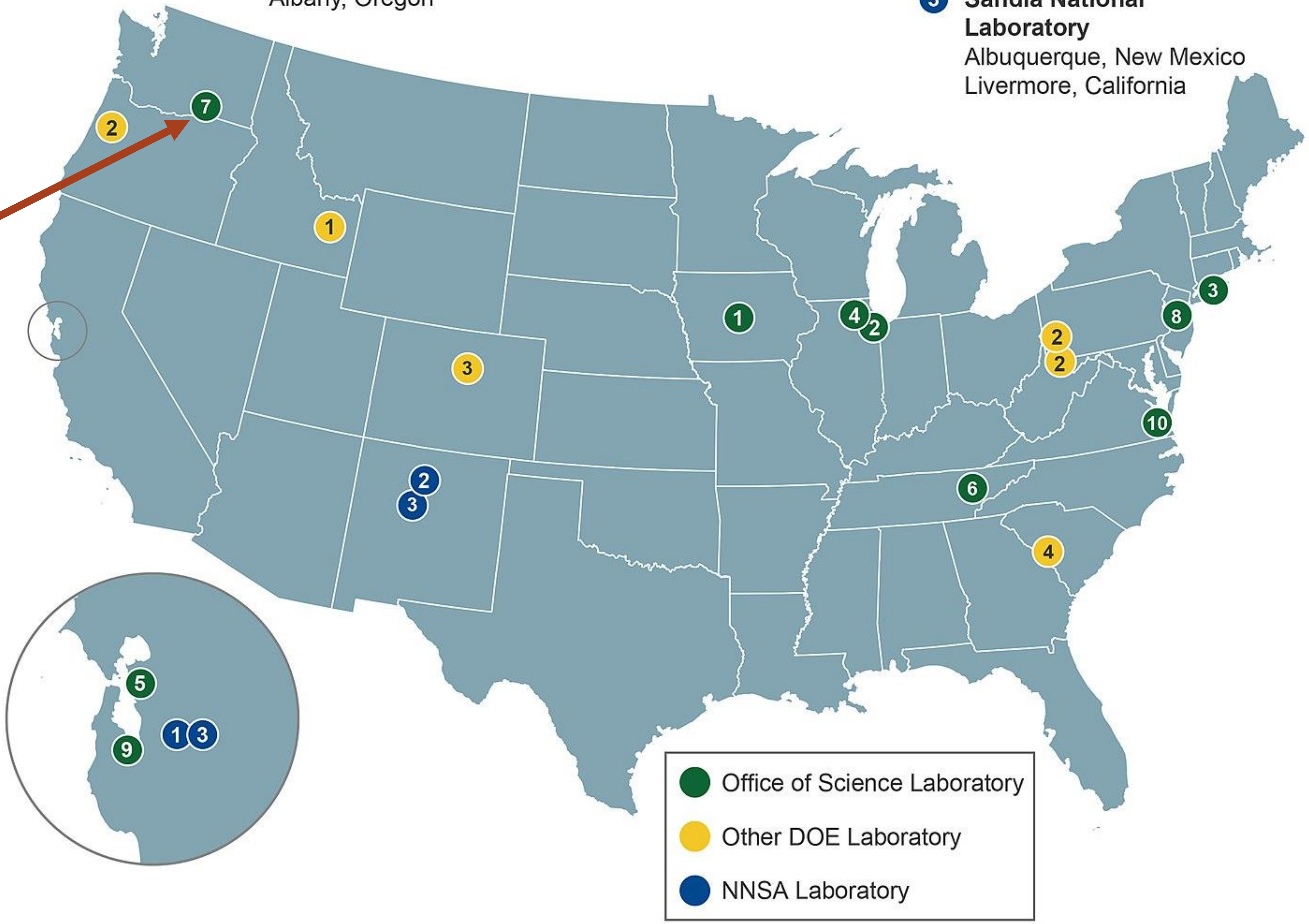
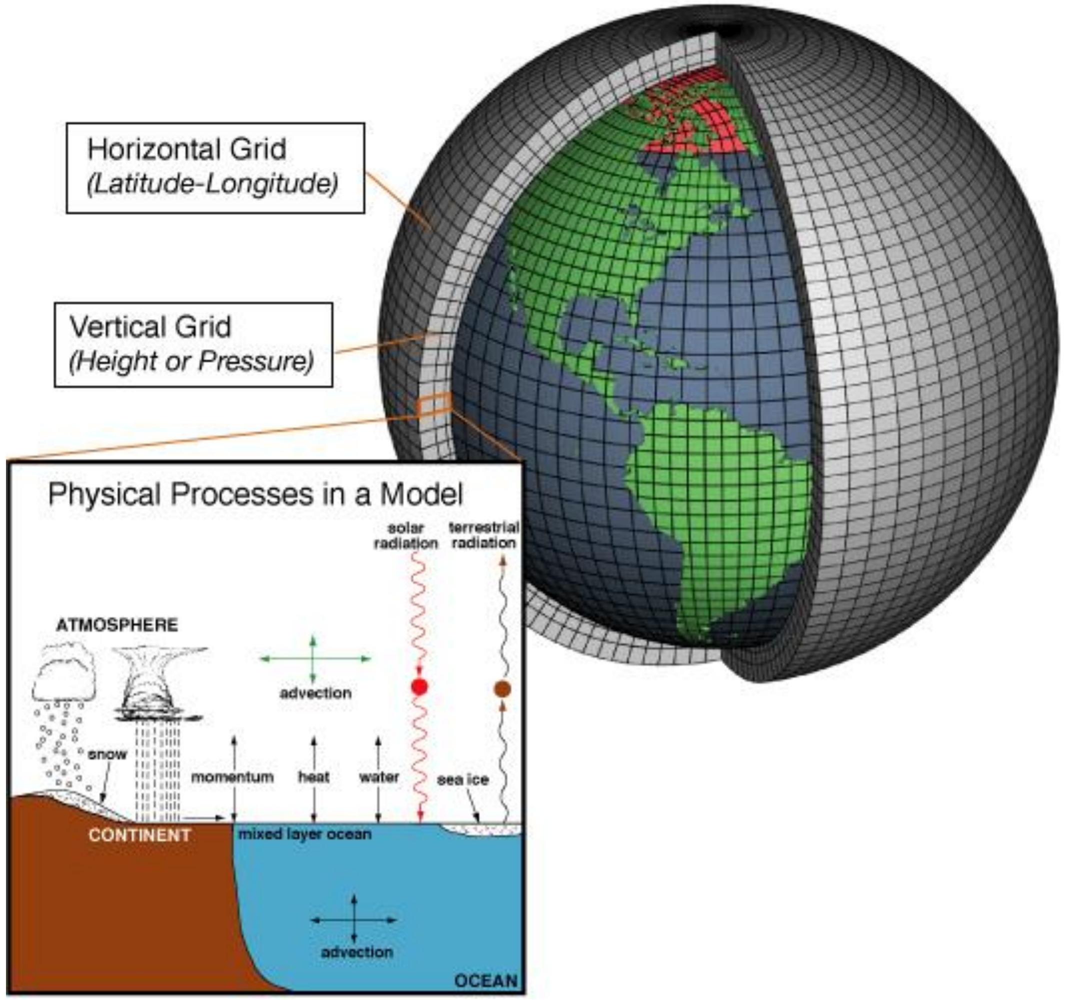


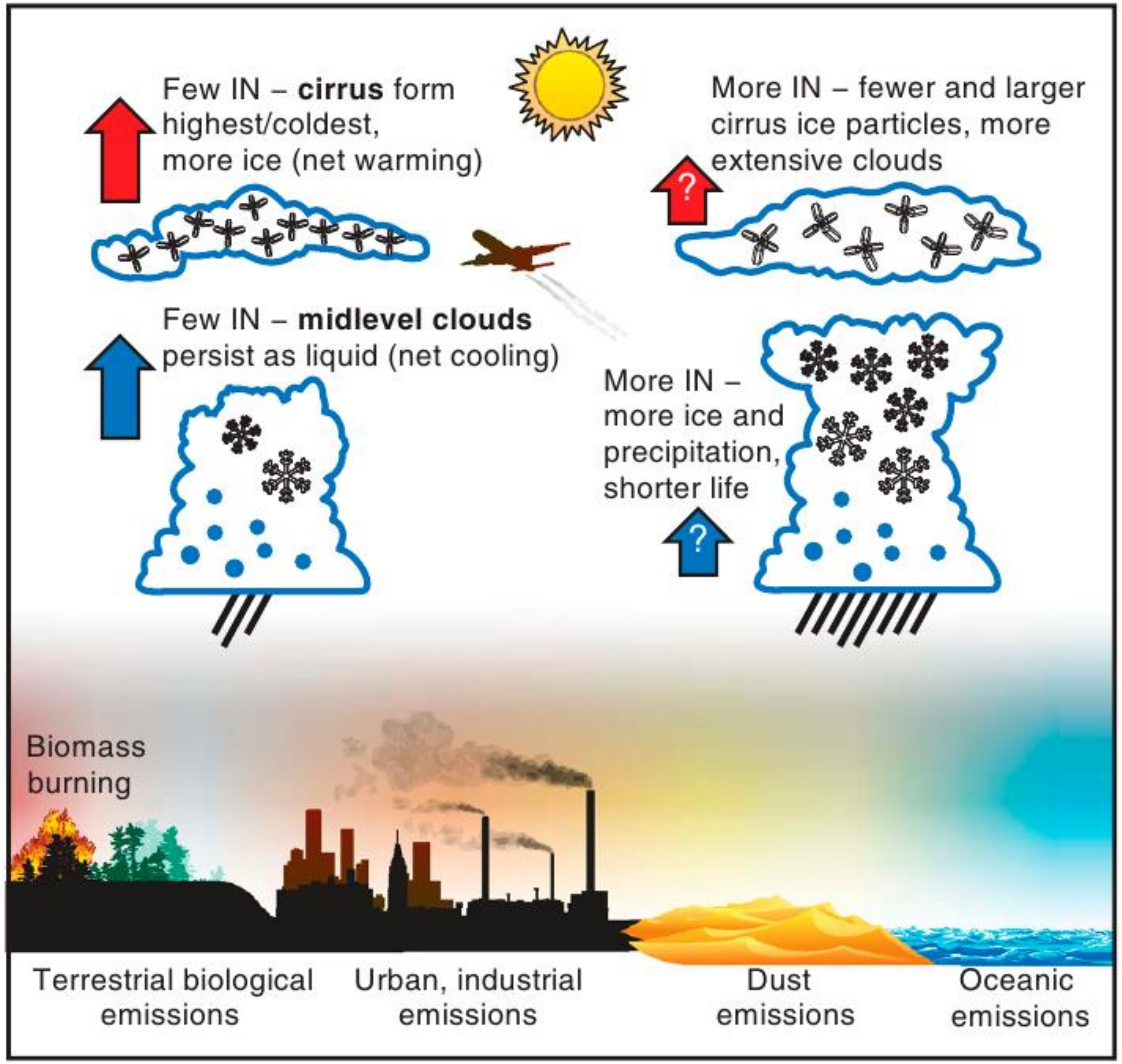


E3SM
Energy Exascale Earth System Model

Earth system dynamics & local process representations

Climate effects and sources of atmospheric ice nuclei

- Freezing by ice-nucleating particles affects:
  - Cloud phase
  - Ice crystal number concentration
  - Formation of precipitation
  - Convective invigoration(?)
  - Lifetime/persistence of clouds (e.g. anvils)
  - Cloud radiative effects



DeMott et al., PNAS, 2010

Most precipitation is formed in clouds containing ice

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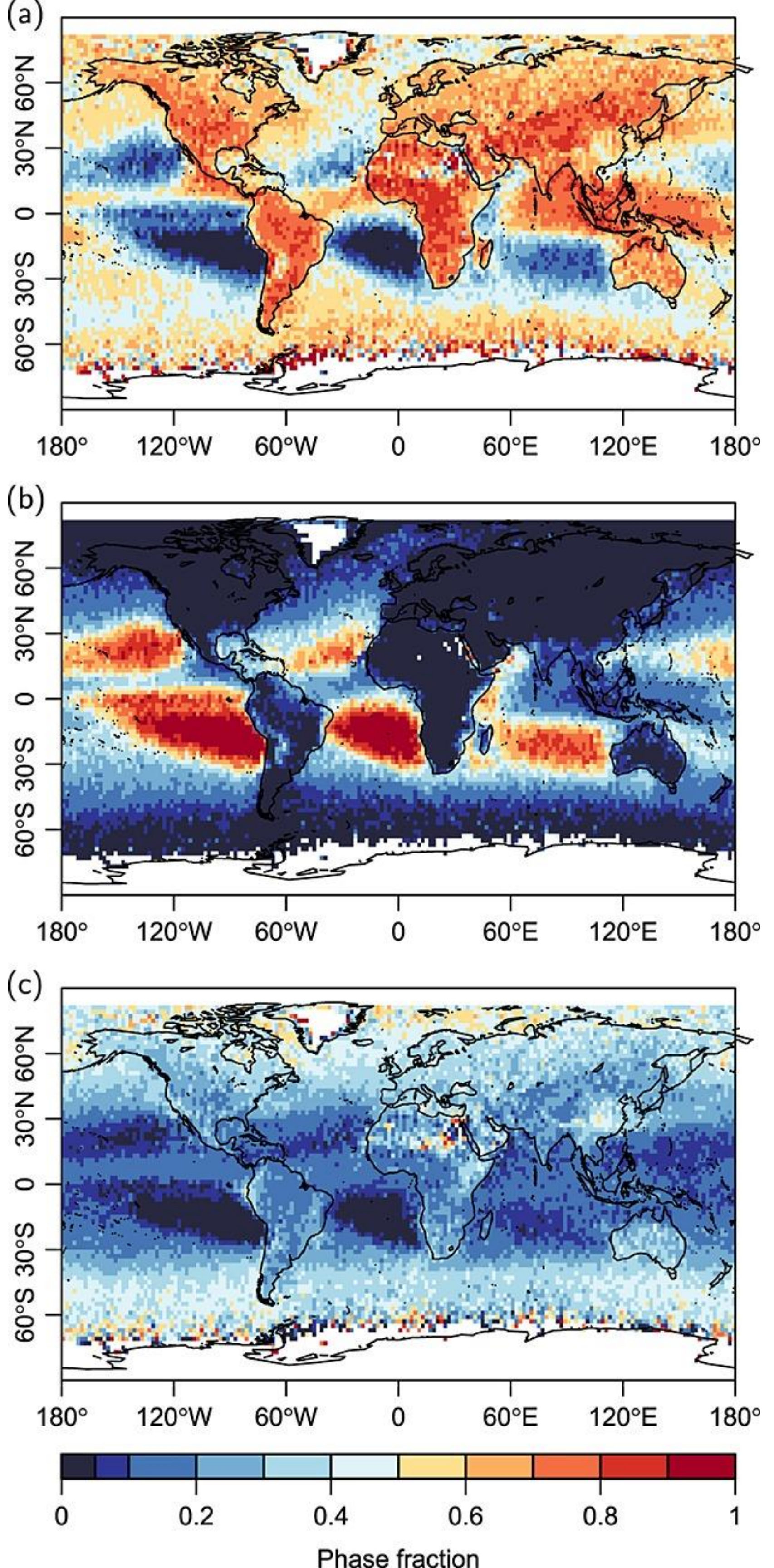
Fraction of raining clouds that are
(a) ice-phase,
(b) liquid-phase, and
(c) mixed-phase

…at cloud **top.**

…averaged over 5 years of collocated CloudSat–CALIPSO data (2006-2011)

Mülmenstädt, et al., 2015

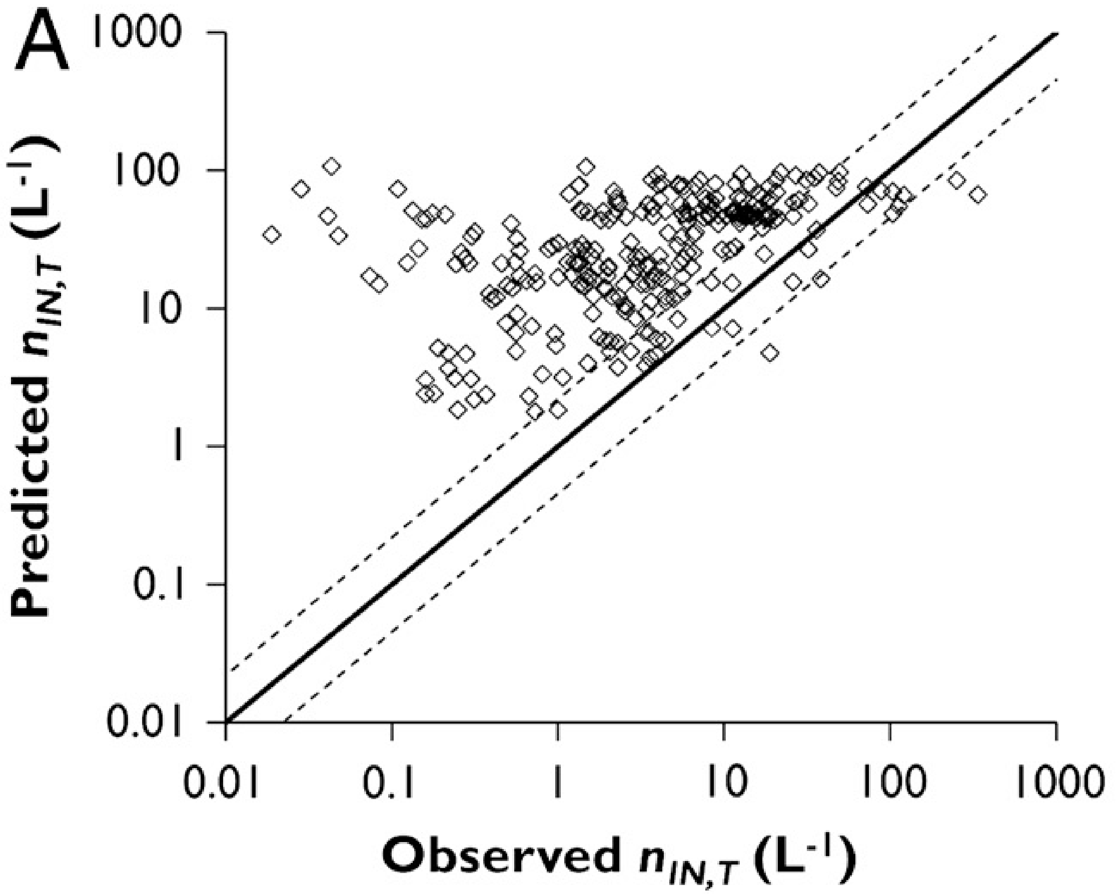


Aerosols are responsible for much of the variance in INP concentrations

- INP concentrations vary by several orders of magnitude, and much of this variance can be explained by variations in aerosol
- Very few atmospheric particles are effective INP: ~ 1 per $10^5 – 10^6$
- Understanding which particles contribute to INP is important to better prediction of their numbers, temporal and spatial variability, and potential response to global change

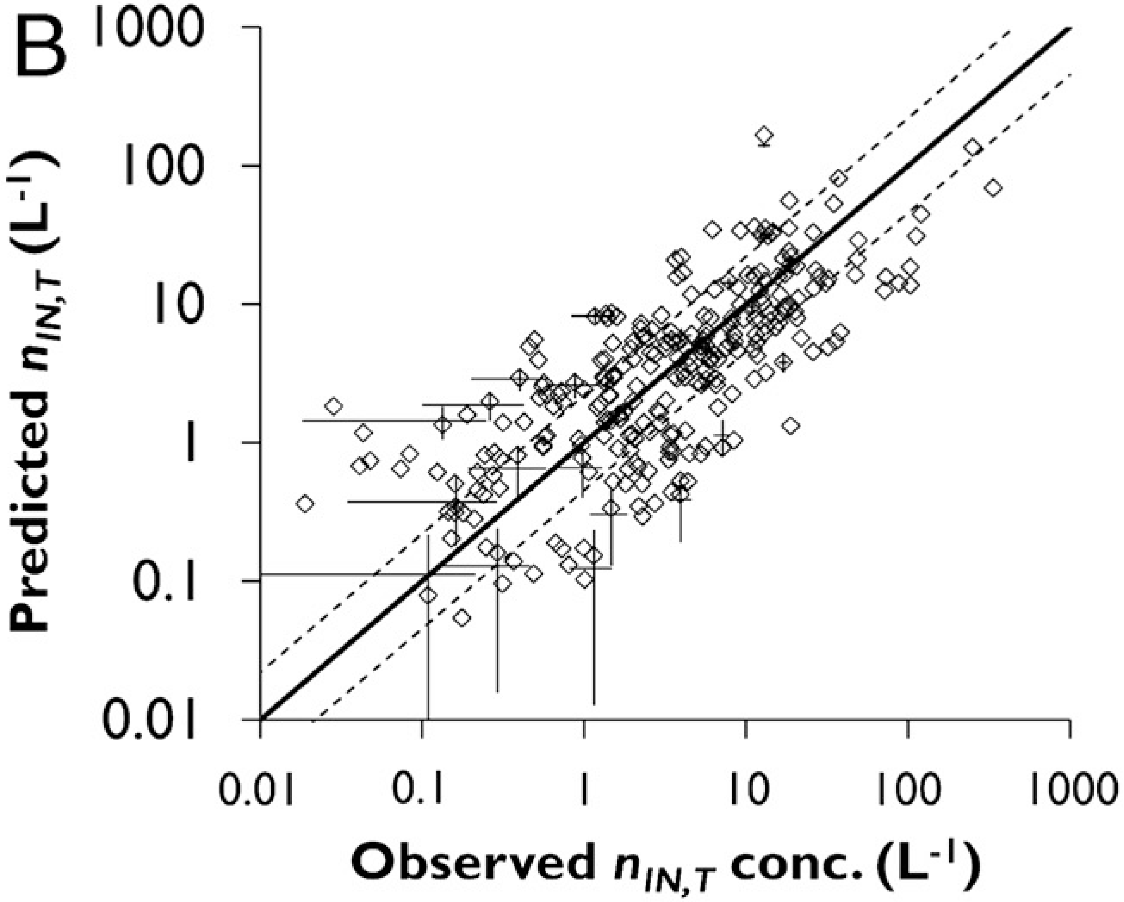
Meyers et al. 1992

$$N_{id} = N_0[(S_i - 1)(S_0 - 1)^{-1}]^b \exp(aT_{sup}).$$



DeMott et al., 2010, PNAS

$$n_{IN,T_k} = a(273.16 - T_k)^b (n_{aer,0.5})^{(c(273.16 - T_k)+d)},$$

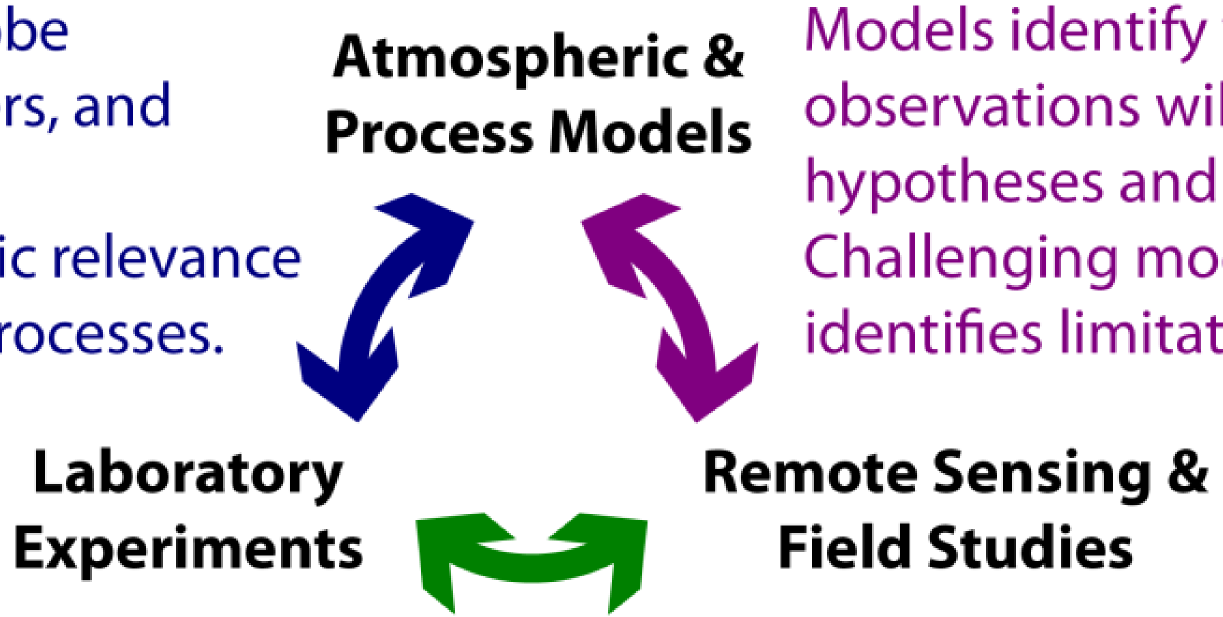


A measurements-to-models approach to advance understanding of ice-nucleating particles

Aim: Improve **predictive understanding** of INP variability:

- We **understand** the particle sources and atmospheric processes that control INP variability at different places and times.
- We can use this understanding to **skillfully predict** INP concentrations in models.

Laboratory experiments probe processes, identify key drivers, and constrain parameter values.
Models quantify atmospheric relevance / importance of proposed processes.

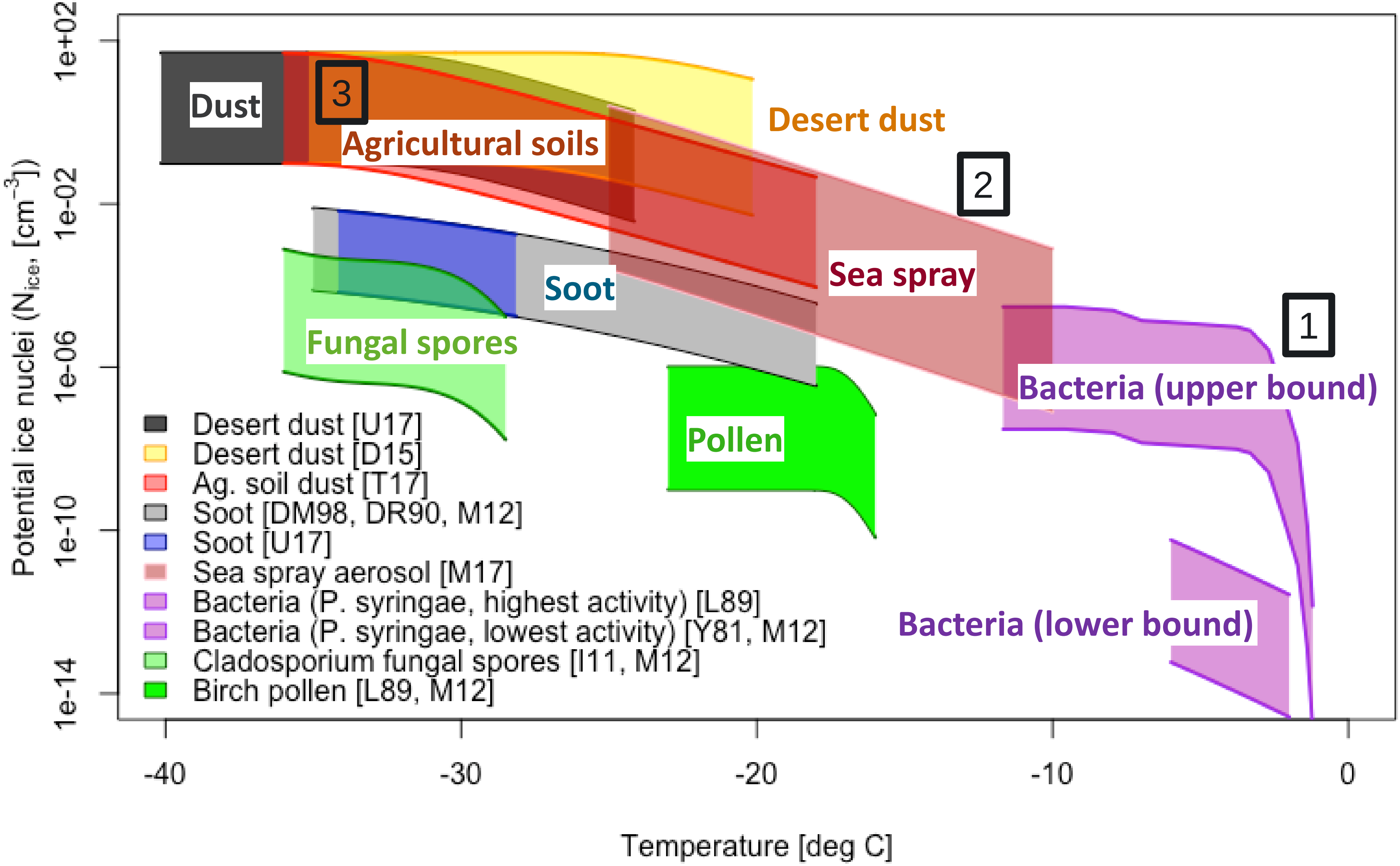


Models identify where and when observations will be most useful in testing hypotheses and constraining models.
Challenging models with observations identifies limitations and knowledge gaps.

Laboratory analyses facilitate interpretation of field observations.
New hypotheses to explain field observations can be tested in the laboratory.

Which particles drive immersion-mode INP number for mixed-phase clouds?

Based on Murray et al. 2012; updated with sea spray and agricultural soil sources



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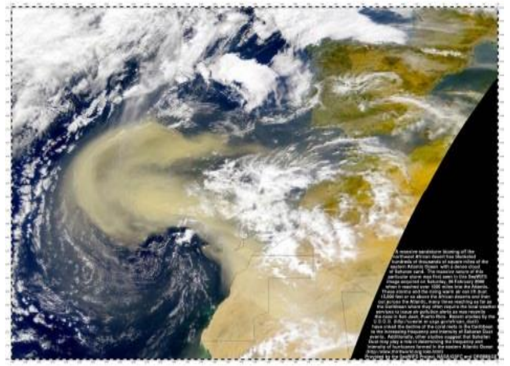
Missing piece 1: Airborne bacteria (??)

Certain bacteria (e.g. *Pseudomonas syringae*) are known to be effective ice nucleators.

Goal: to place upper/lower bounds on the potential of bacteria-bearing particles to contribute to atmospheric INPs.

Real-world mechanisms of bacteria emissions



Lofted with dust and soil

Shaking leaves

Sea spray

Inter-ecosystem transport simulated by a global atmospheric model (with emissions, transport and removal)

Simplified model of bacteria emissions and transport

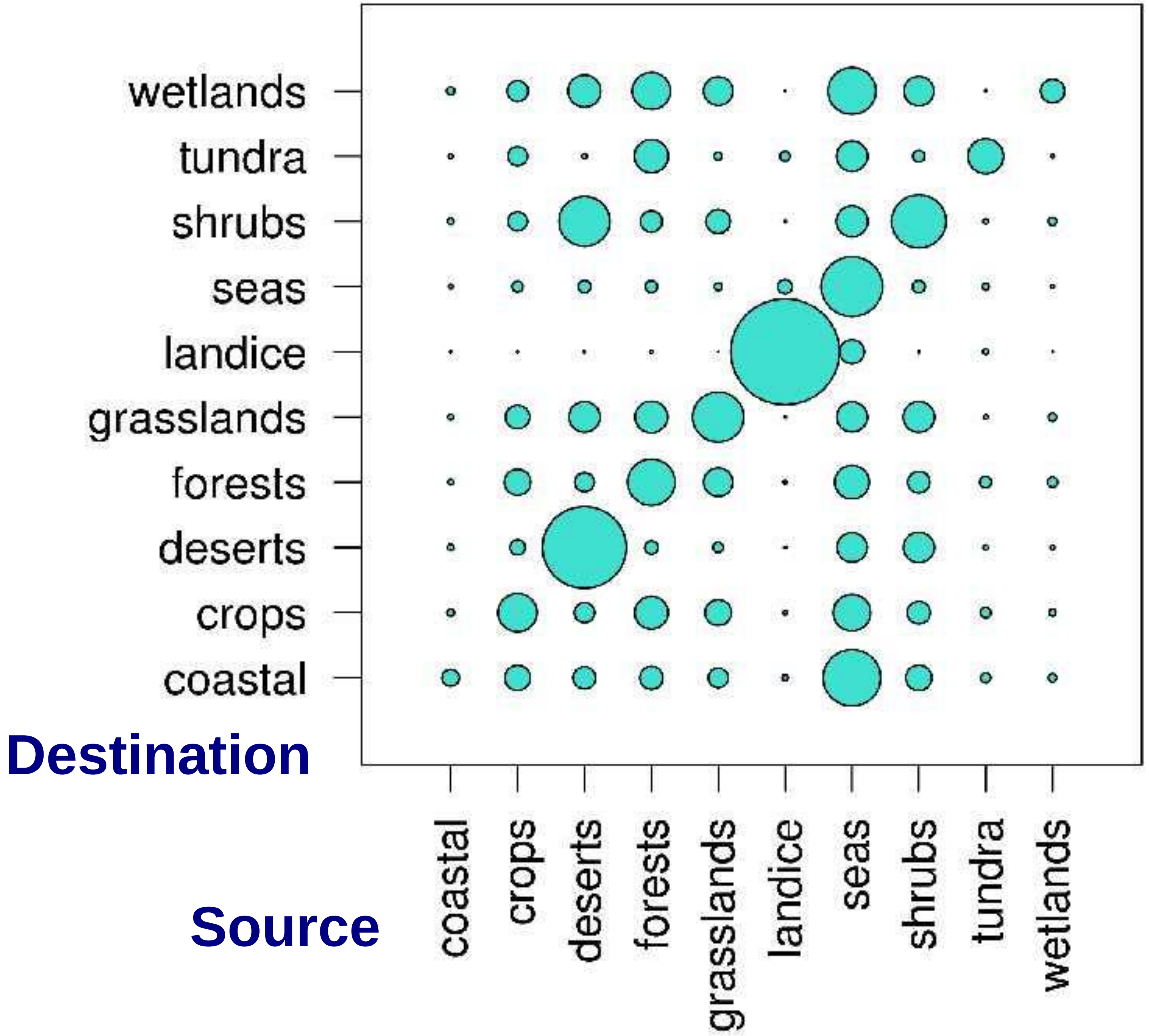
Constant, homogeneous source from each of ten ecosystems

Monodisperse aerosol with 1µm diameter

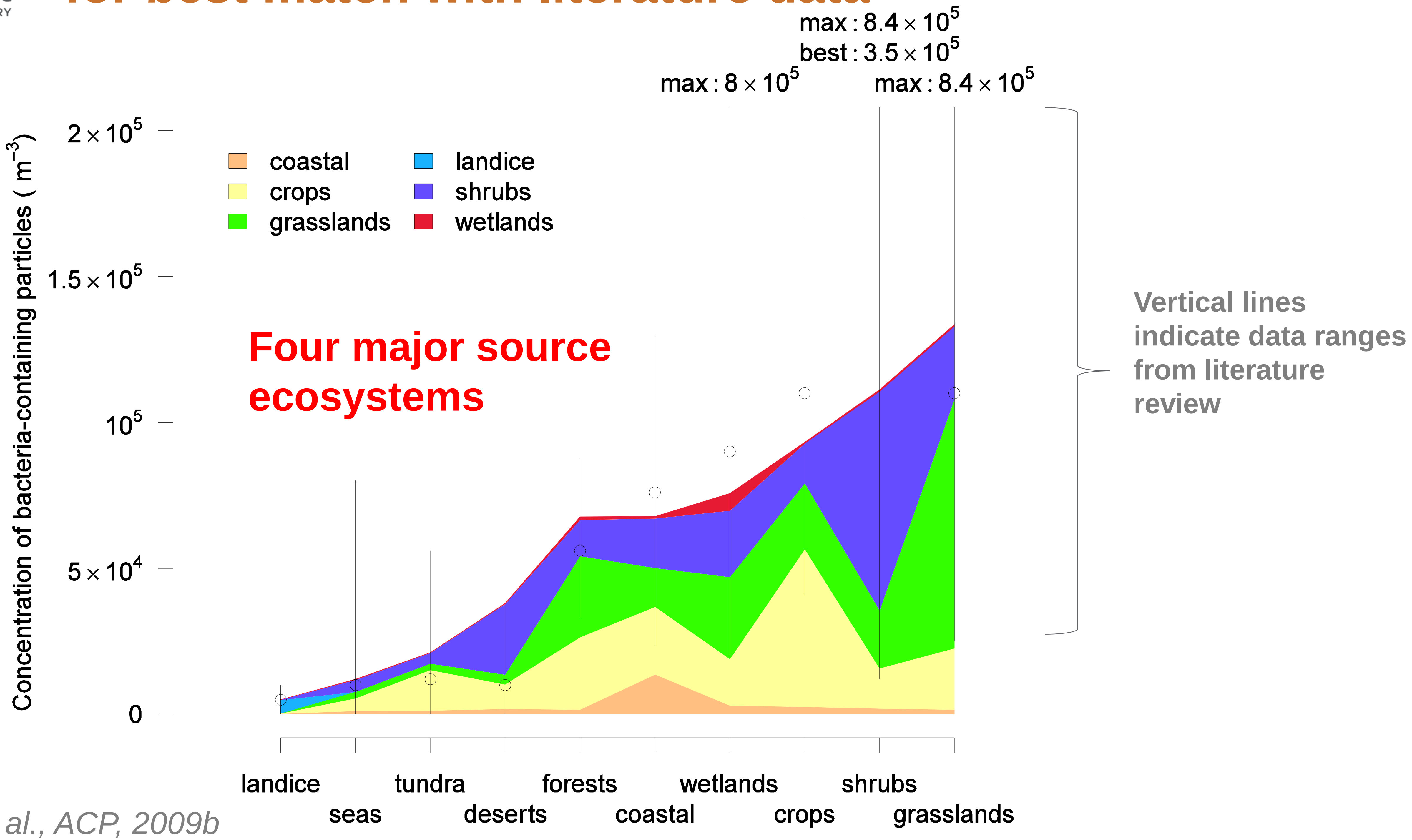
Transport and removal by wet and dry deposition

Simulations conducted within the ECHAM/MESSy-atmospheric chemistry (EMAC) model

Burrows et al., ACP, 2009b



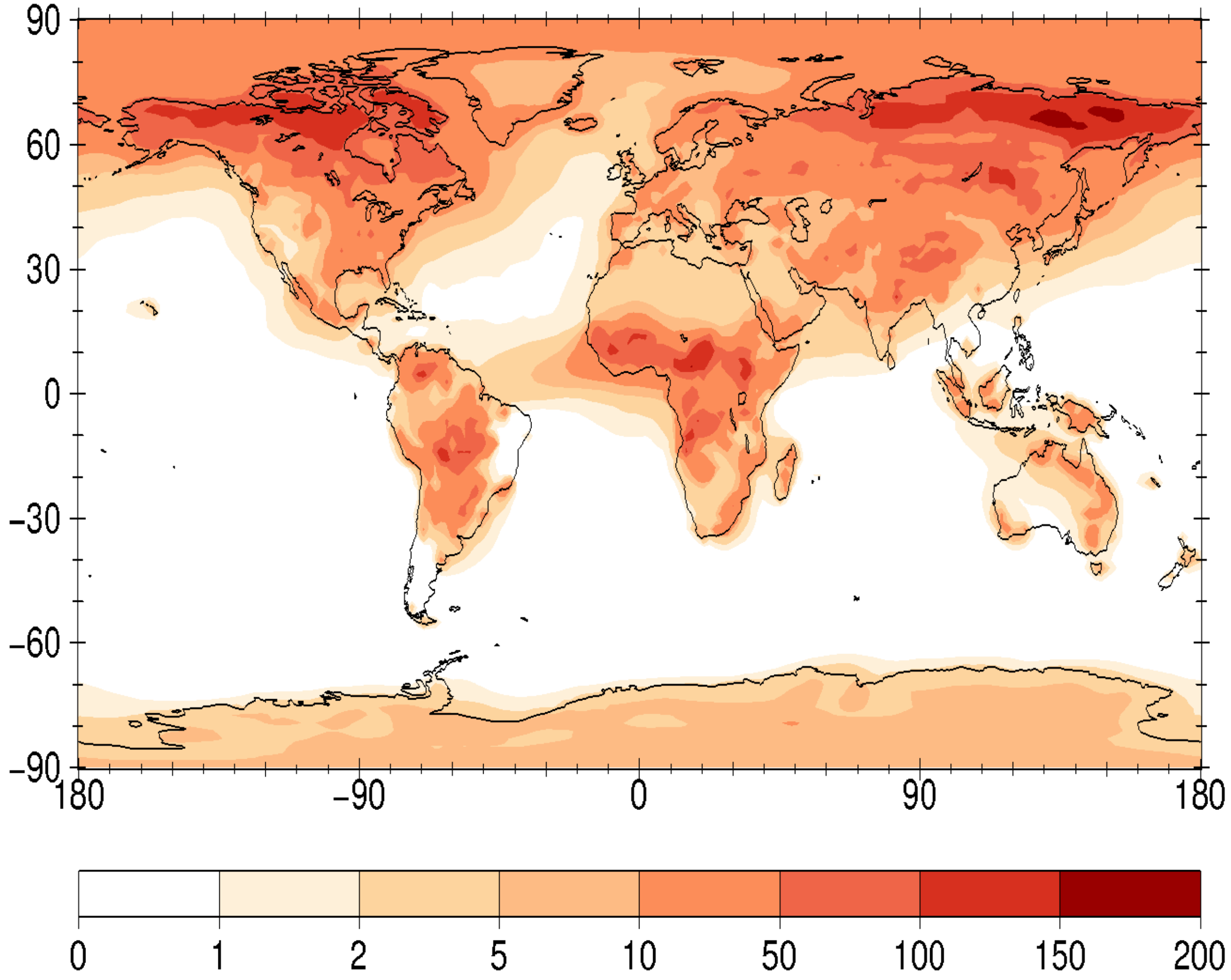
Simulated bacteria-containing particle concentrations in near-surface air by ecosystem, after optimizing fluxes for best match with literature data



Burrows et al., ACP, 2009b

Global estimates of bacteria emissions

	Ensemble mean	Ensemble range (5%-95%)
Mean emissions from land (particles m^{-2} s^{-1})	250	140 - 380
Mean emissions from seas (particles m^{-2} s^{-1})	0	0 - 226
Global emissions (particles per year)	1.4×10^{23}	$(7.6 – 35) \times 10^{23}$
Global emissions (Gg per year)	740	400 – 1800



Modeled concentration of bacteria-containing particles (10^6 per m^{-3})

Burrows et al., ACP, 2009b

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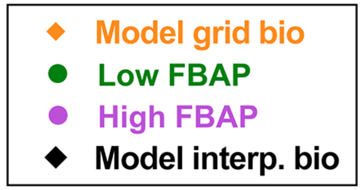
Comparison of models with airborne measurements of biological particles

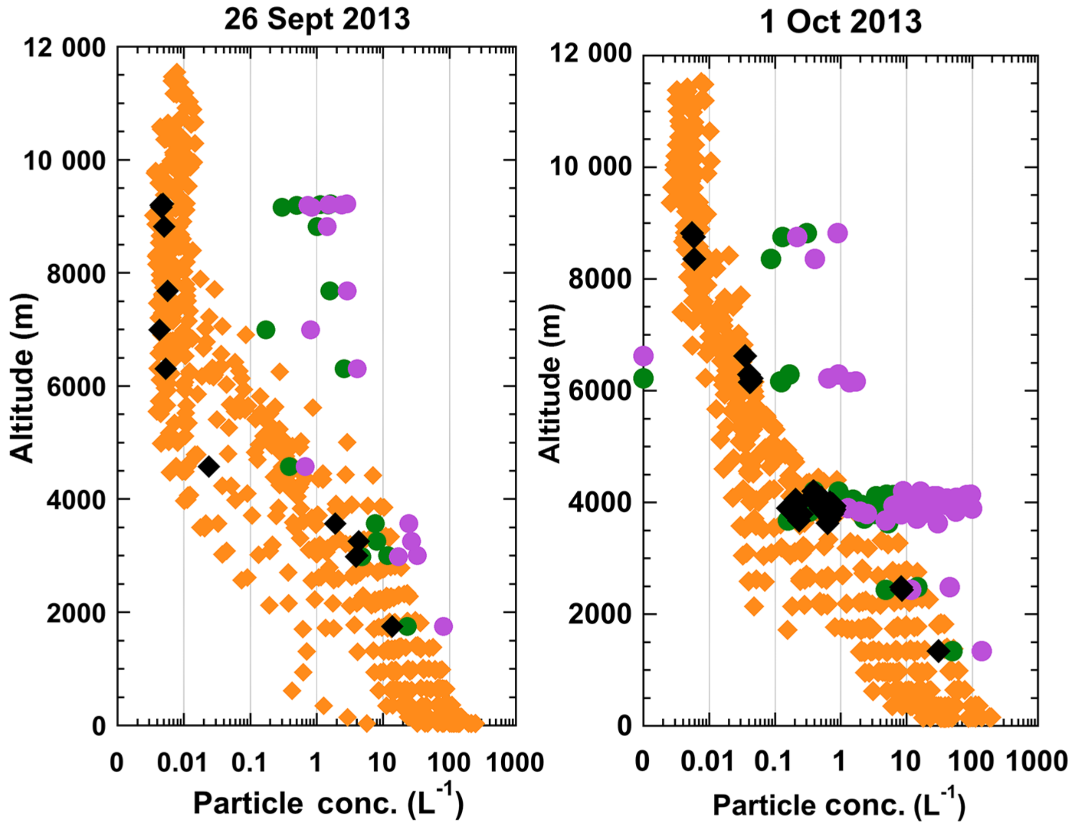
FBAP = “Fluorescent Biological Aerosol Particles”

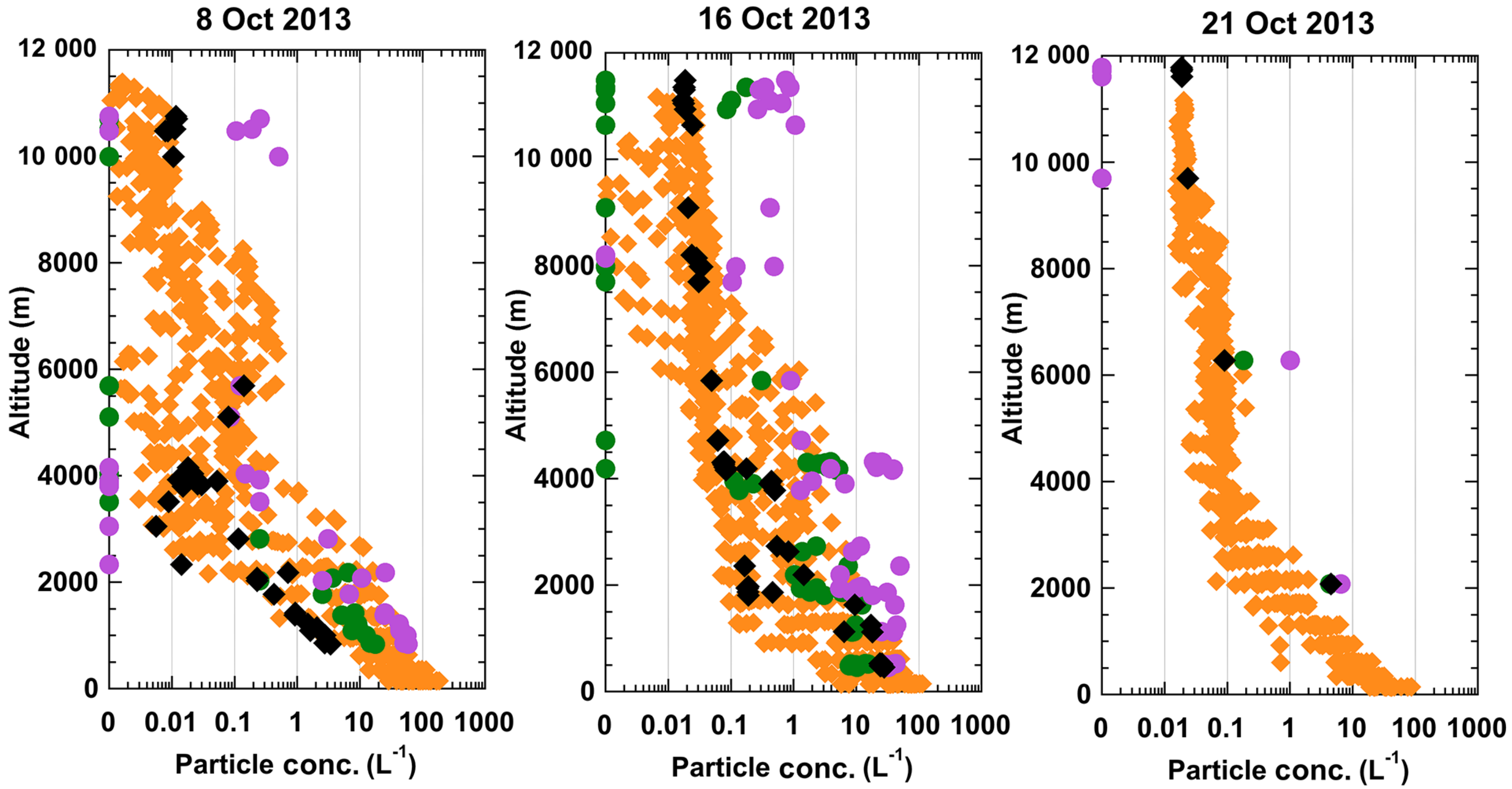
Real-time measurement of particle fluorescence and aerodynamic size by WIBS instrument.

Over US Western Plains in autumn.

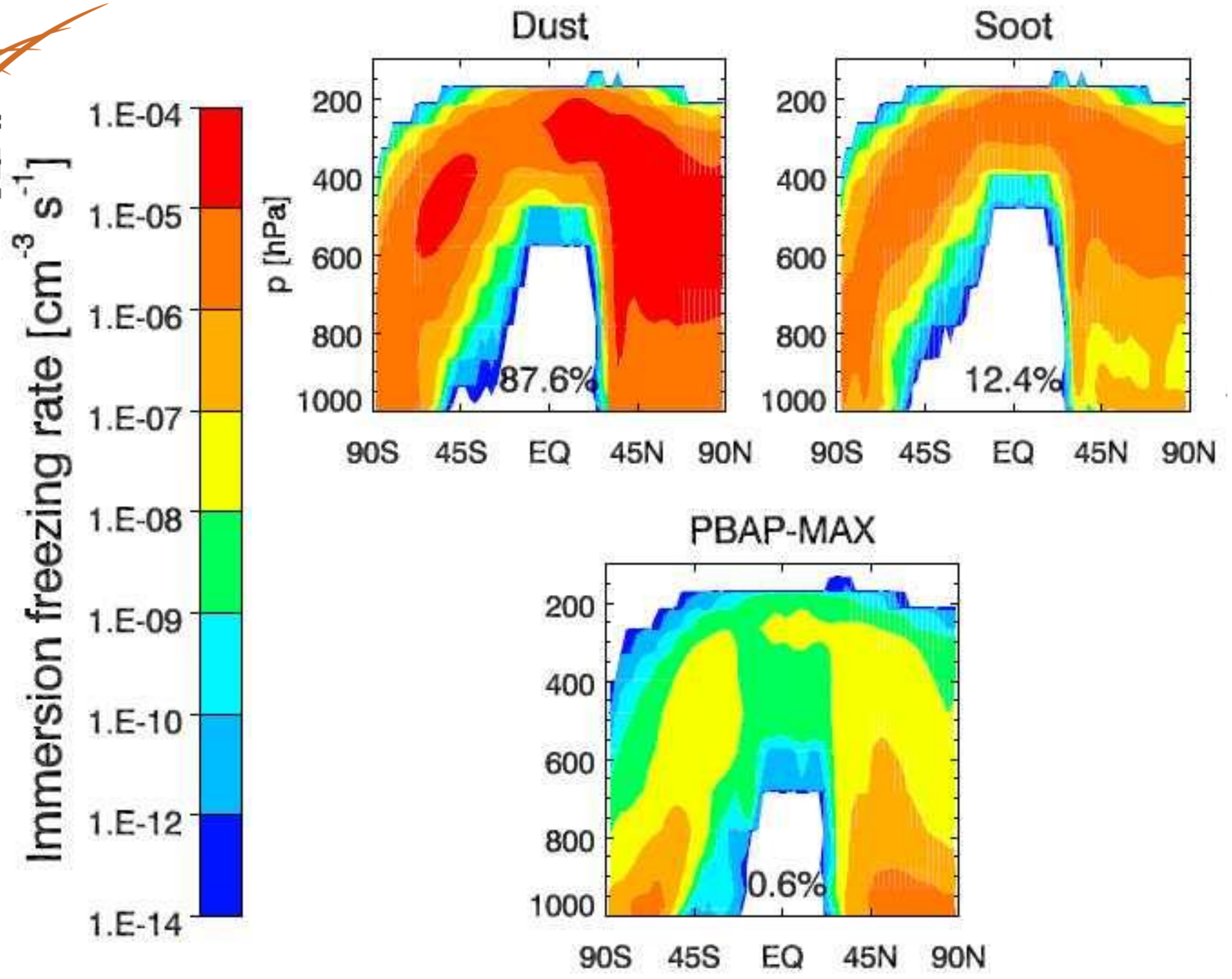
Twohy et al., 2016, ACP







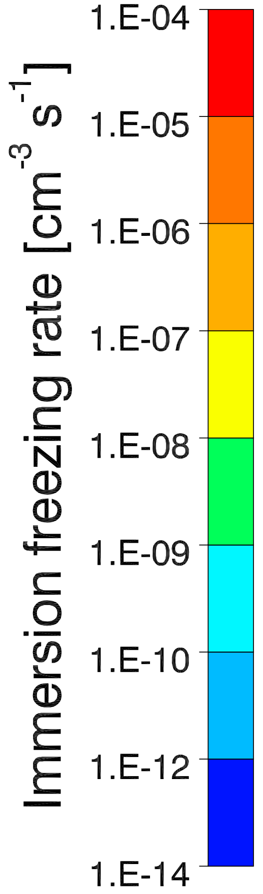
Simulated freezing rate

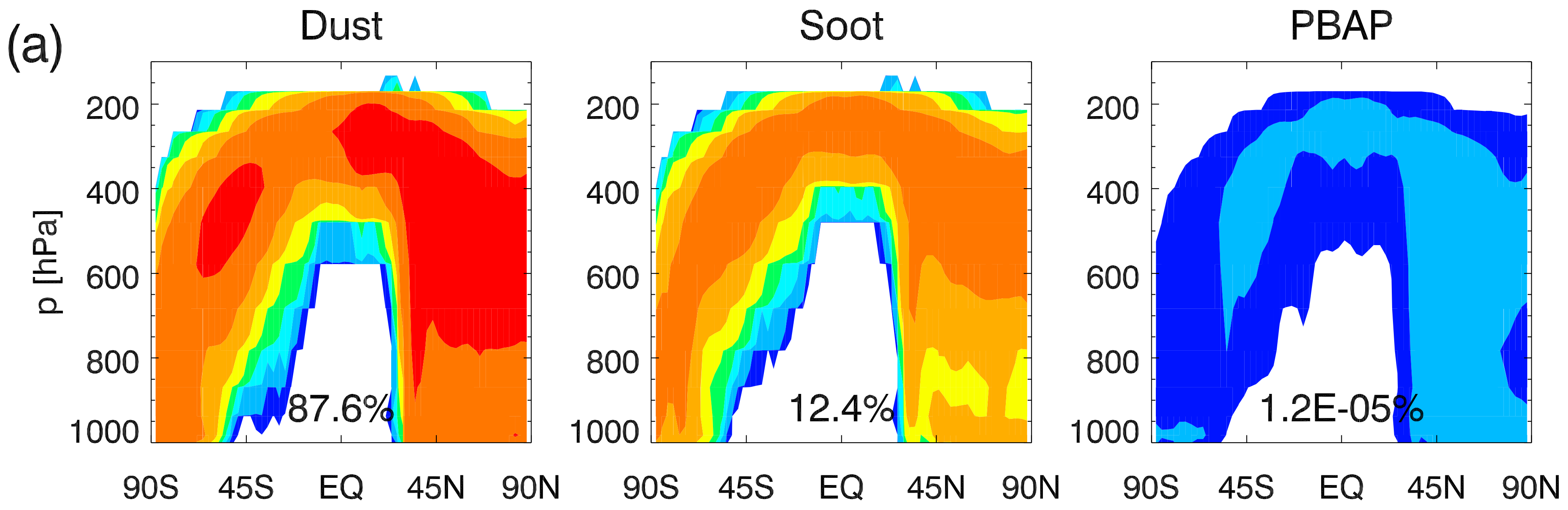


Uppermost estimate:
Mean contribution of 0.6% to global ice nucleation

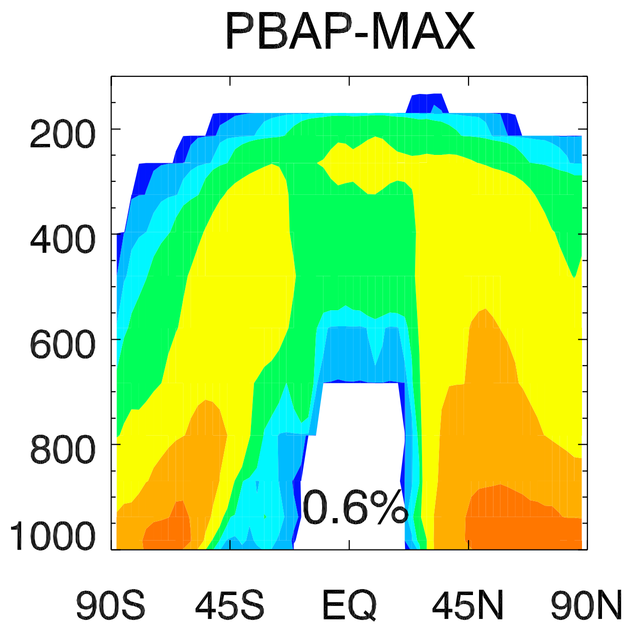
Generous assumptions about IN activity (100% Ps. syr.-like, higher emissions)

CAM-Oslo, Hoose et al, ERL 2010





- Primary Biological Aerosol Particles (PBAP) – here: bacteria, fungal spores, pollen.
- Even with very generous assumptions, PBAP contribute at most 0.6% to global immersion freezing rate in this study.



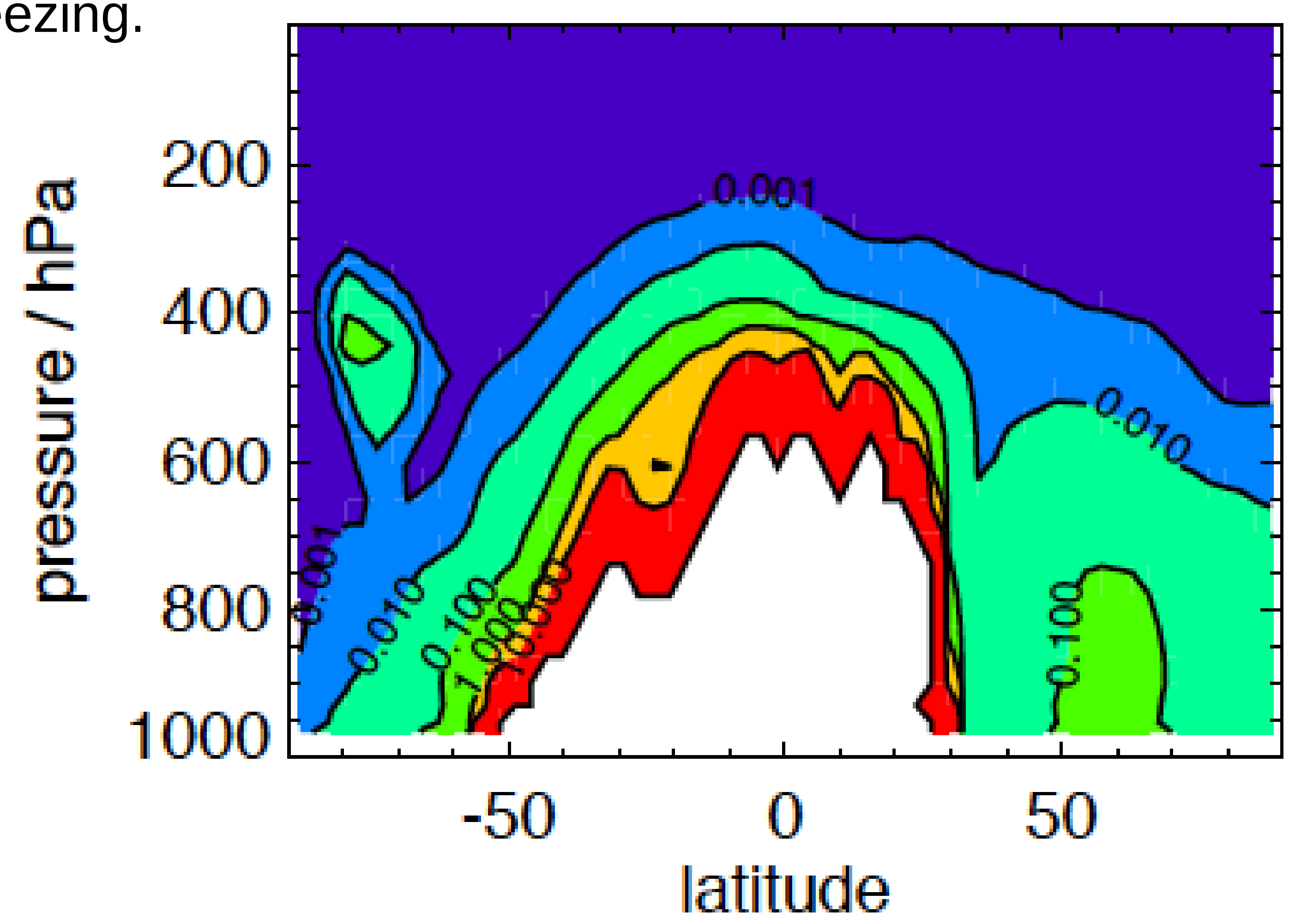
When and where might PBAP matter as IN?

- In regions where dust, soot influence is low (e.g. Amazon, Southern Ocean)?
- In low-lying, warmer parts of mixed-phase clouds

Hoose, Kristjánsson and Burrows, ERL, 2010

Primary Biological Aerosol Particles may be important in initiating cloud drop freezing at lower altitudes

Upper limit contribution of PBAP to immersion freezing as a percentage of total immersion freezing.



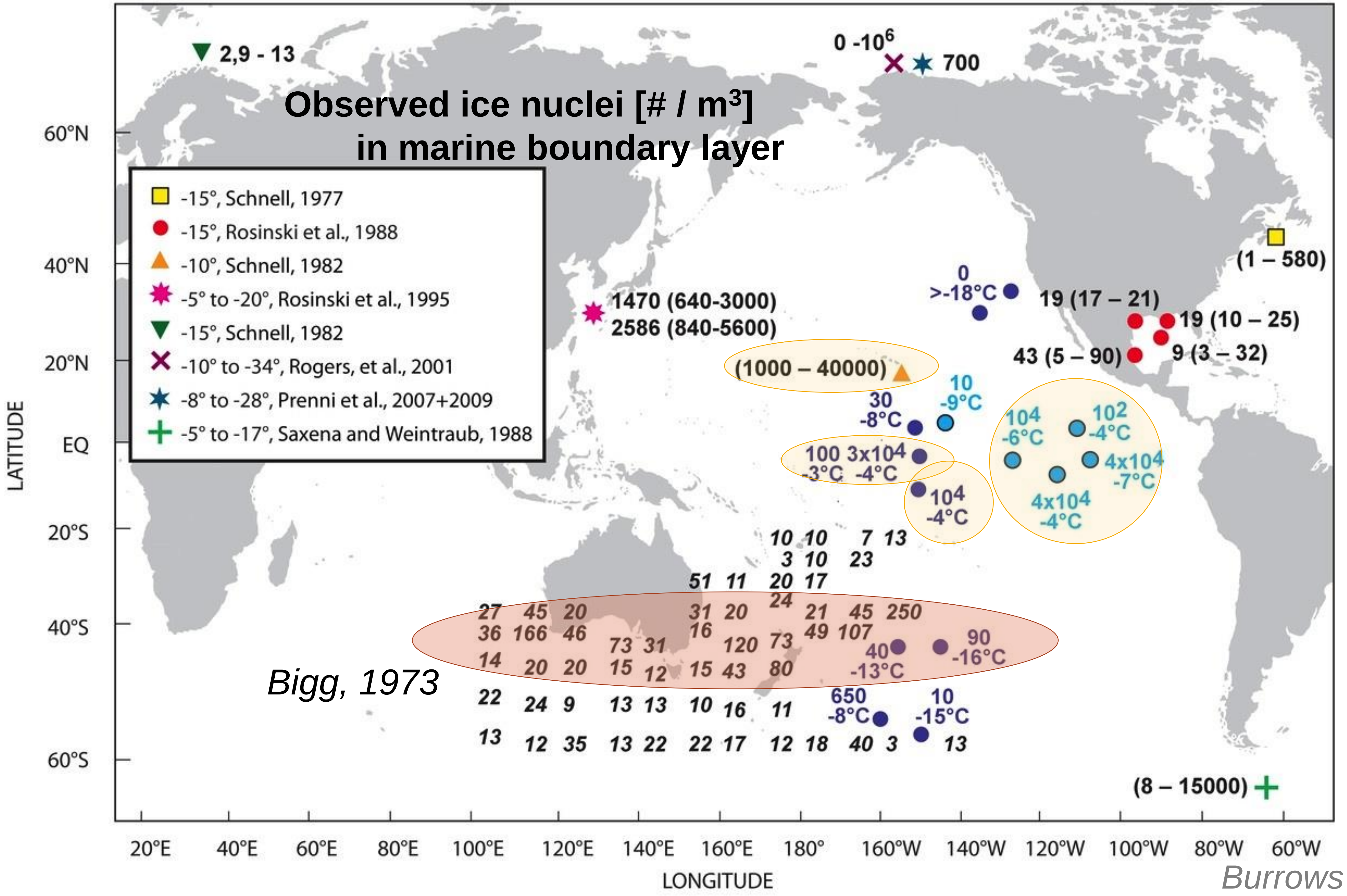
PBAPs may be important in initiation ice formation in the warmer part of low-level clouds.

Spracklen and Heald, 2014

Missing piece 2: sea spray organic matter

Observed marine IN concentrations are higher over phytoplankton bloom regions.

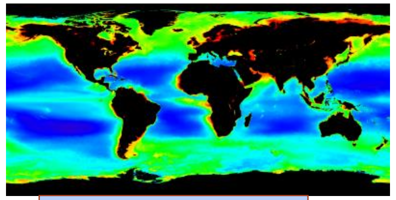
Occasionally, very high IN concentrations have been reported over active blooms.



Burrows et al., ACP, 2013a

Marine biological IN estimate

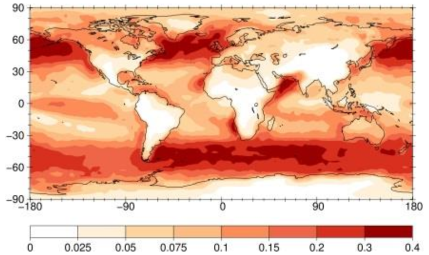
Satellite data: proxies for marine biological activity (POC, Chl-a)



Satellite: POC

Model parameterization: Sea spray emissions

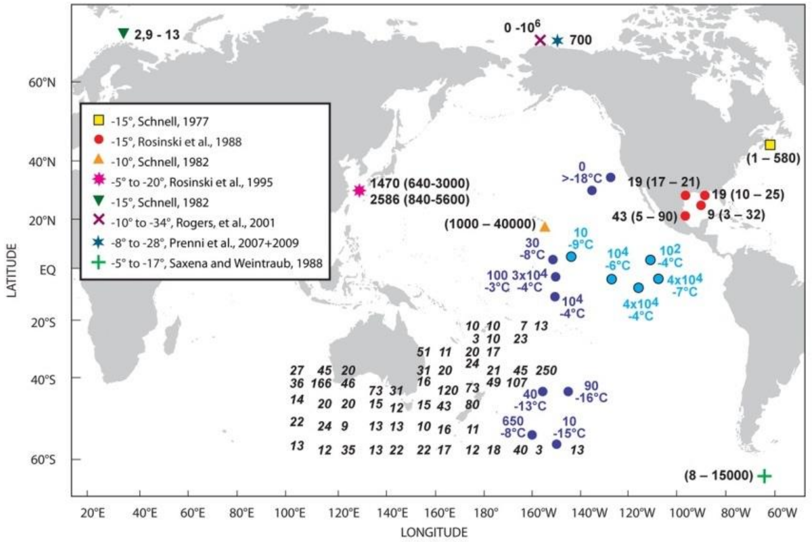
Intermediate result from simulations: Particulate organic matter in sea spray



In situ data: IN concentration in marine plankton bloom

<u>Result</u>: IN estimate in sea spray

Comparison with filter measurements and estimated dust IN concentrations



Burrows et al., 2013

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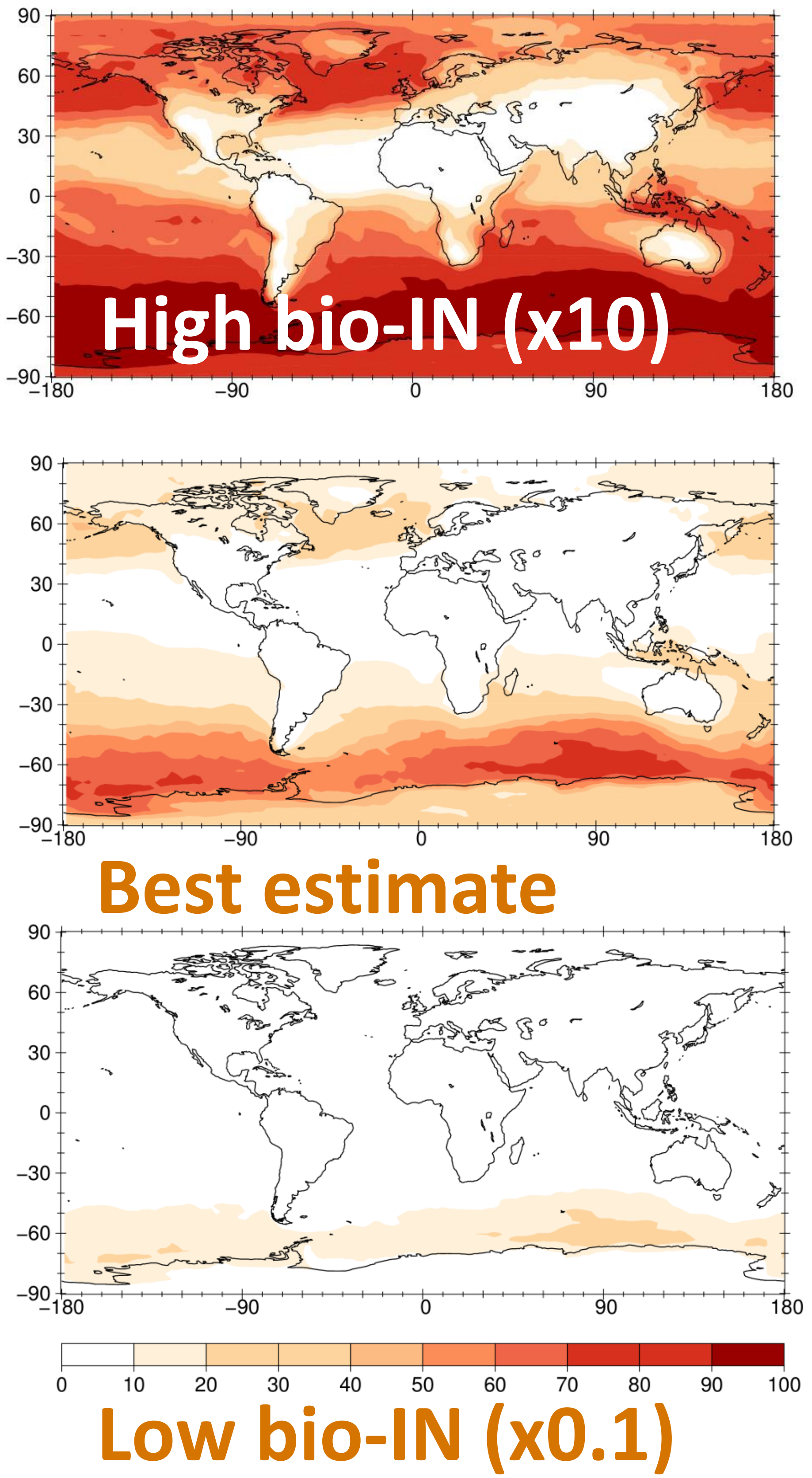
Percent contribution
of sea spray organic INP to total INP in the marine boundary layer

- Best “bounding” estimate using observational data available at the time.
- Relied on a single, decades-old measurement of ocean surface material INP efficiency.
- No modern observations of INP in marine air were available for evaluation of this estimate.



Burrows et al., 2013

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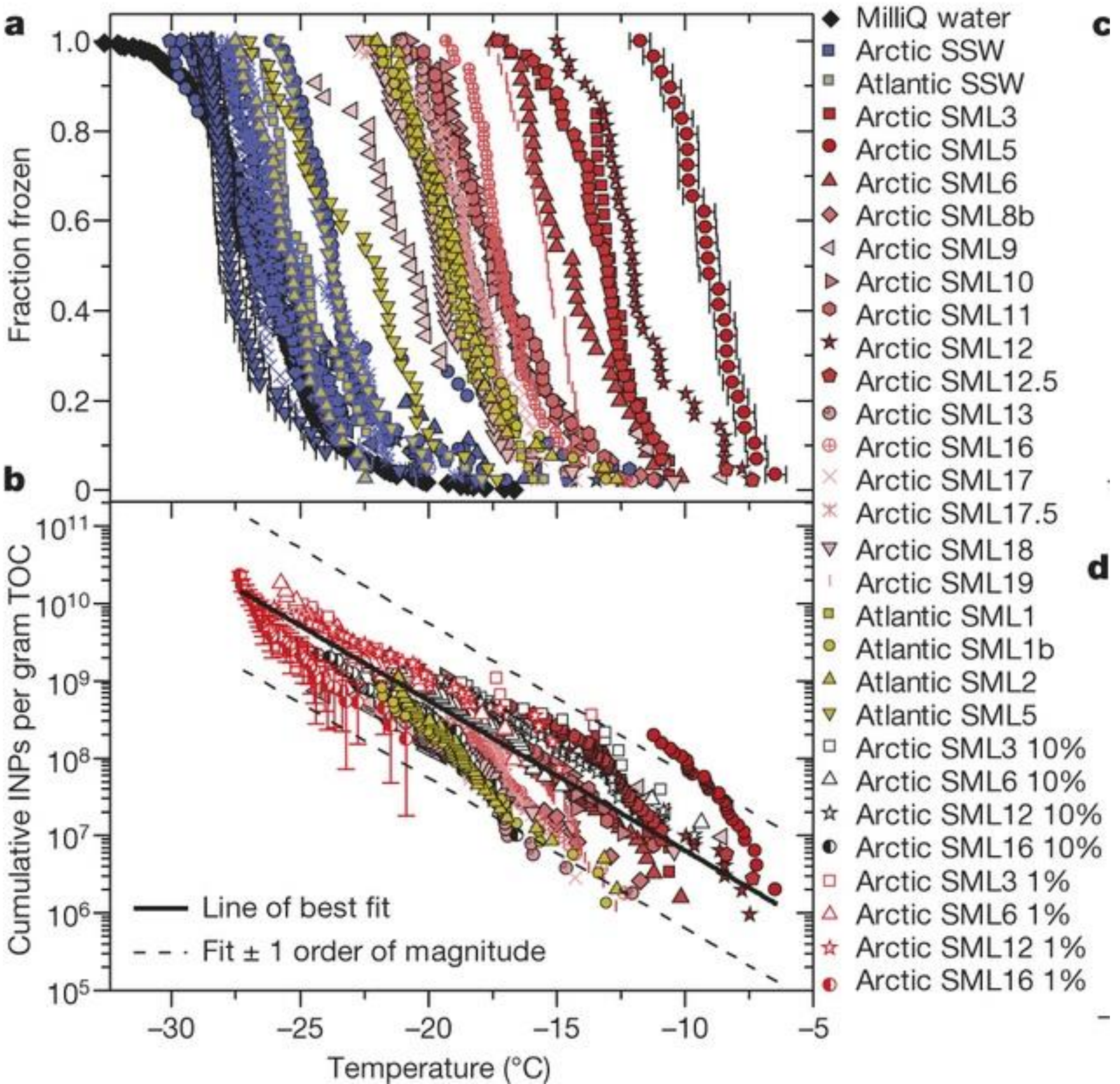
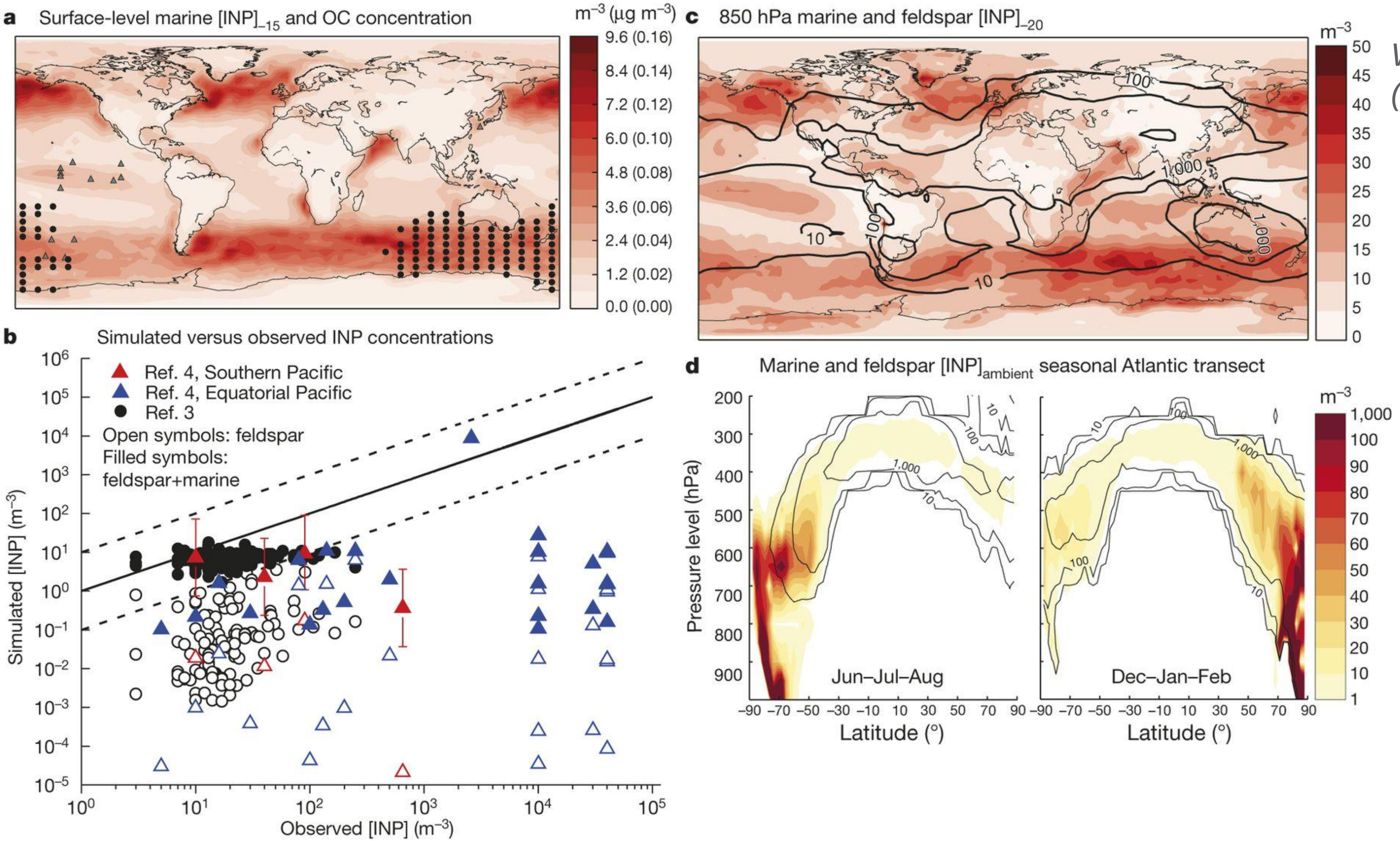
Sea surface microlayer material as a source of ice nucleating particles



Wilson et al., 2015, *Nature*.

New measurements of INP in ocean surface microlayer material enable first estimate of sea spray INP using modern measurements of source material

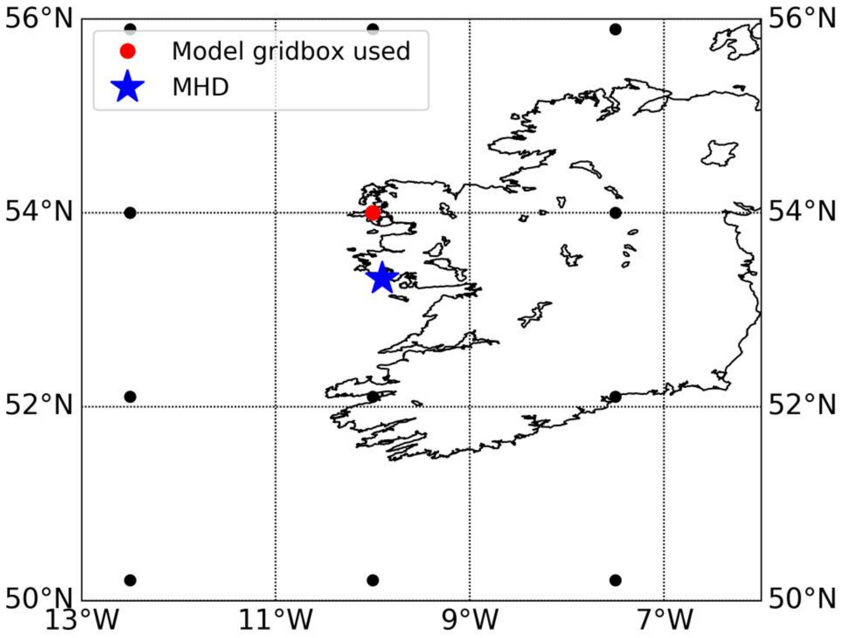
Wilson et al. (2015)

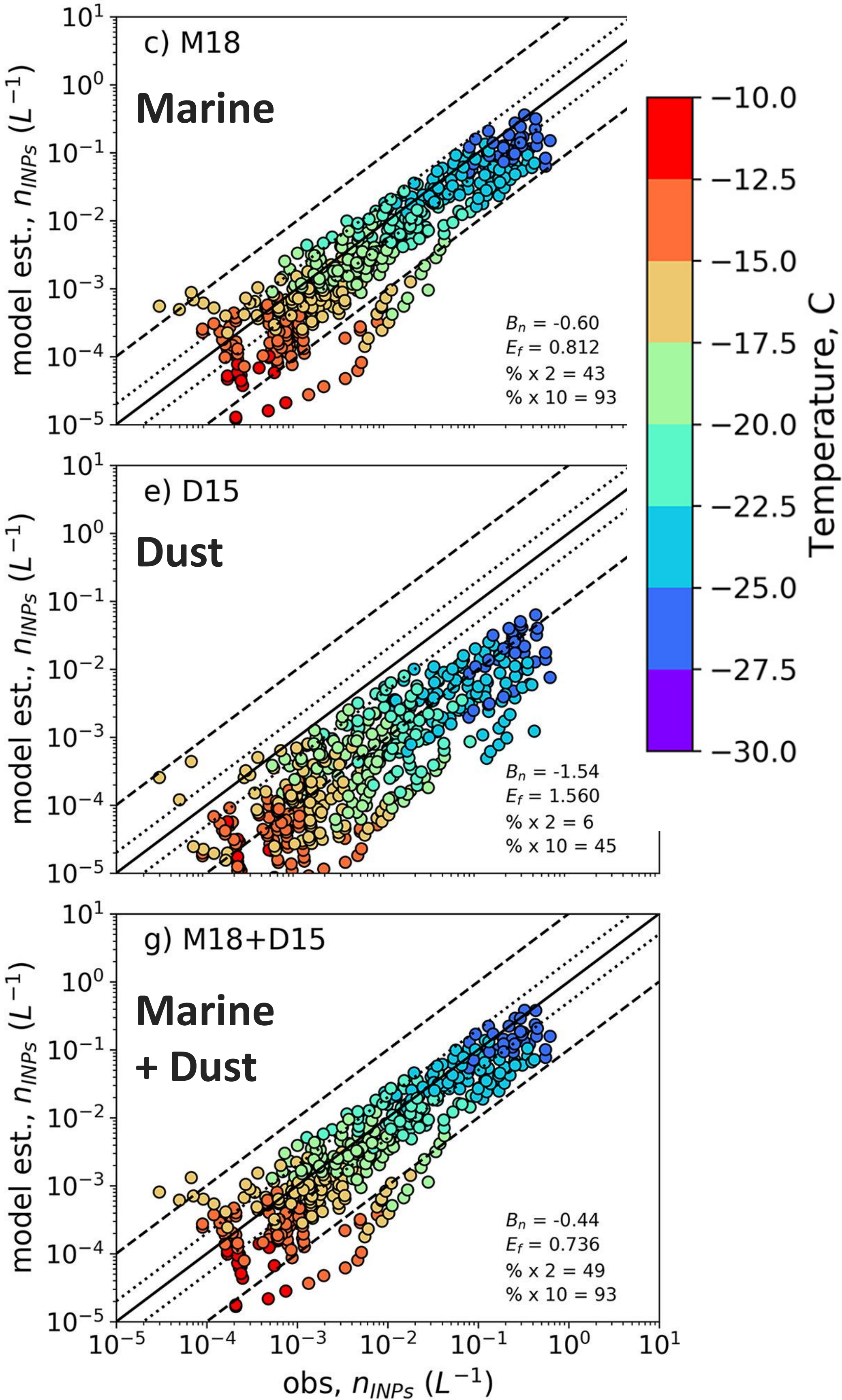


Accounting for sea spray improves model agreement with observed INP number

DOE SCGSR graduate student fellowship award to Christina McCluskey, CSU

Mace Head, Ireland: August 2015



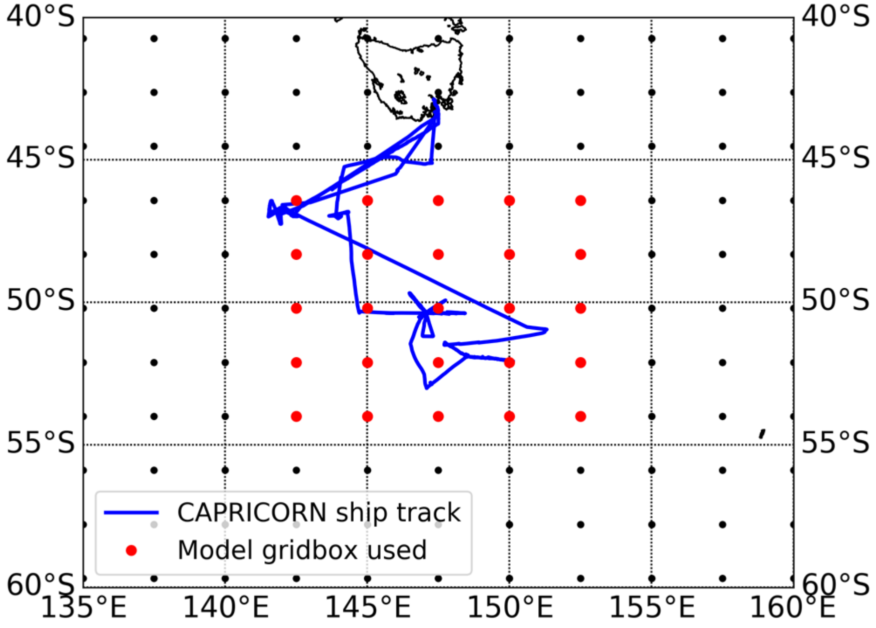


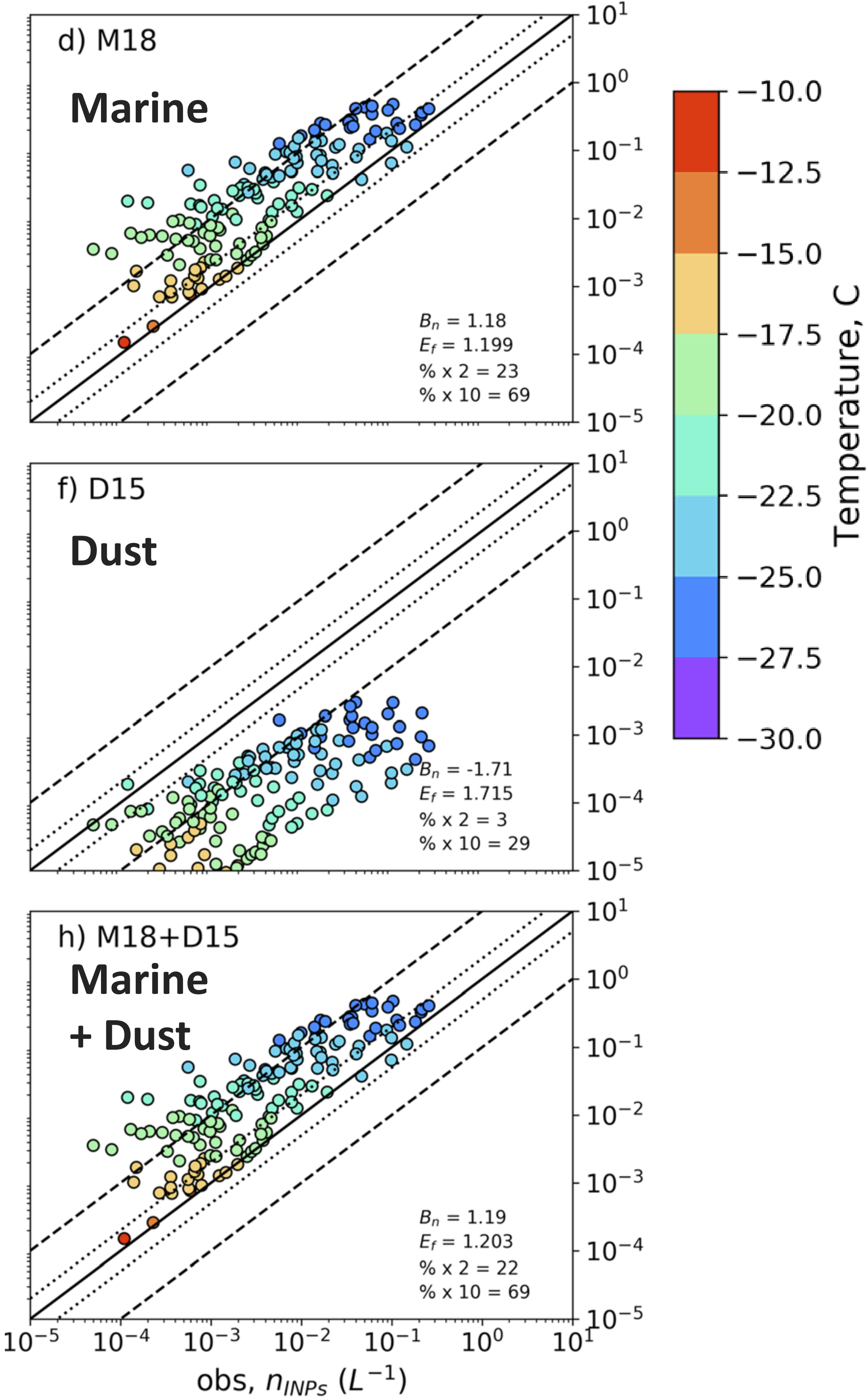
McCluskey et al., 2019

Accounting for sea spray improves model agreement with observed INP number

DOE SCGSR graduate student fellowship award to Christina McCluskey, CSU

CAPRICORN ship campaign, Southern Ocean: Mar-Apr 2016





McCluskey et al., 2019

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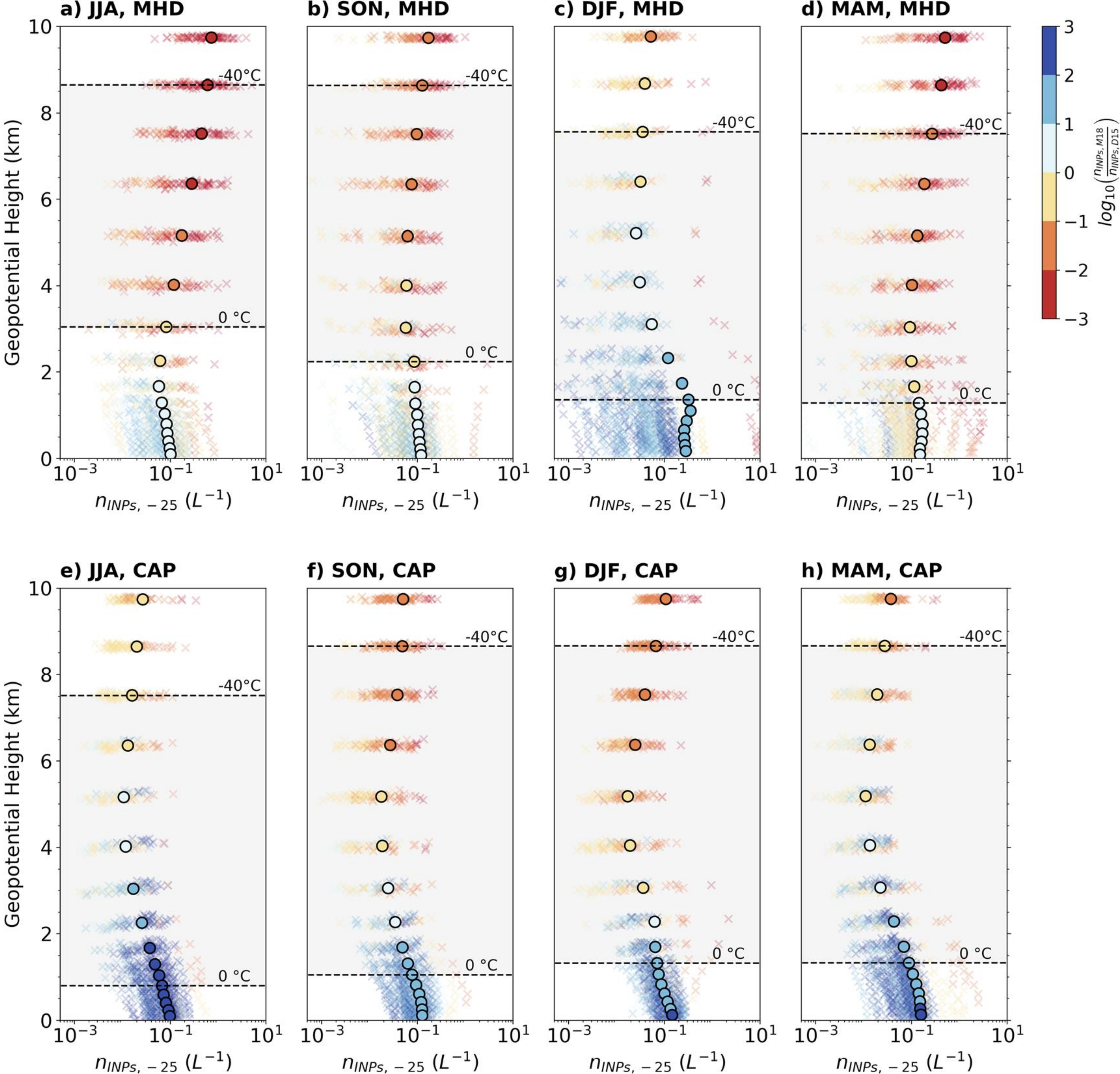
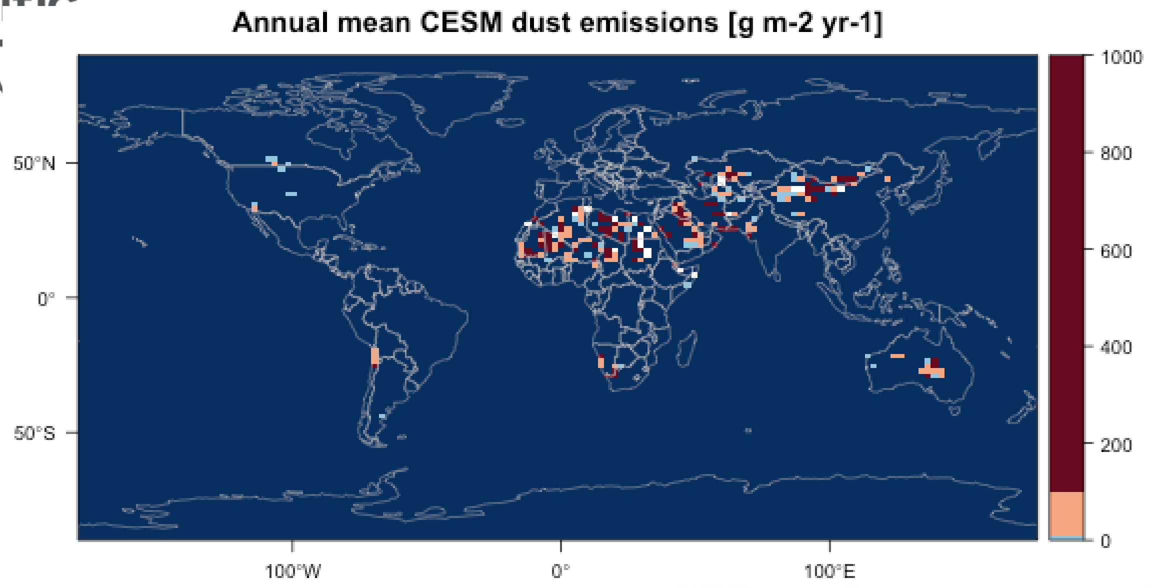
Seasonal variability in INP vertical profiles

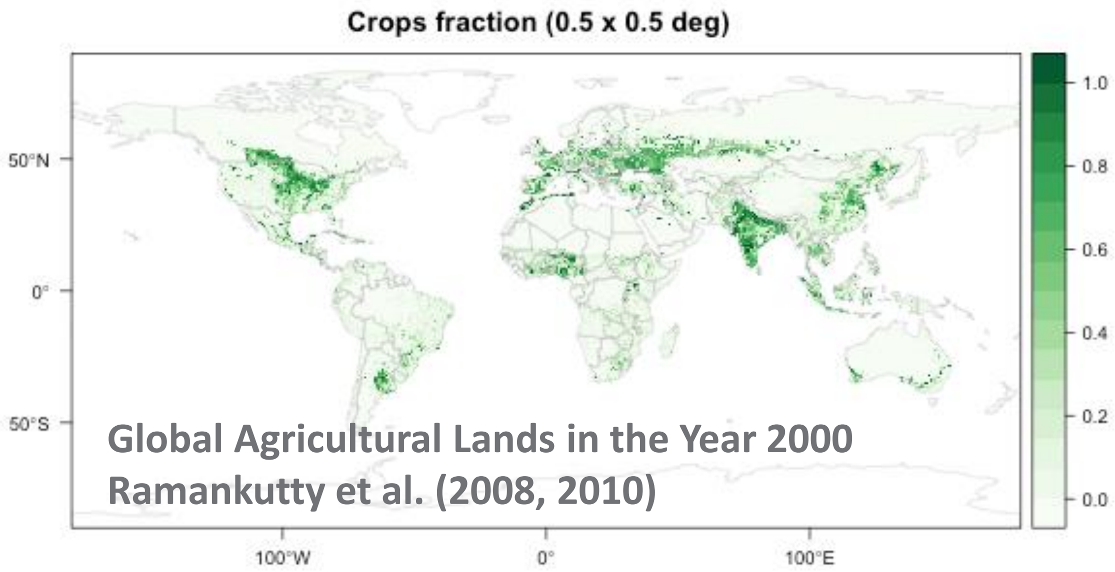
n_{INPs} (L^{-1}) @ -25° C



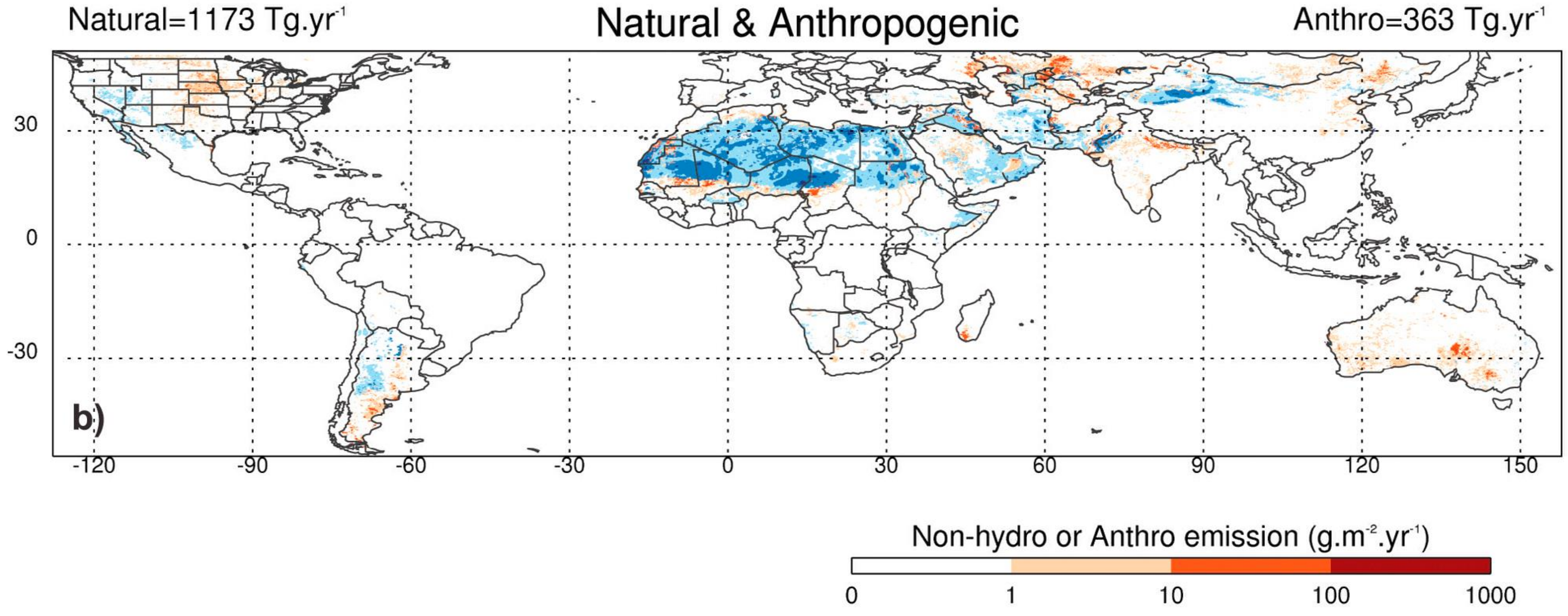
McCluskey et al., GRL, 2019

Missing piece 3: Organic-rich agricultural soils





”natural” (blue) vs
”anthropogenic” (red; mostly agriculture)

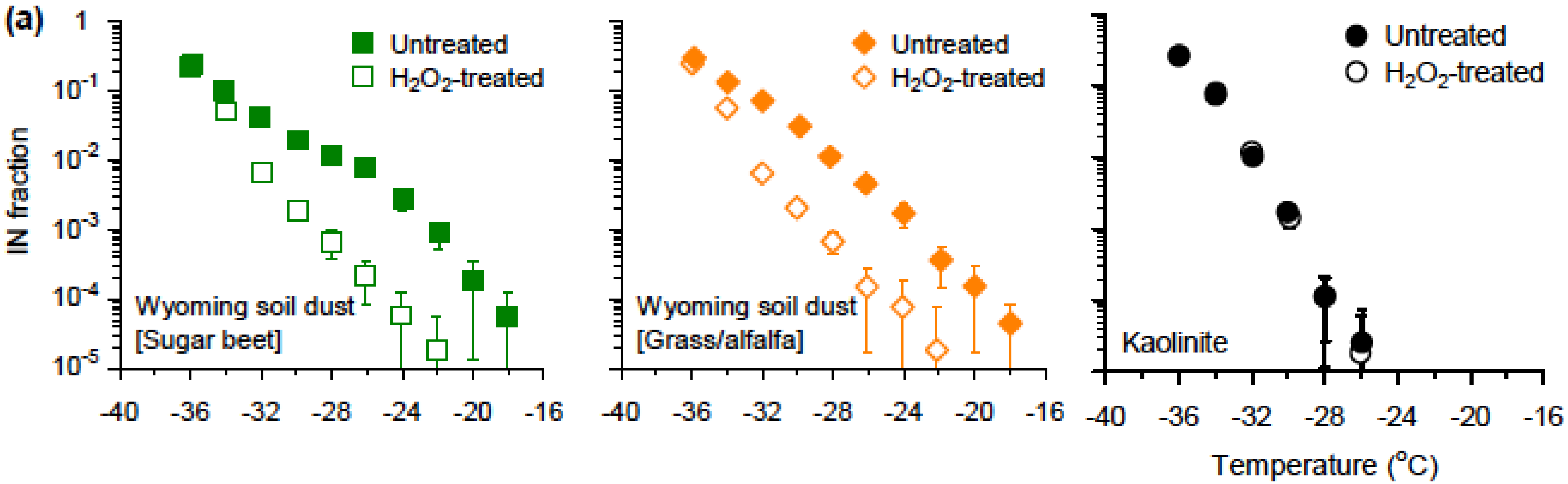


Ginoux et al. (2012)

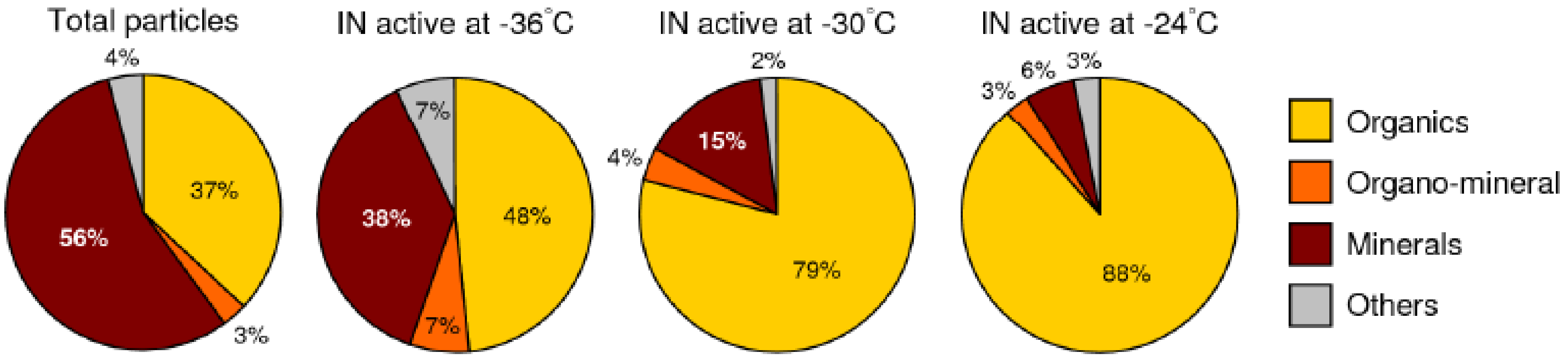
Agricultural soil INPs

Tobo et al., 2014

INP fraction from Continuous Flow Diffusion Chamber (CFDC)

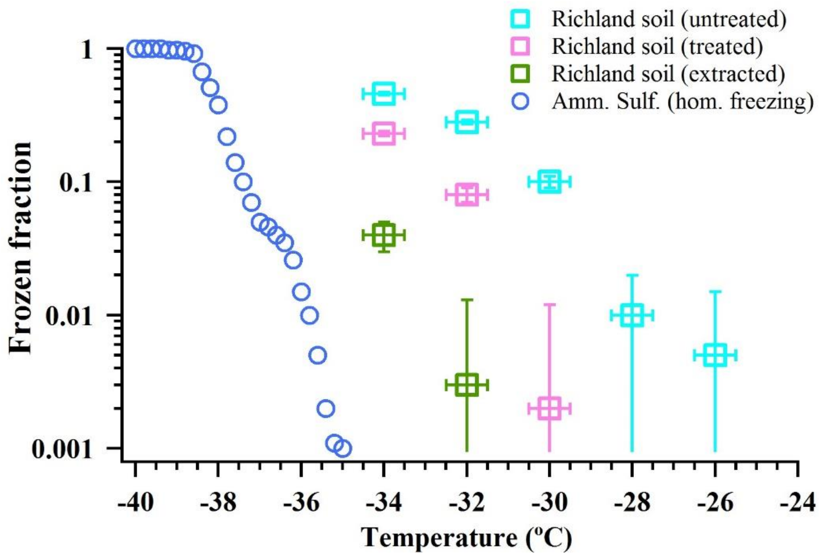


Composition of total particles and INPs from SEM-EDX

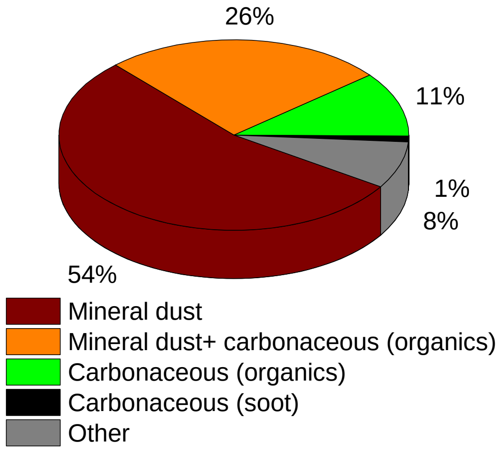


IN-activity of agricultural soil samples from Richland and SGP

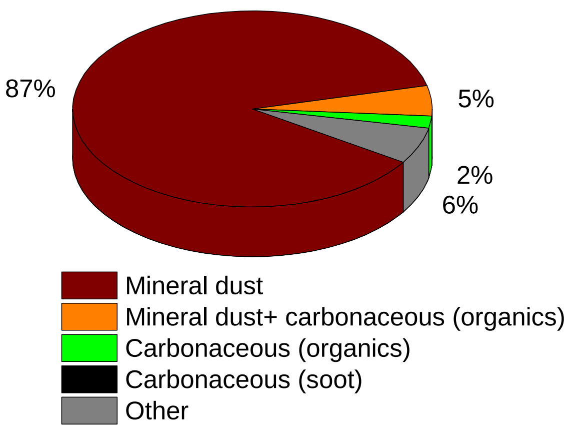
Richland soil



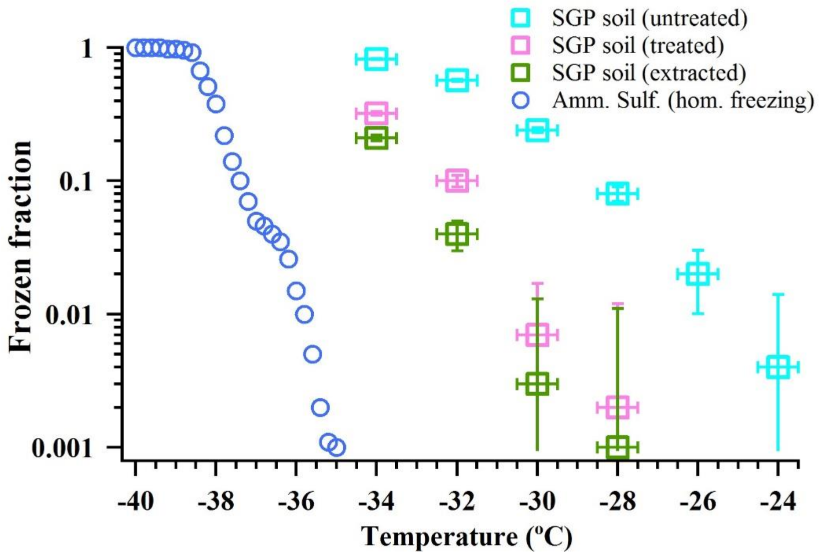
Total soil



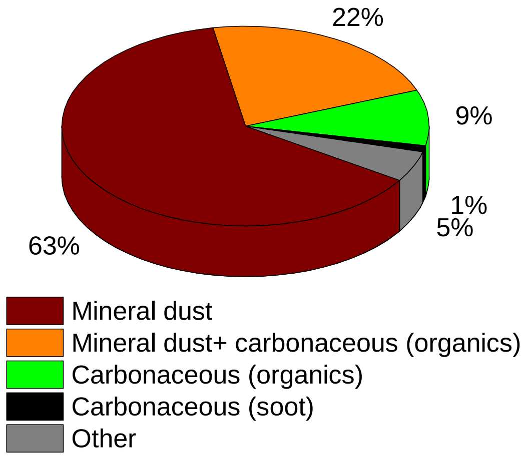
Residual



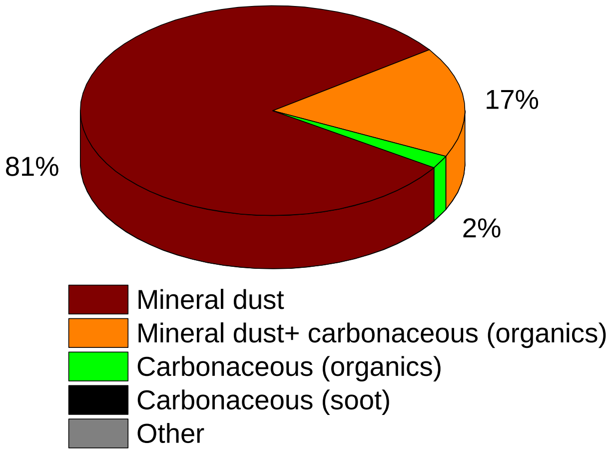
SGP soil



Total soil



Residual



Measurements: Swarup China and Gourihar Kulkarni

Funding: FICUS (Joint EMSL-JGI) User Proposal

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Building a Comprehensive Understanding of Ice-Nucleating Particles from the Ground Up: Establishing the Impact of Sea Spray and Agricultural Soils

U.S. Department of Energy (DOE) Early Career project

PD: Isabelle Steinke

PD: Gavin Cornwell

PD: Aish Raman

Collaborators:

Alla Zelenyuk, PNNL (miniSPLAT: single-particle mass spectrometer)

Gourihar Kulkarni, PNNL (INP Chamber)

Alex Laskin, Purdue

Swarup China, PNNL

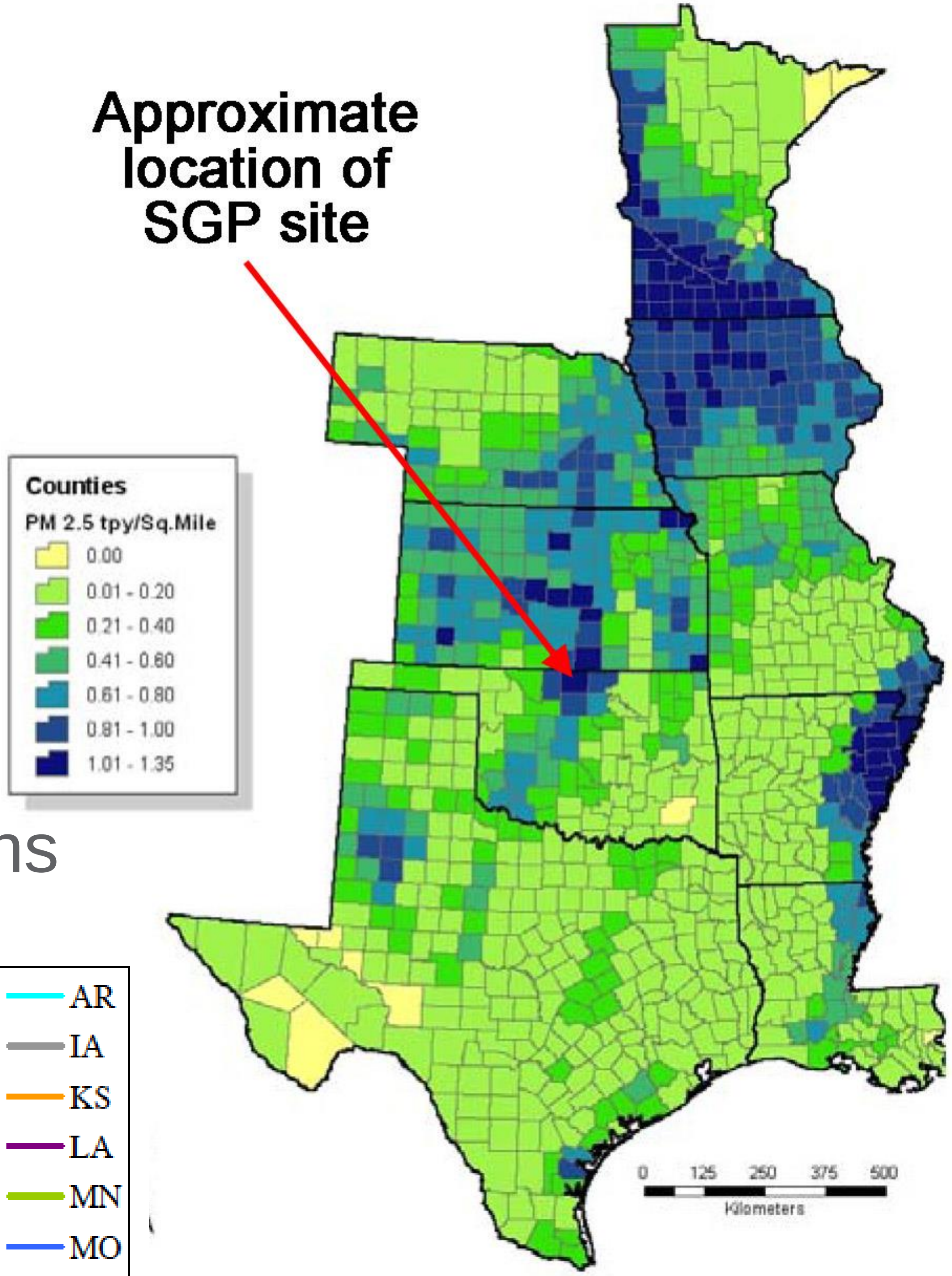
(Offline analyses: IN-ESEM, SEM-EDS, Raman, etc.)

Alex Huffman, U. Denver (Fluorescent particles)

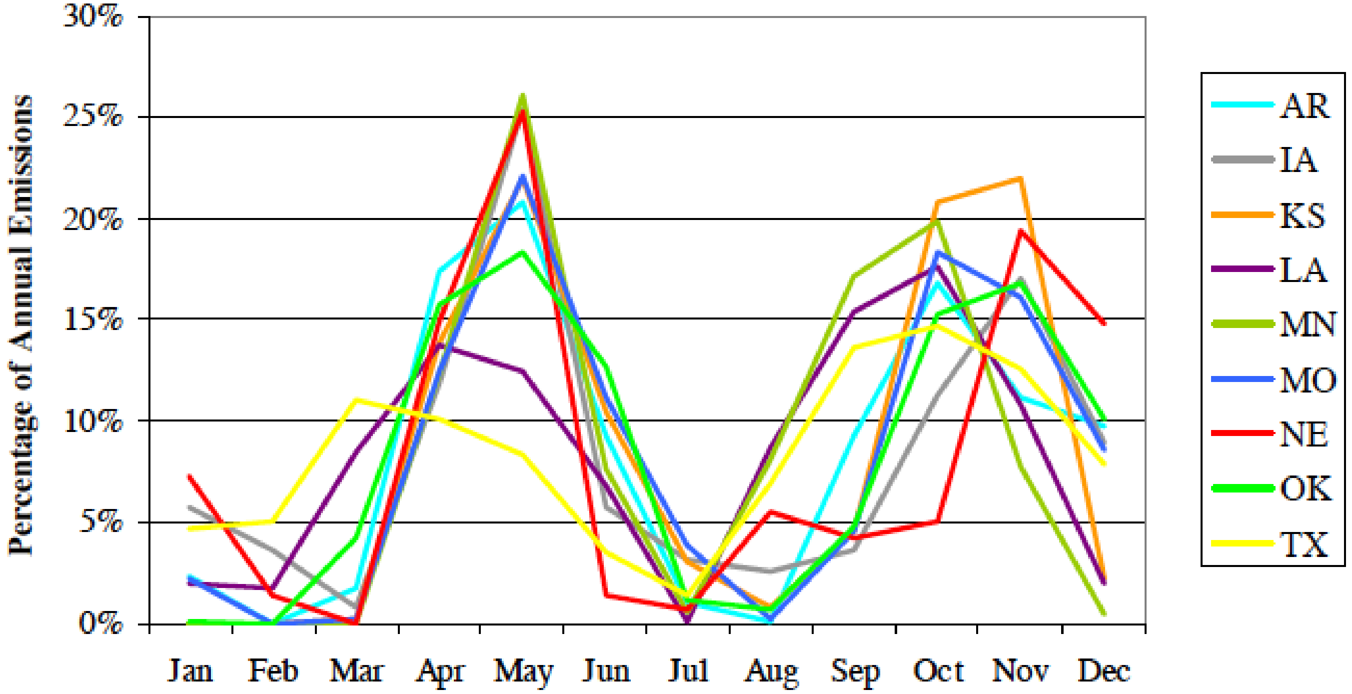
Paul DeMott, CSU (worldwide INP observations)

Upcoming field campaign will target agricultural dust INPs

Emissions of soil dusts in the Great Plains are mainly associated with agricultural activities (tilling, harvesting)



Seasonal cycle of tilling emissions



Reflections on a decade+ of work on modelling INP sources

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- We have learned a lot in the past 10 years!
  - Biological particles can now be better-measured and characterized through fluorescence measurements
  - Sea spray particles are now understood to be weak INPs, and to contribute to INP populations in remote marine air
  - Increasingly, improved INP parameterizations are being tested in models and shown to have skill in predicting INP number
- Bold claim! We are on the cusp of greatly improving the integration of INP measurements into atmospheric modelling
  - More measurements globally in more environments (although still few long-term)
  - Greater understanding of measurement uncertainties
- Progress comes from working together across expertise and disciplinary boundaries.
  - How can modelers more effectively provide guidance to the experimental community?

Thank you

NSF graduate research fellowship

Max Planck Institute for Chemistry /
Max Planck Graduate School

DOE Office of Science:

- Earth and Environmental System Modelling (EESM)
- Atmospheric System Research (ASR)
- Early Career Research Program
- Office of Science Graduate Student Research (SCGSR)