Spatial Variability and Composition of Ice Nucleating Particles over the Southern Ocean

Kathryn Moore, Colorado State University

Thomas Hill, Christina McCluskey, Bryan Rainwater, Darin Toohey, Cynthia Twohy, Jorgen Jensen, Morgane Perron, Andrew Bowie, Sonia Kreidenweis, Paul DeMott, SOARS Team

This presentation participates in OSPP

Outstanding Student & PhD candidate Presentation contest

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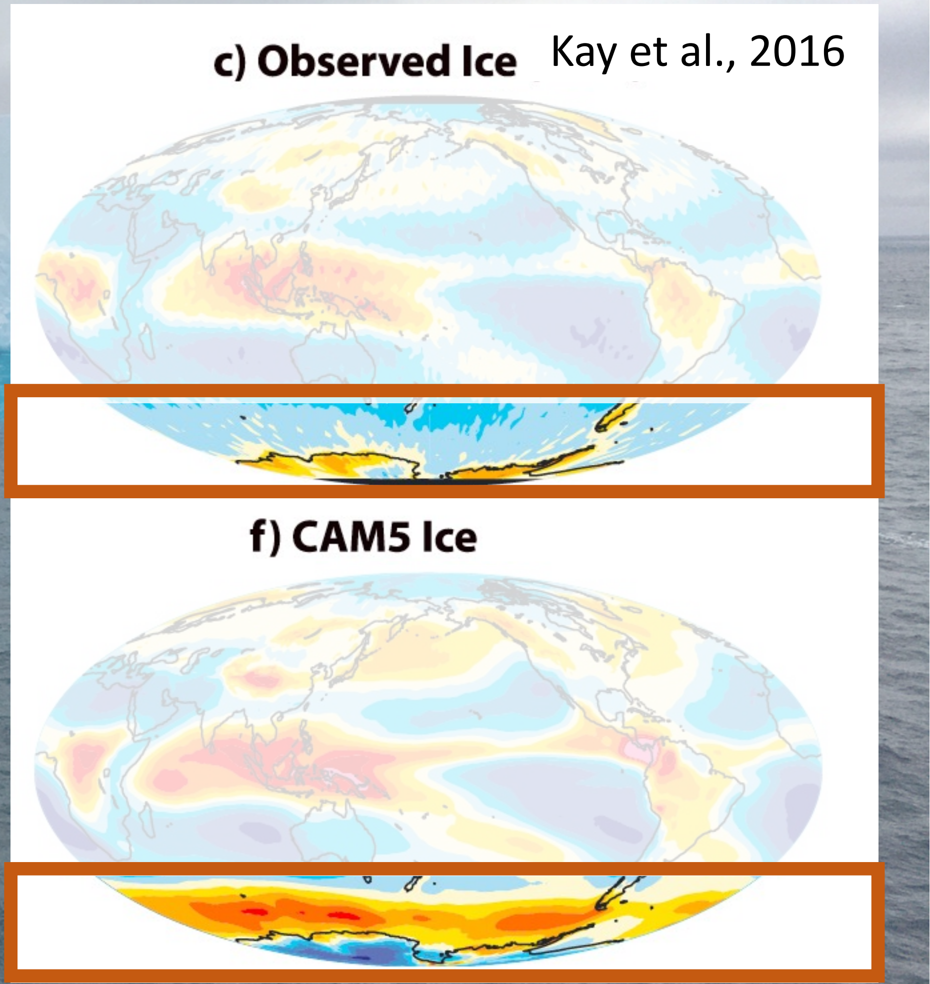
- Many global models overestimate ice and underestimate supercooled liquid water occurrence in Southern Ocean clouds
- Ice nucleating particles (INPs) play a key role in cloud glaciation
- Improvements in model parameterizations needed to capture variability of INP observations

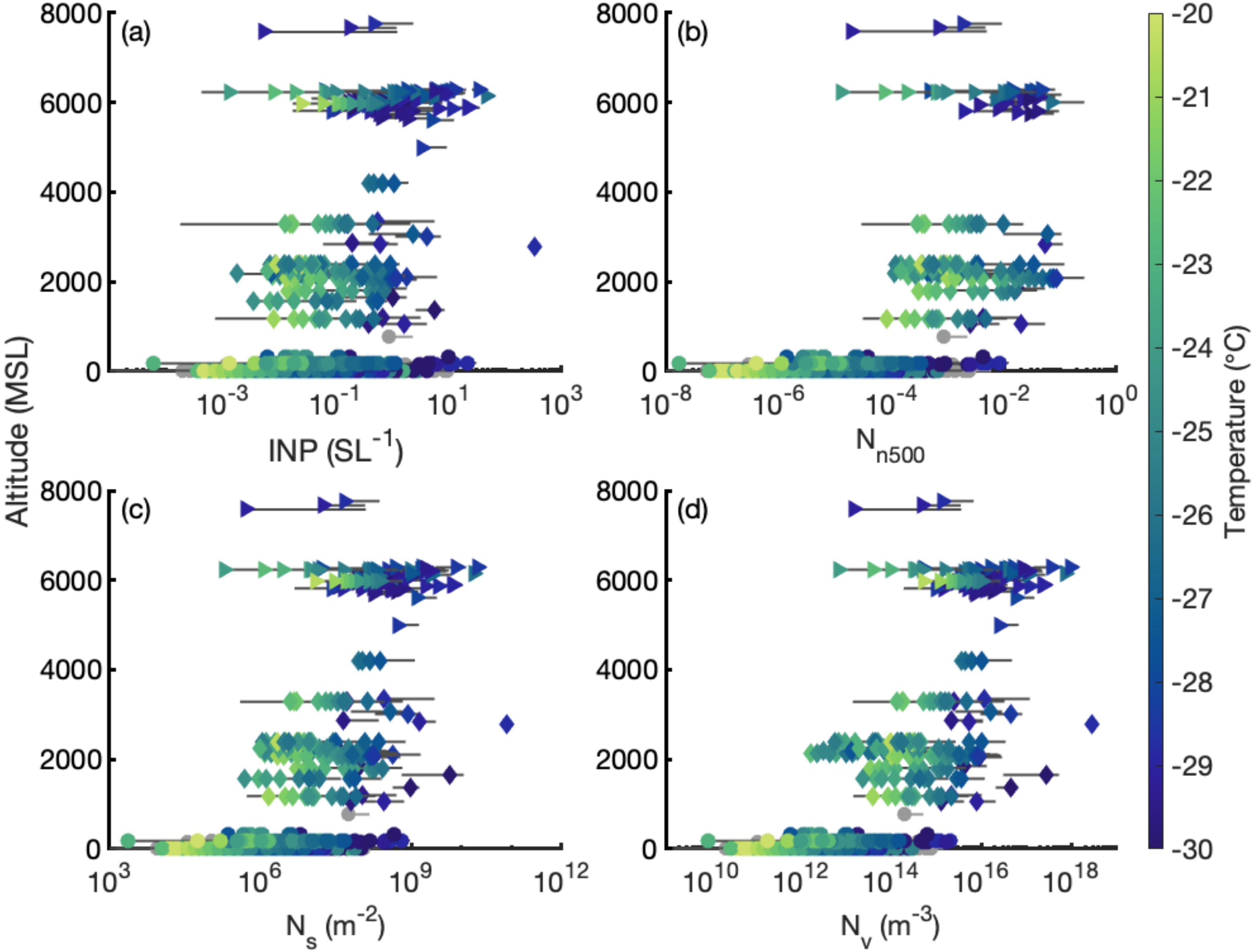


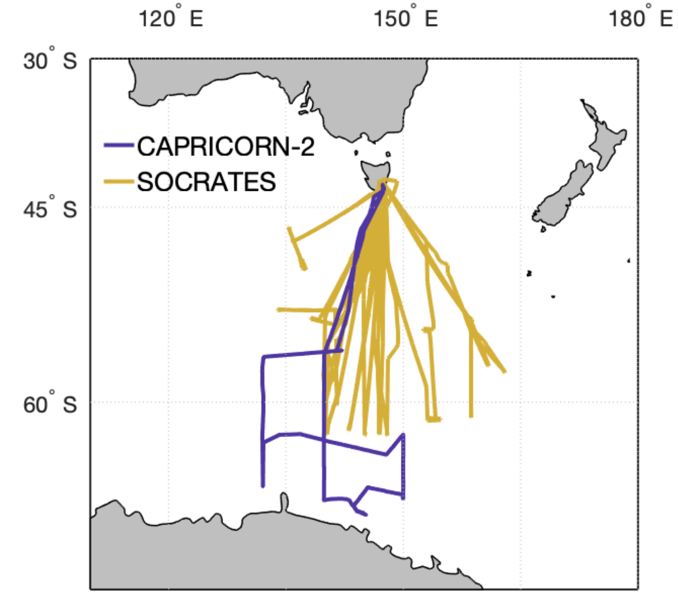
c) Observed Ice

Kay et al., 2016

f) CAM5 Ice

SOCRATES aircraft observations have provided the first vertically-resolved measurements of INPs over the Southern Ocean, including in-cloud



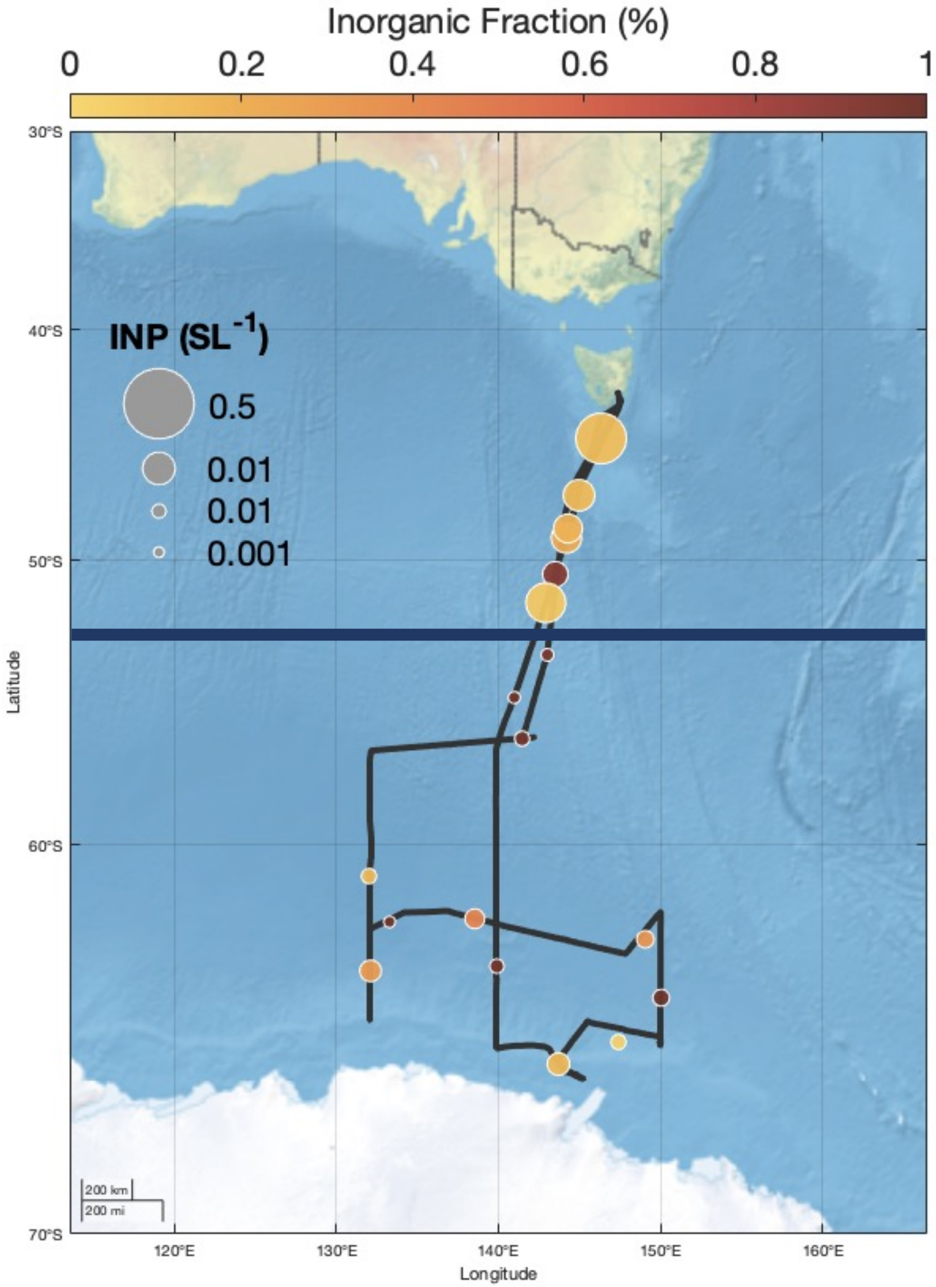


CAPRICORN-2

INP composition and concentration varies latitudinally in the Southern Ocean marine boundary layer

Higher organic fraction

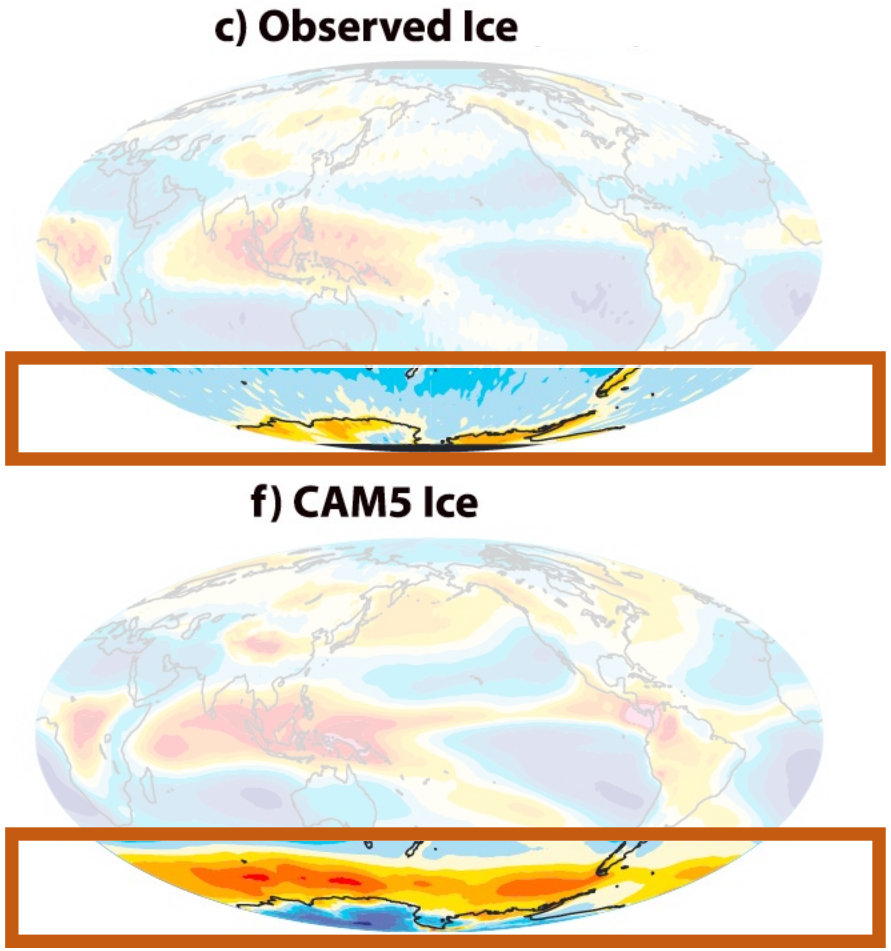
Higher concentrations



Higher inorganic fraction

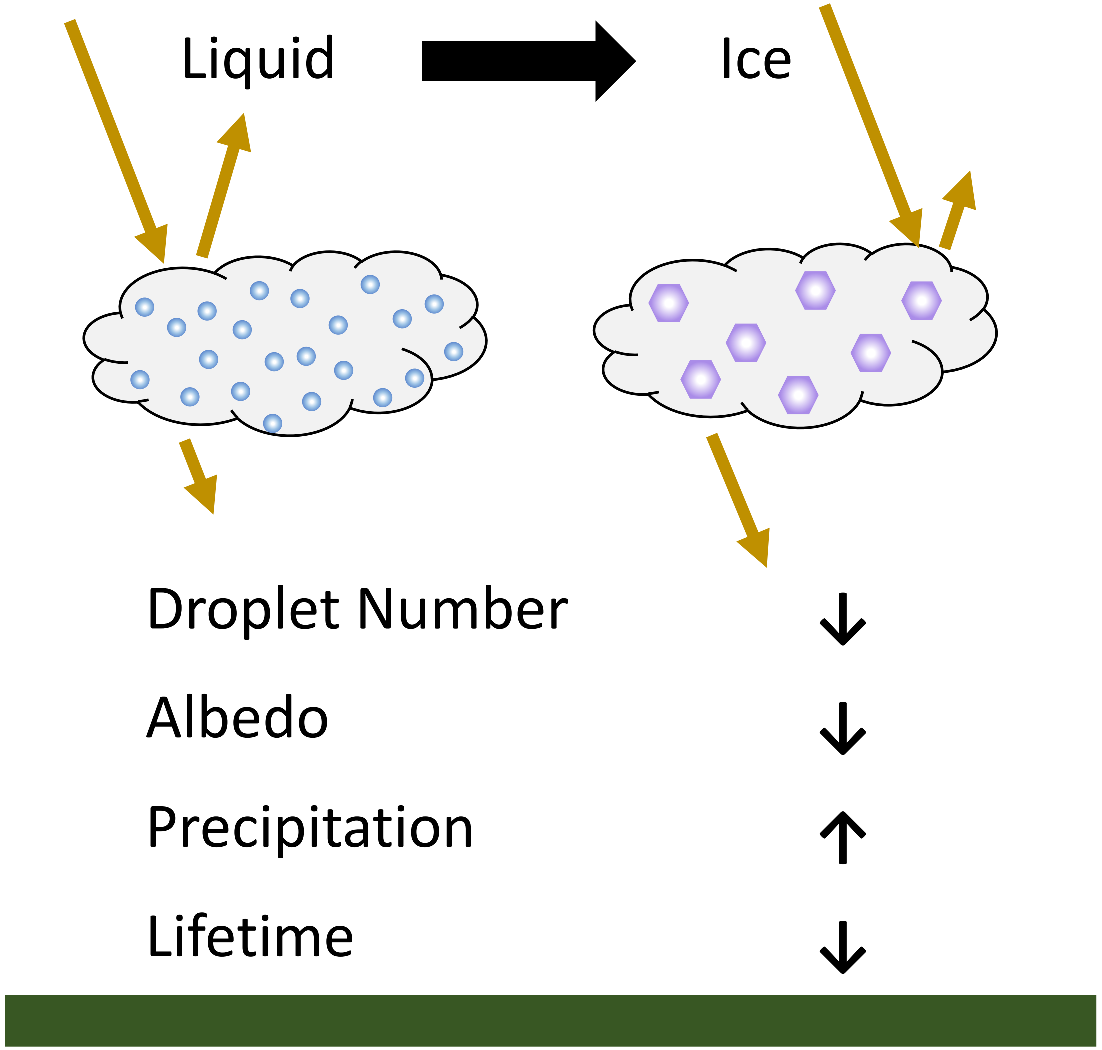
Lower concentrations

Modeled cloud phase biases over the Southern Ocean impact climate



Global models underestimate the number and lifetime of supercooled clouds

Kay et al., 2016



Droplet Number ↓

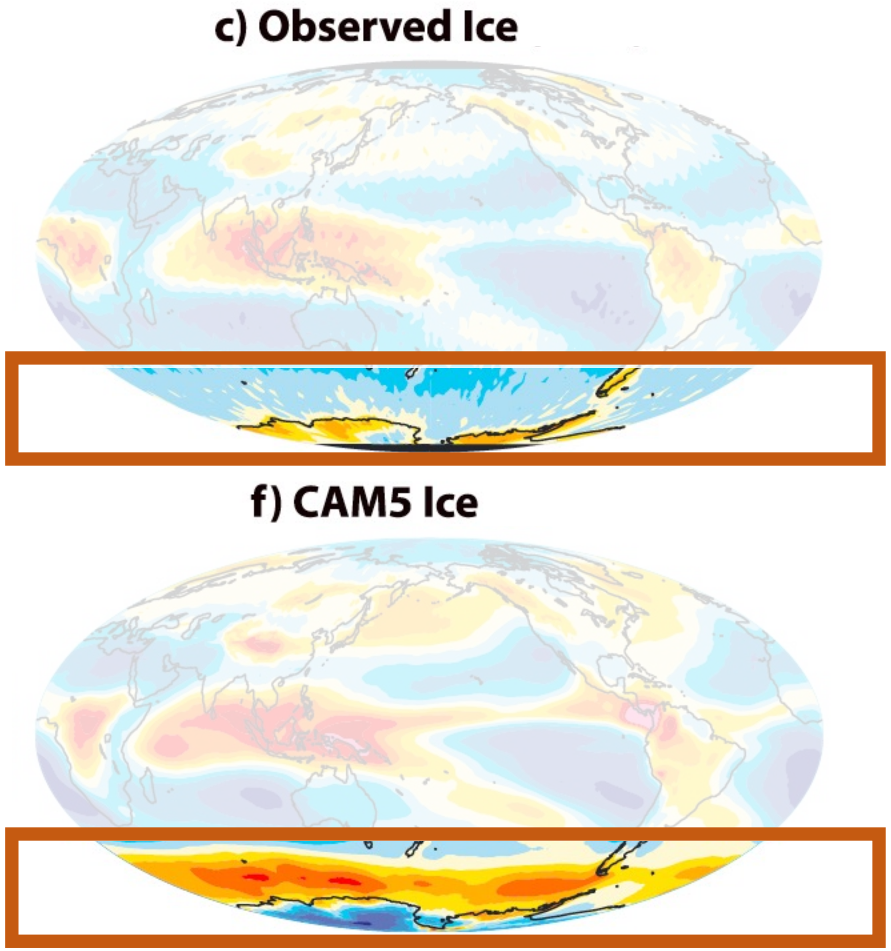
Albedo ↓

Precipitation ↑

Lifetime ↓

Cloud glaciation alters the radiative and hydrological properties of clouds

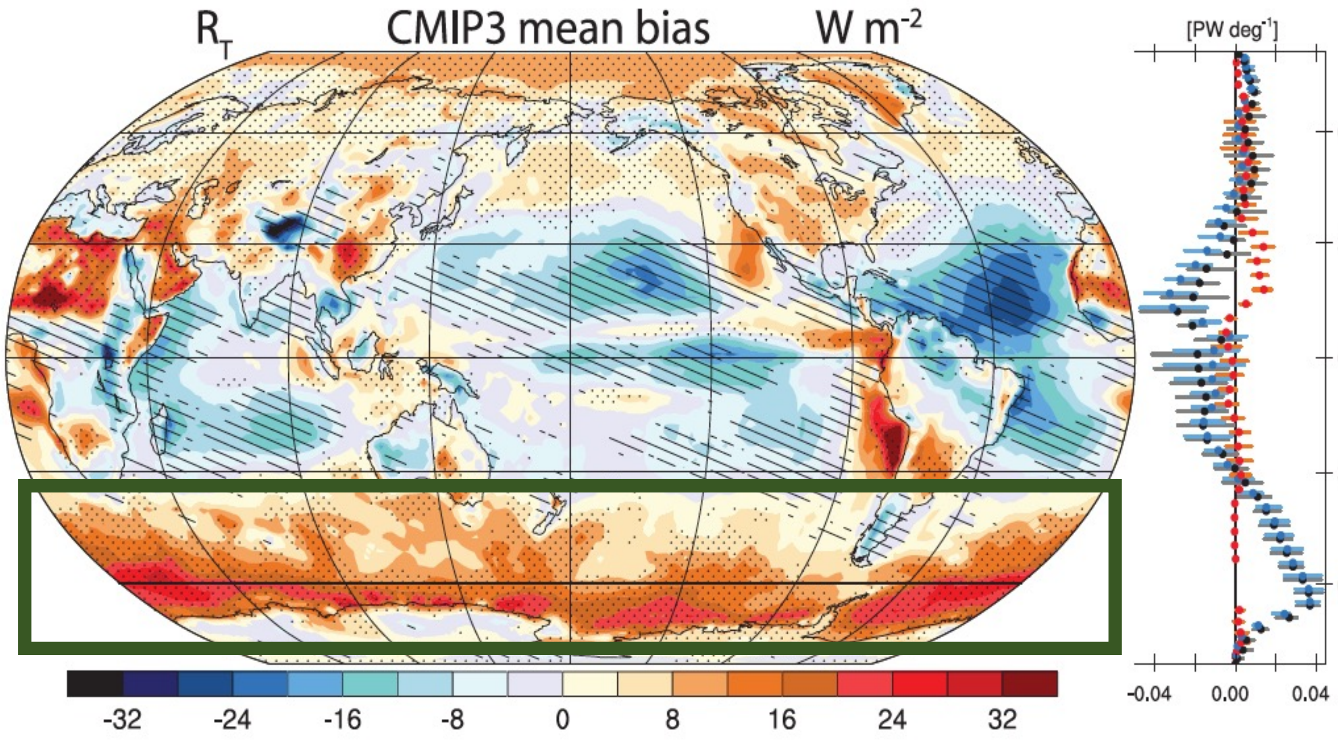
Modeled cloud phase biases over the Southern Ocean impact climate



Global models underestimate the number and lifetime of supercooled clouds

Kay et al., 2016

Bias in TOA net downward radiation



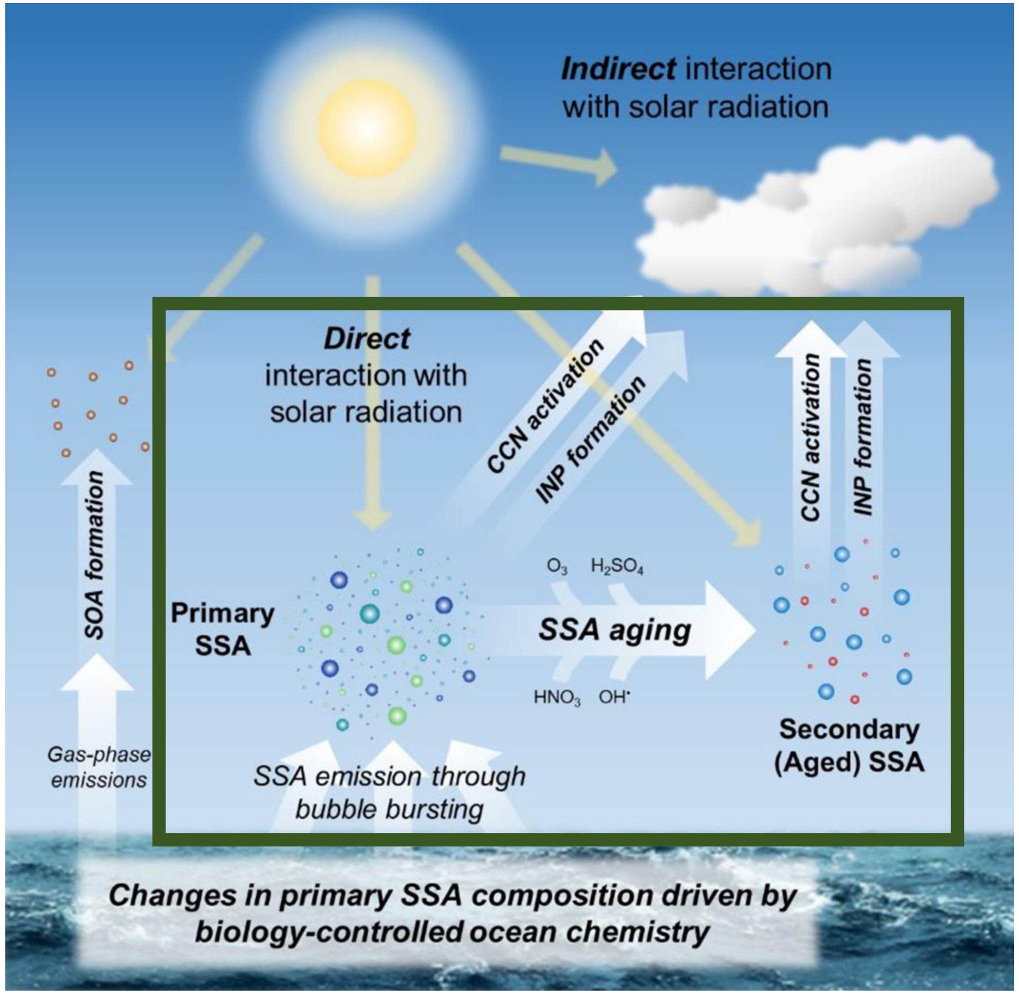
Global models do not reflect enough sunlight over the Southern Ocean (SO)

Bodas-Salcedo et al. 2013

Trenberth & Fasullo, 2010

Ice nucleating particles have multiple sources, and different aerosol types vary in ice nucleation efficiency

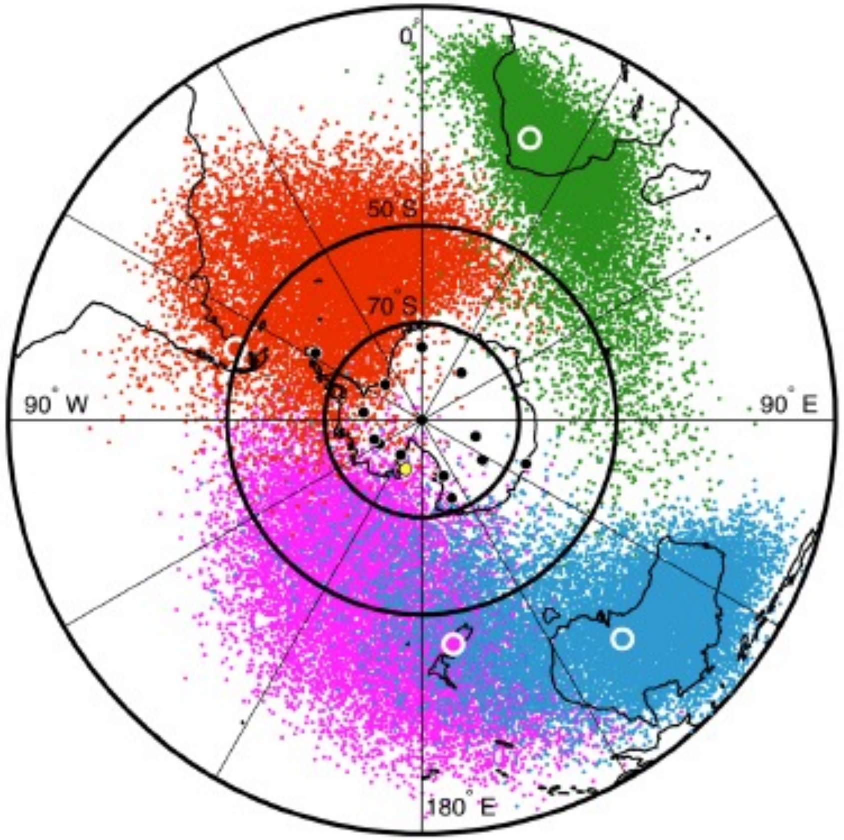
Local marine aerosol



Cochran et al., 2017

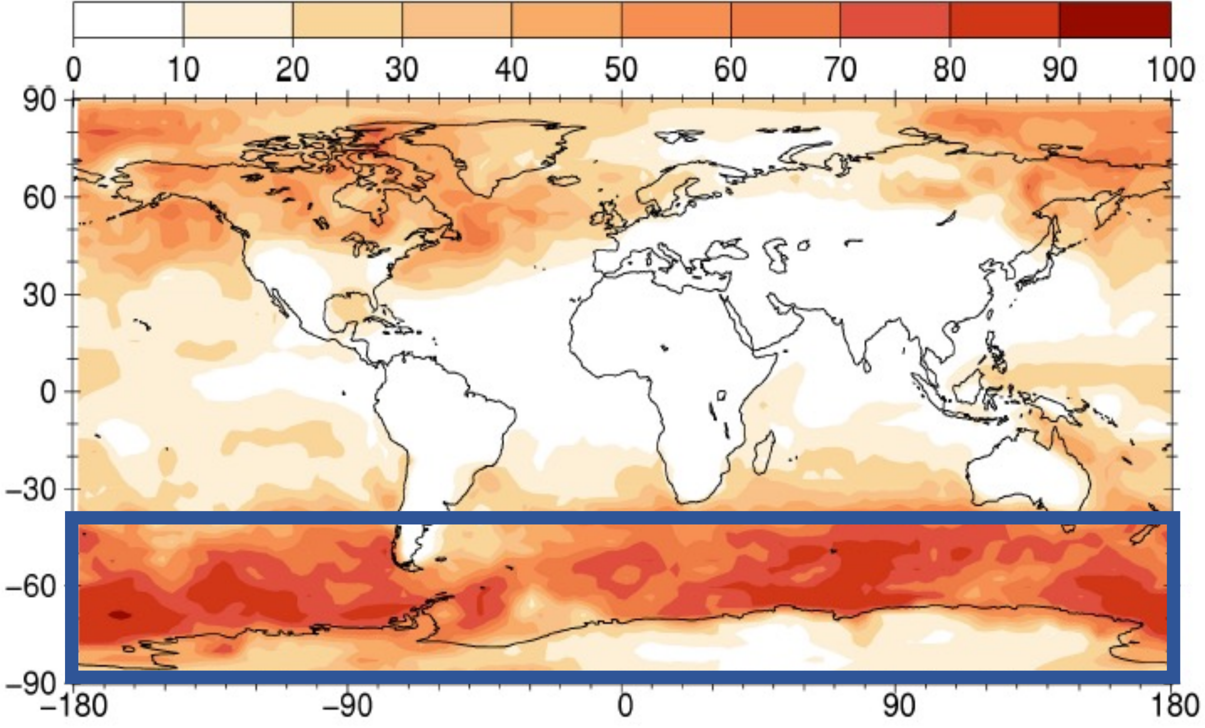
\+

Southern Ocean dust source regions



Neff and Bertler 2015

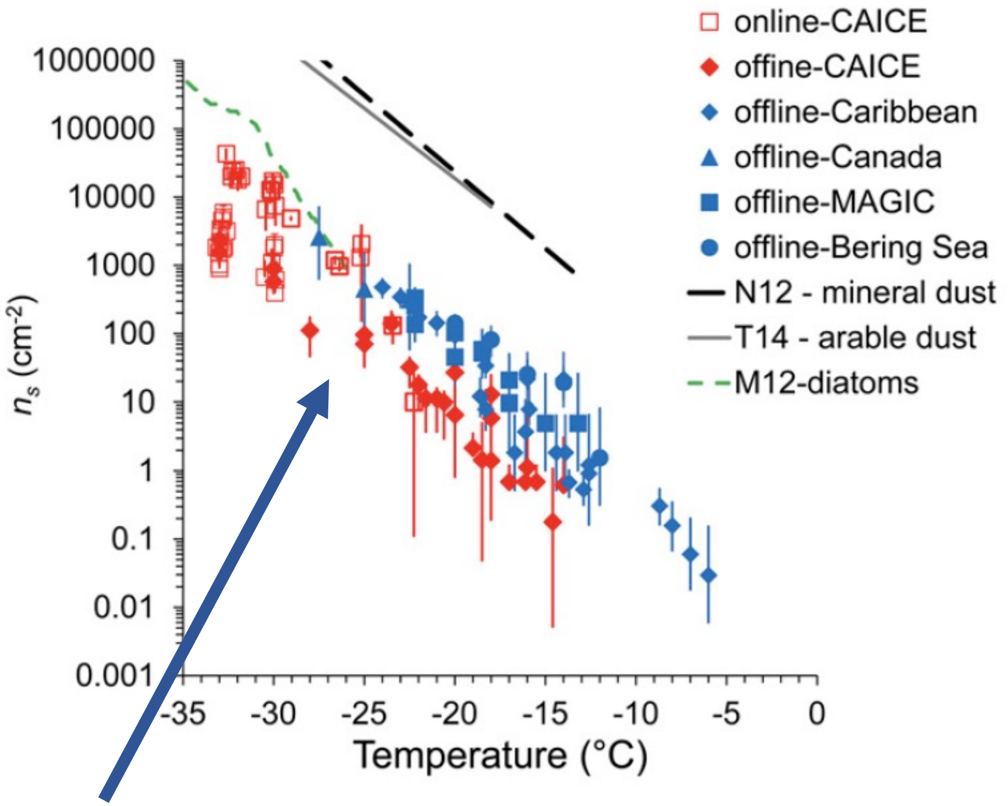
The Southern Ocean is the only region hypothesized to be dominated by marine INPs, which are much less efficient than mineral dust



Contribution of marine biogenic INP to total

Burrows et al., 2013

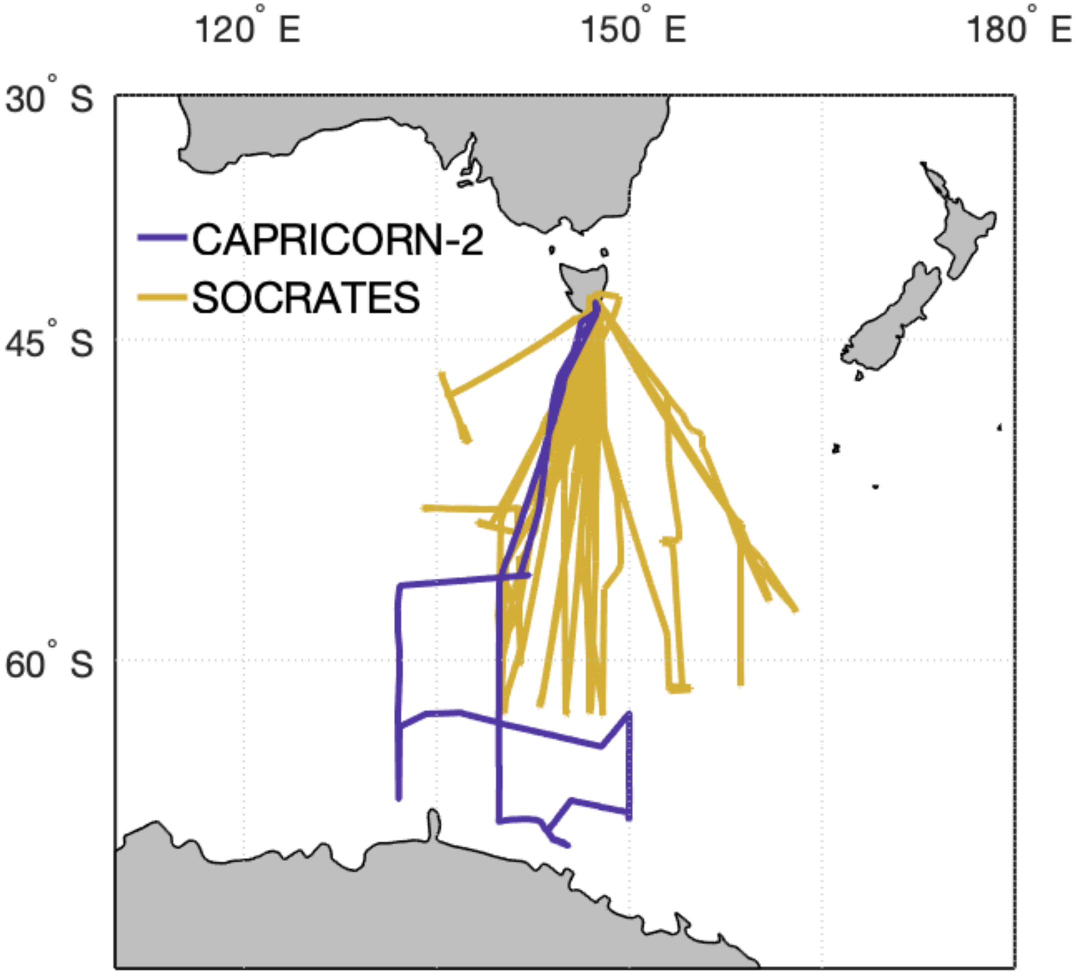
$$n_s(T) = \frac{n_{INPs}(T)}{Aerosol\ Surface\ Area}$$



Marine ice nucleating particles are less efficient than mineral dust on a per-surface area or per-number basis

DeMott et al., 2016

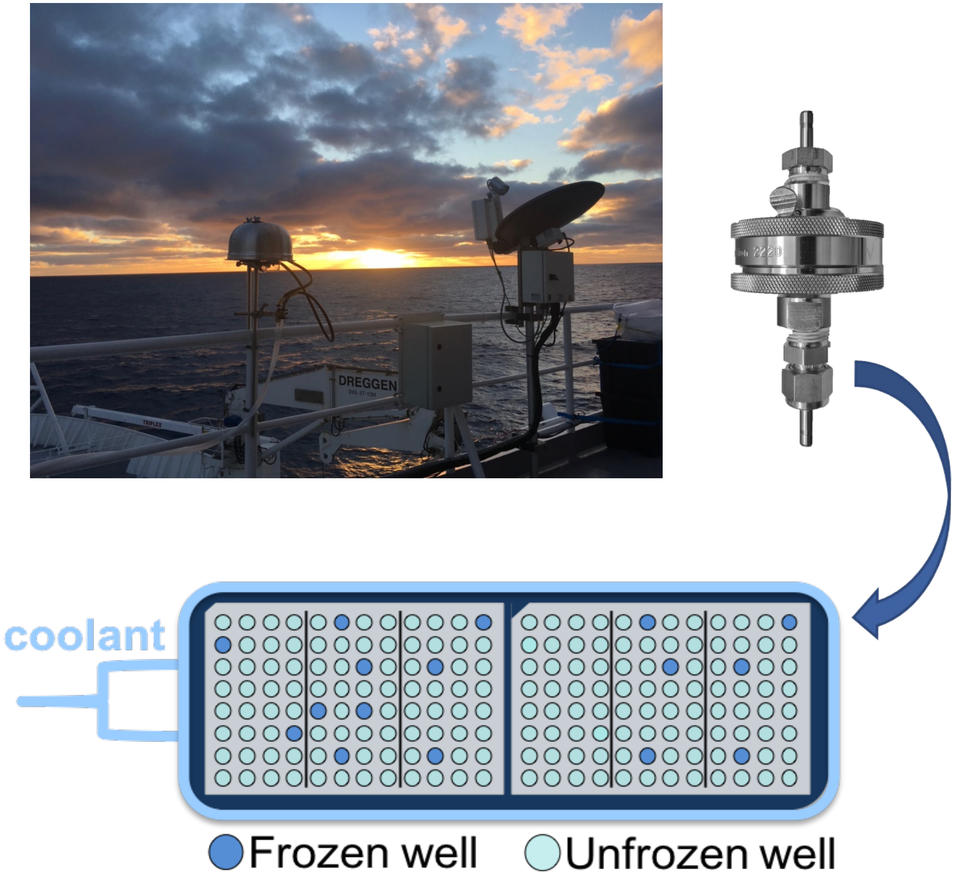
SOCRATES and CAPRICORN-2 measurements were collected in Austral summer, 2018



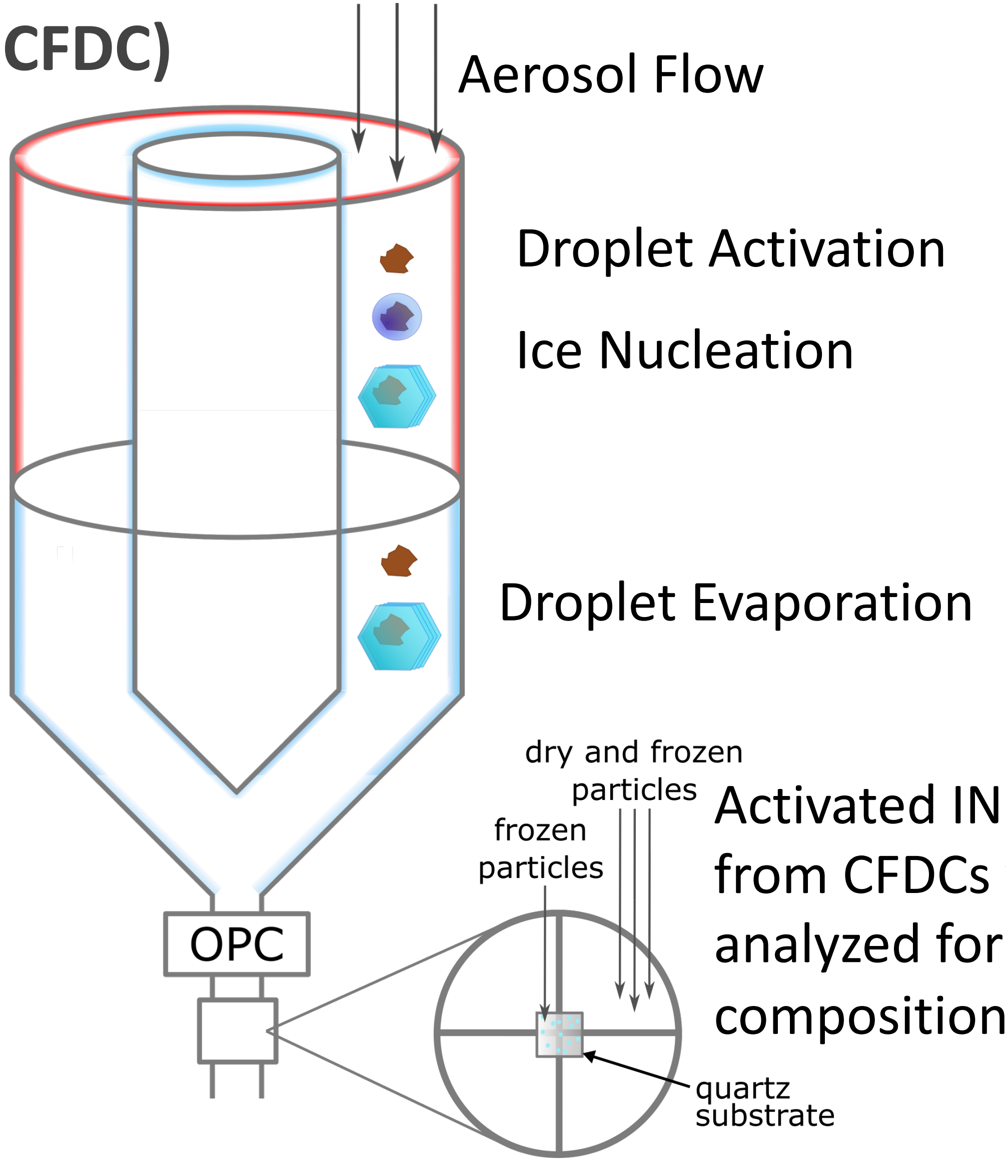
Online (CFDC) and offline (filters) INP concentration measurements

SOCRATES and CAPRICORN-2 online and offline ice nucleating particle measurements

Ice Spectrometer (IS)



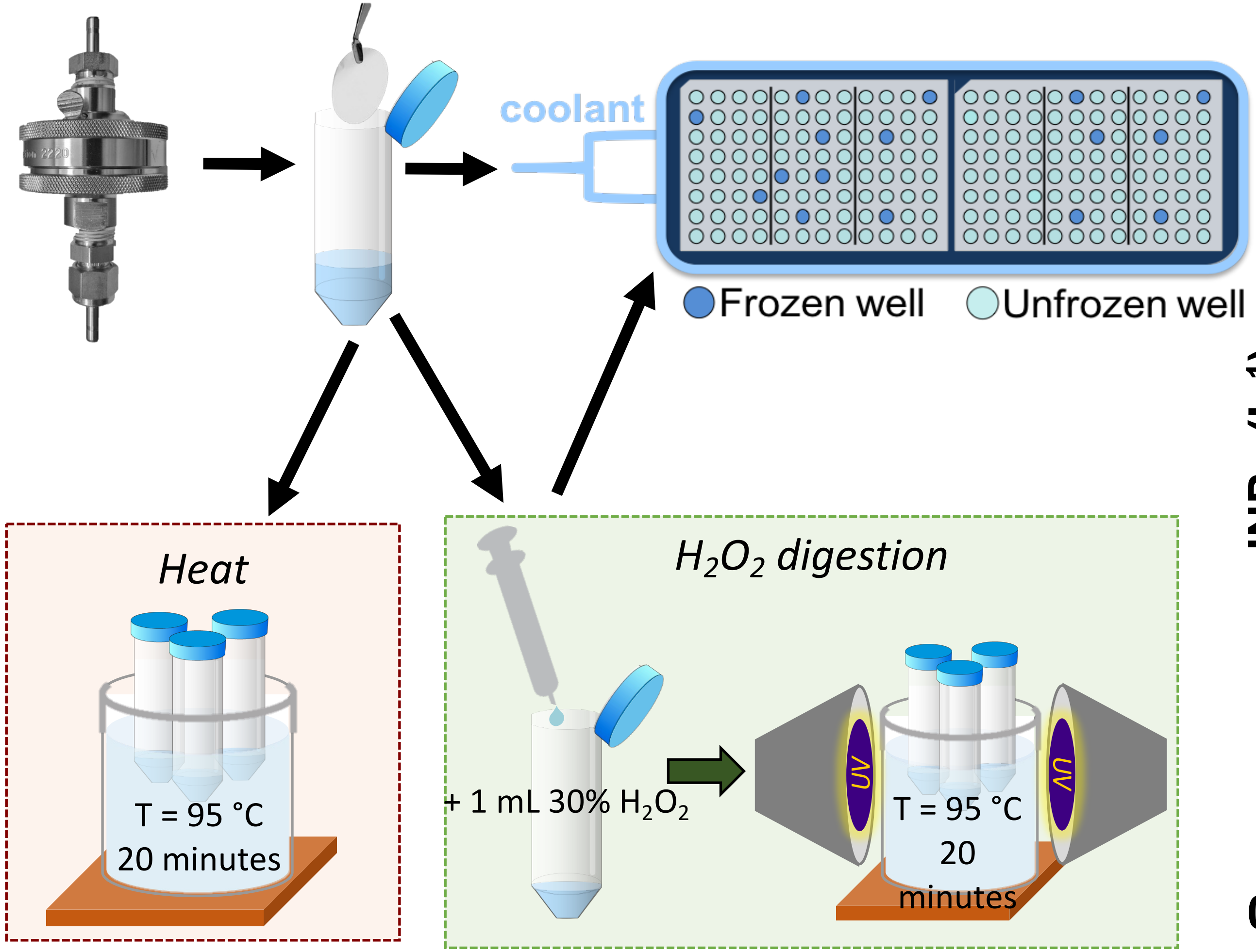
Continuous Flow Diffusion Chamber (CFDC)



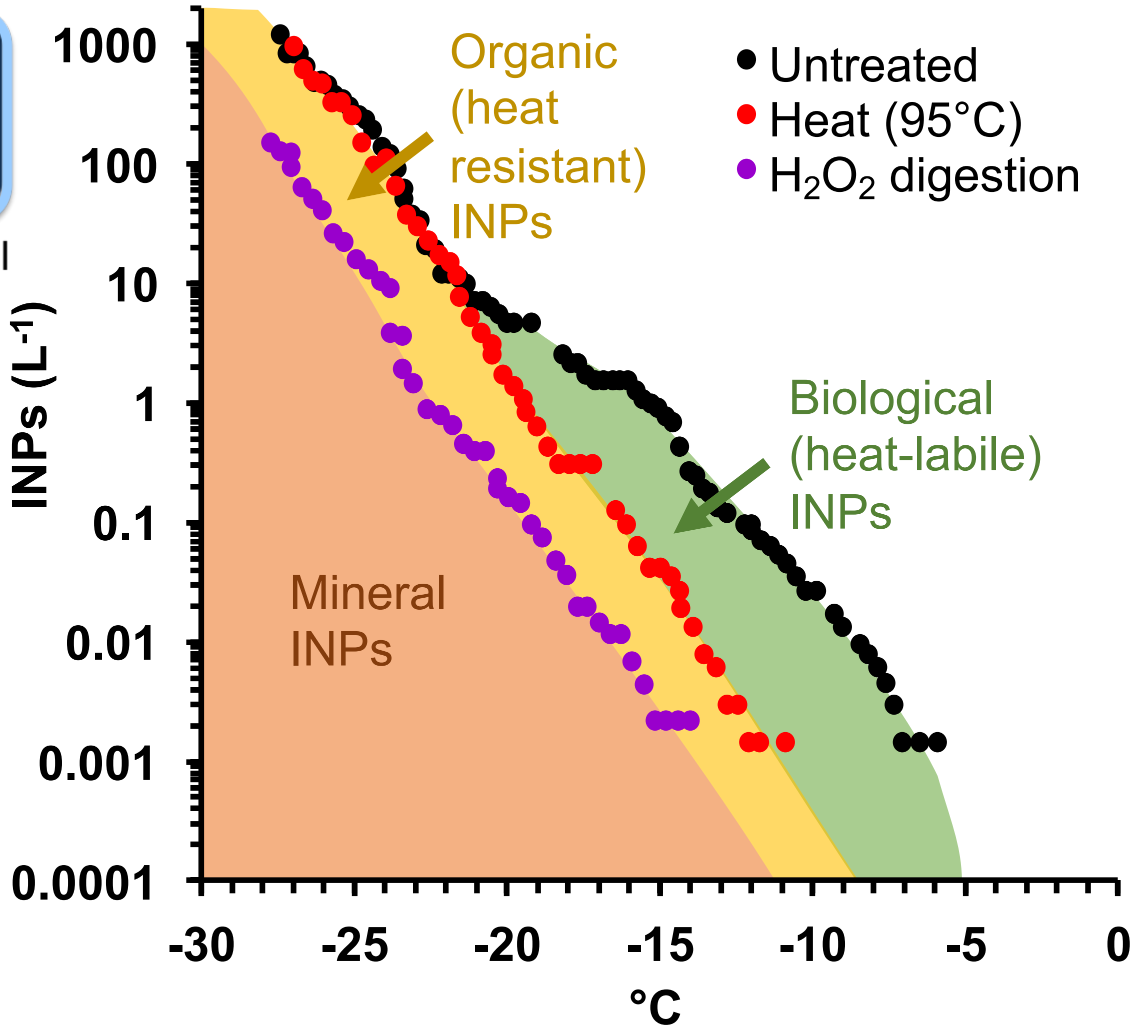
Activated INPs collected from CFDCs were analyzed for chemical composition by TEM

INP chemical composition inferred from Ice Spectrometer measurements

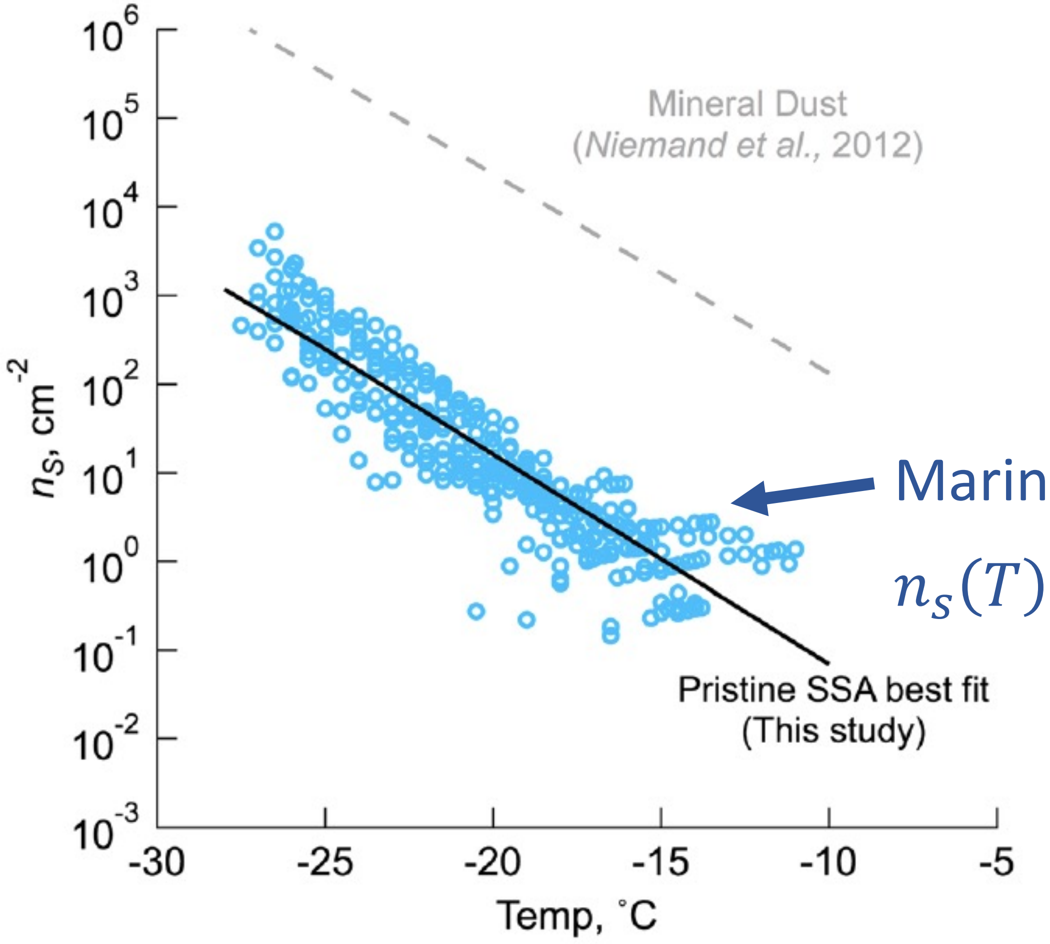
Ice Spectrometer (IS)



Chemical Composition



INPs are typically parameterized based on aerosol number or surface area concentrations



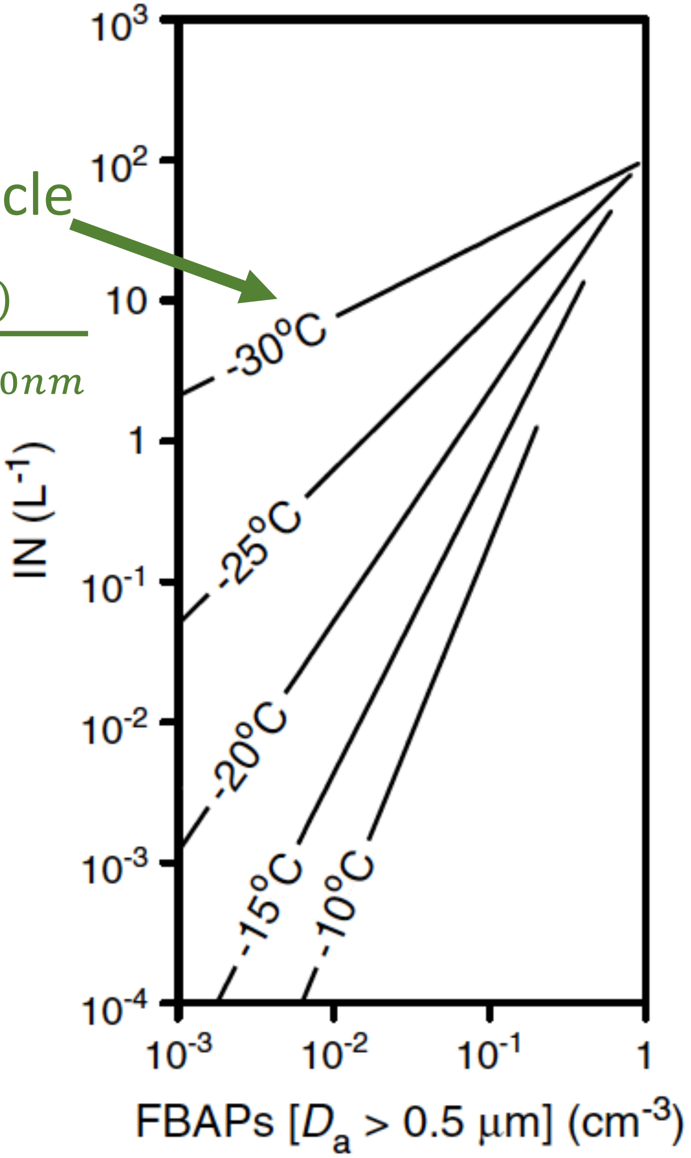
Marine aerosol

$$n_s(T) = \frac{n_{INPs}(T)}{Aerosol\ Surface\ Area}$$

McCluskey et al., 2018

FBAP= fluorescent biological aerosol particle

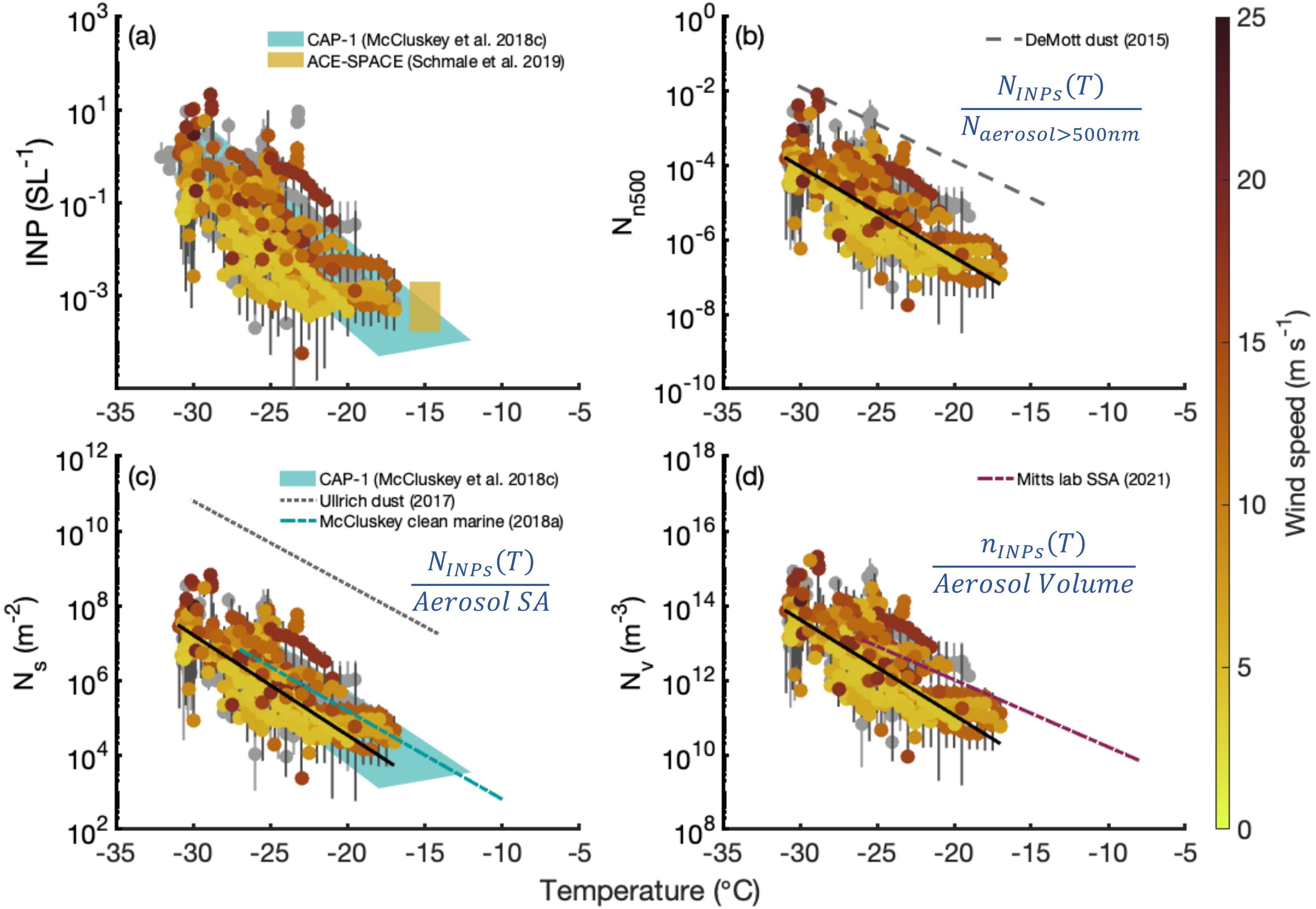
$$N_{n500}(T) = \frac{N_{INPs}(T)}{N_{aerosol>500nm}}$$



Tobo et al., 2013

Parameterizing INPs in Models

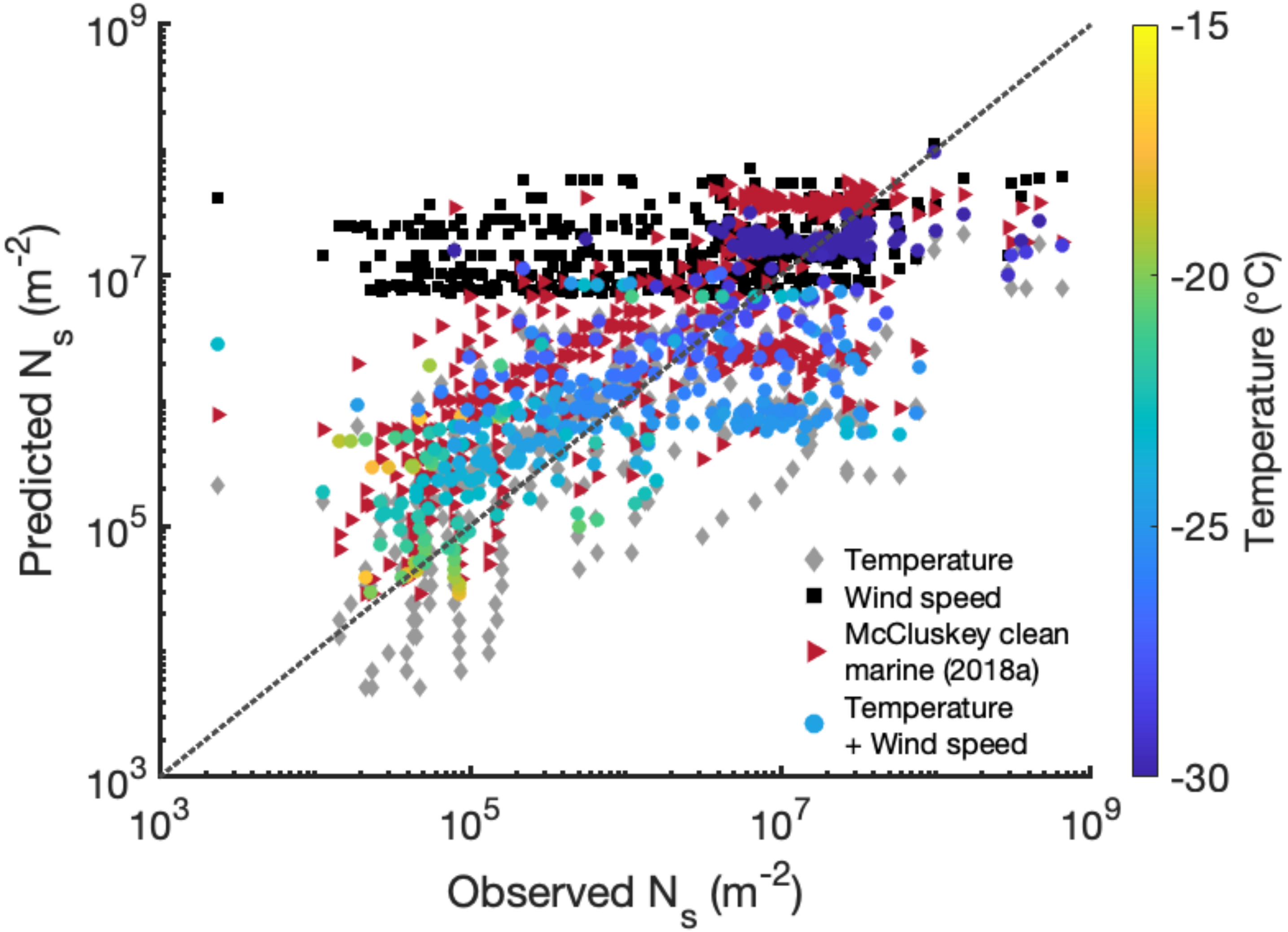
Existing parameterizations capture mean relationship between ice nucleating particle (INP) concentration and temperature, but not variability



INP concentrations increase with wind speed at all measurement temperatures

Normalizing INPs by aerosol concentration DOES NOT account for increased SSA production at high wind speeds

Including wind speed and temperature in marine INP parameterization reduces modified normalized mean bias (B_n)



McCluskey et al. 2018 clean marine parameterization: B_n=0.55

Temperature only: B_n=-0.2

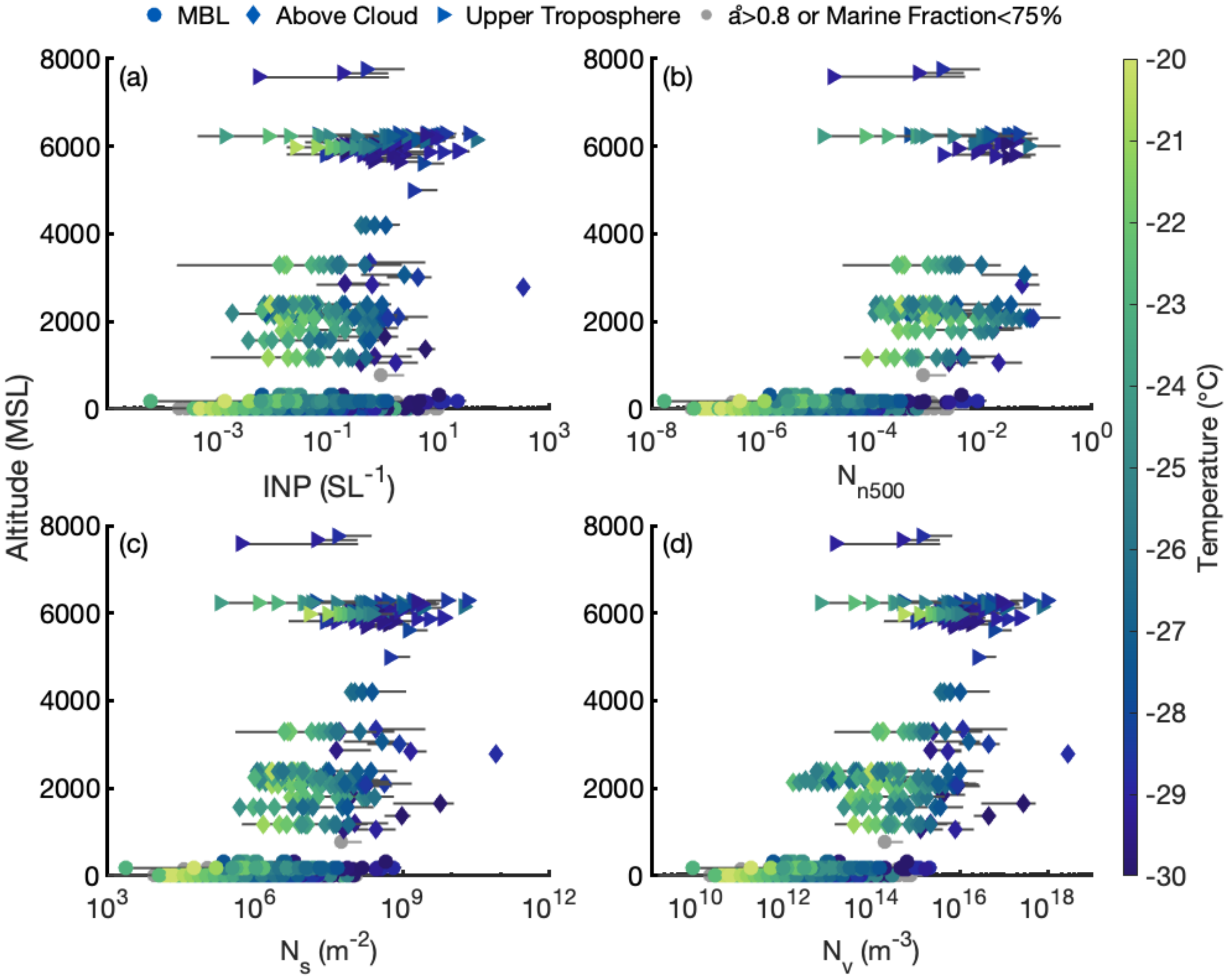
Wind speed only: B_n=1.07

Temperature + wind speed: B_n=0.09

McCluskey et al., 2018; Moore et al. 2023, in prep

Altitude dependence

SOCRATES aircraft observations have provided the first vertically-resolved measurements of INPs over the Southern Ocean, including in-cloud



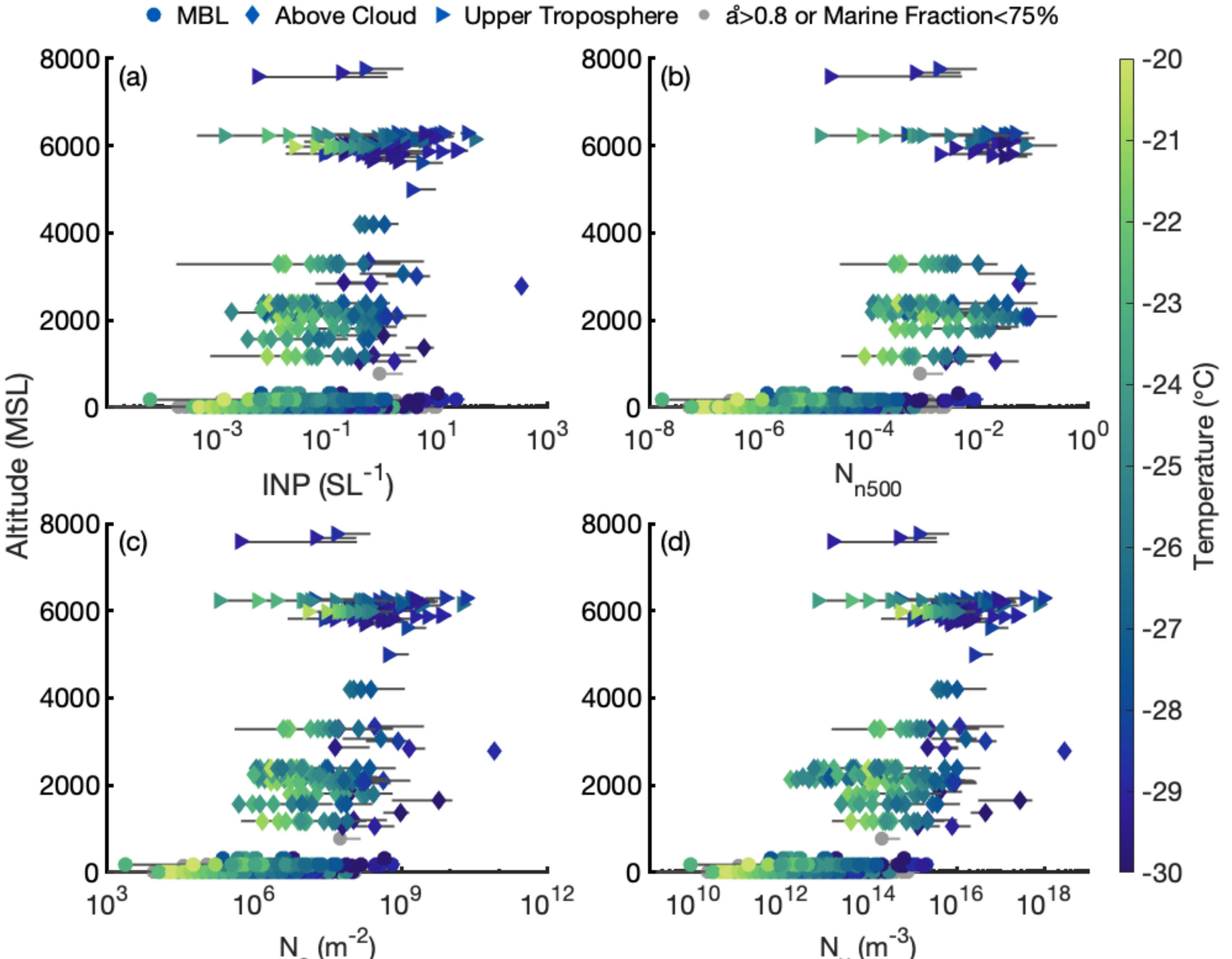
Minimum in mean INP concentrations between 1-4 km

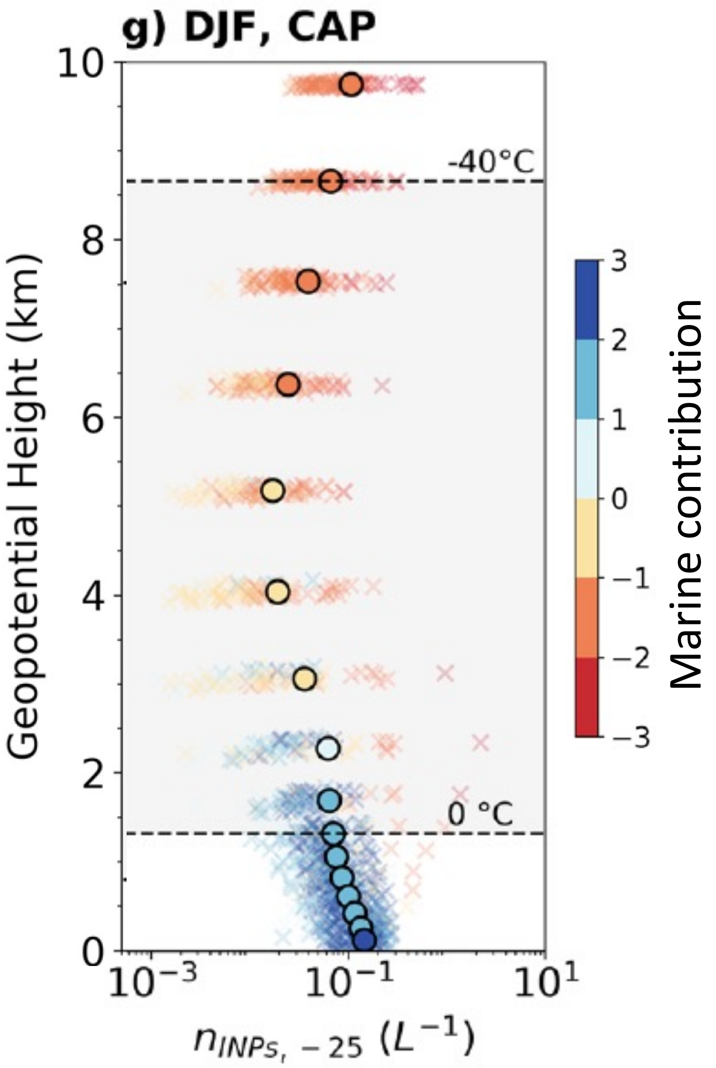
N_{n500}, N_s and N_v were consistently higher above cloud and in the upper troposphere (>5000 m) than in the marine boundary layer

Consistent with different sources of INPs below and above-cloud

SOCRATES vertical INP profiles similar to CAM5 simulations for the same region and season

Altitude dependence

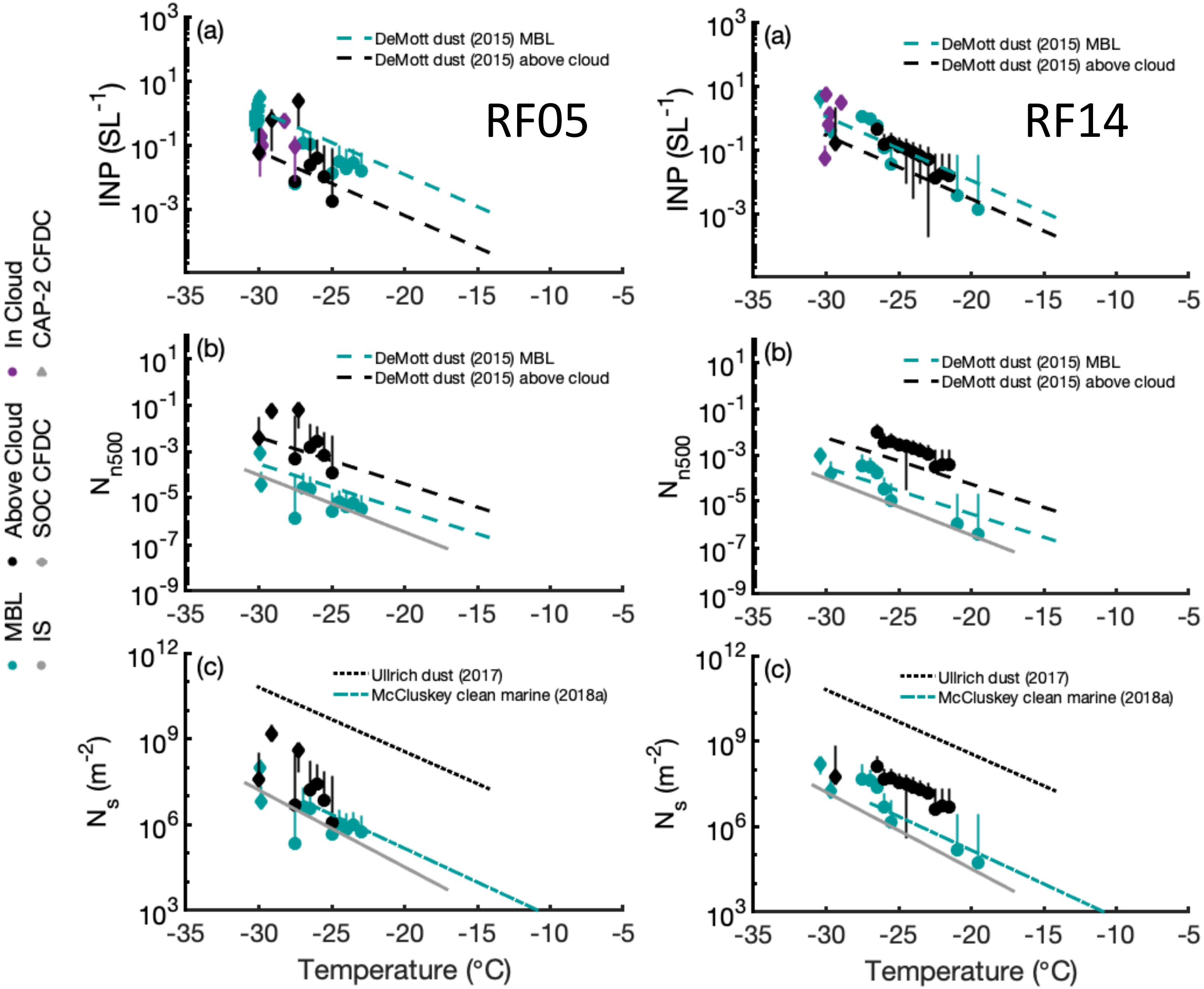




McCluskey et al., 2019

Altitude dependence

Above and below cloud INPs have very different activated fractions, consistent with different composition and sources



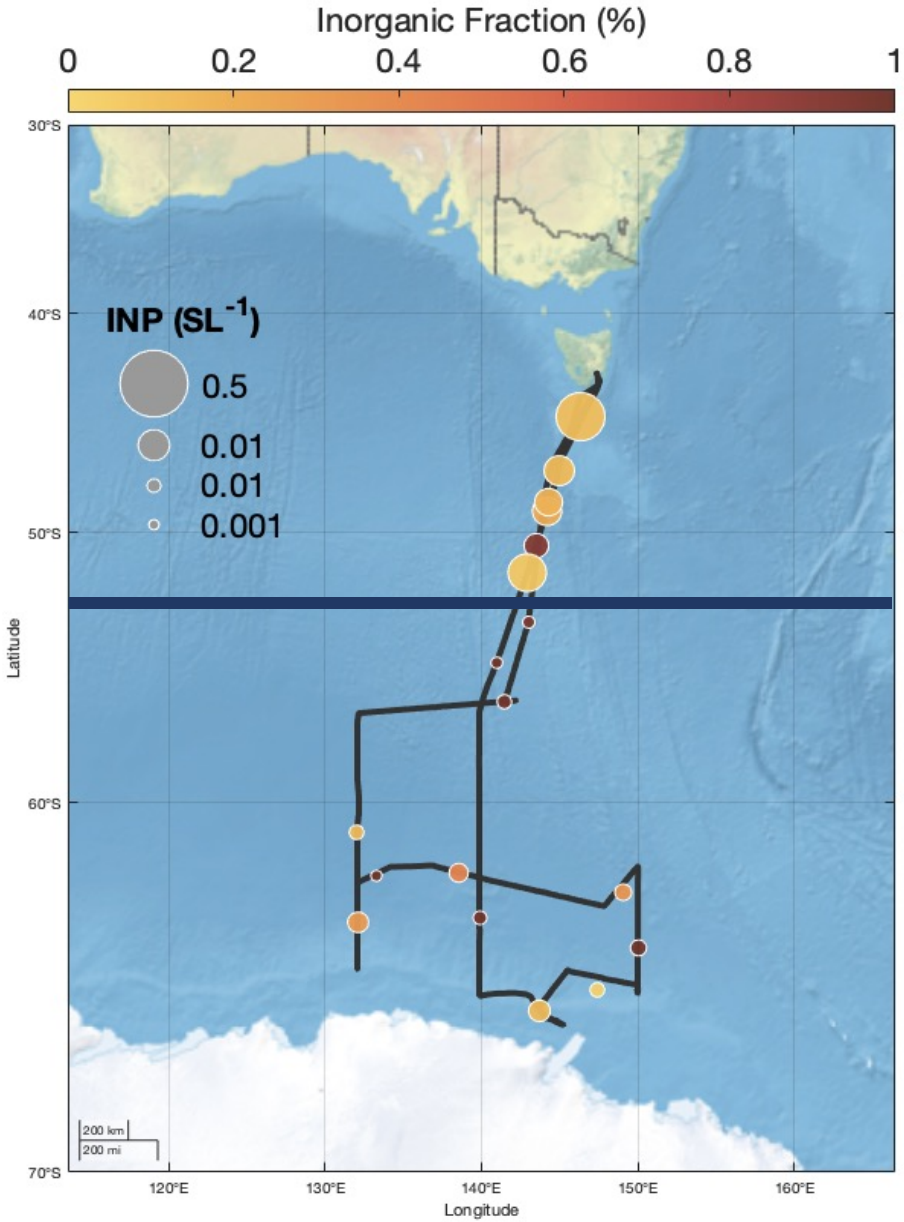
Amount of dust measured by SOCRATES TEM aerosol collections sufficient to account for INPs measured at all heights

Potential large role for small amounts of long-range transported dust

Twohy et al., 2021

MBL INP Composition

INP composition and concentration varies latitudinally in the Southern Ocean marine boundary layer



Higher organic fraction

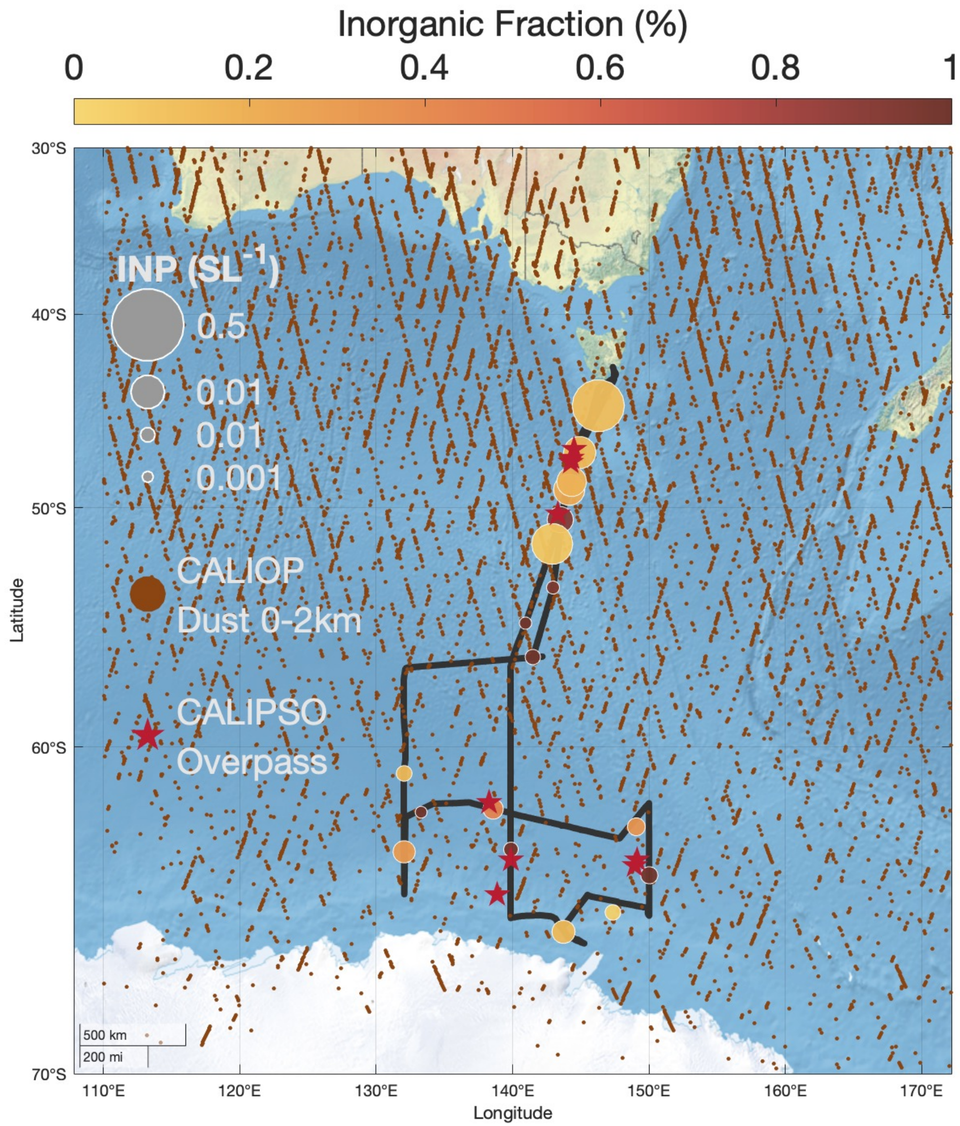
Higher concentrations

Higher inorganic fraction

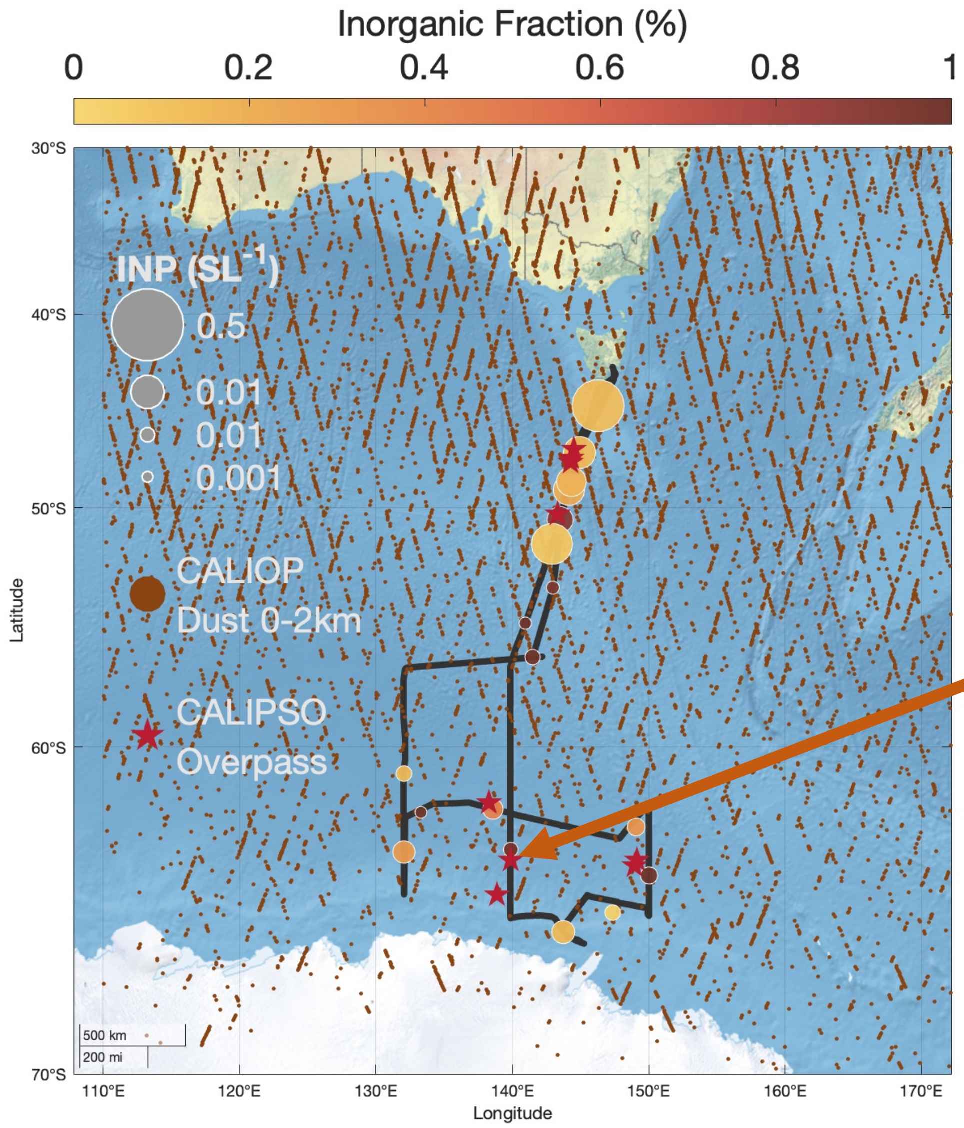
Lower concentrations

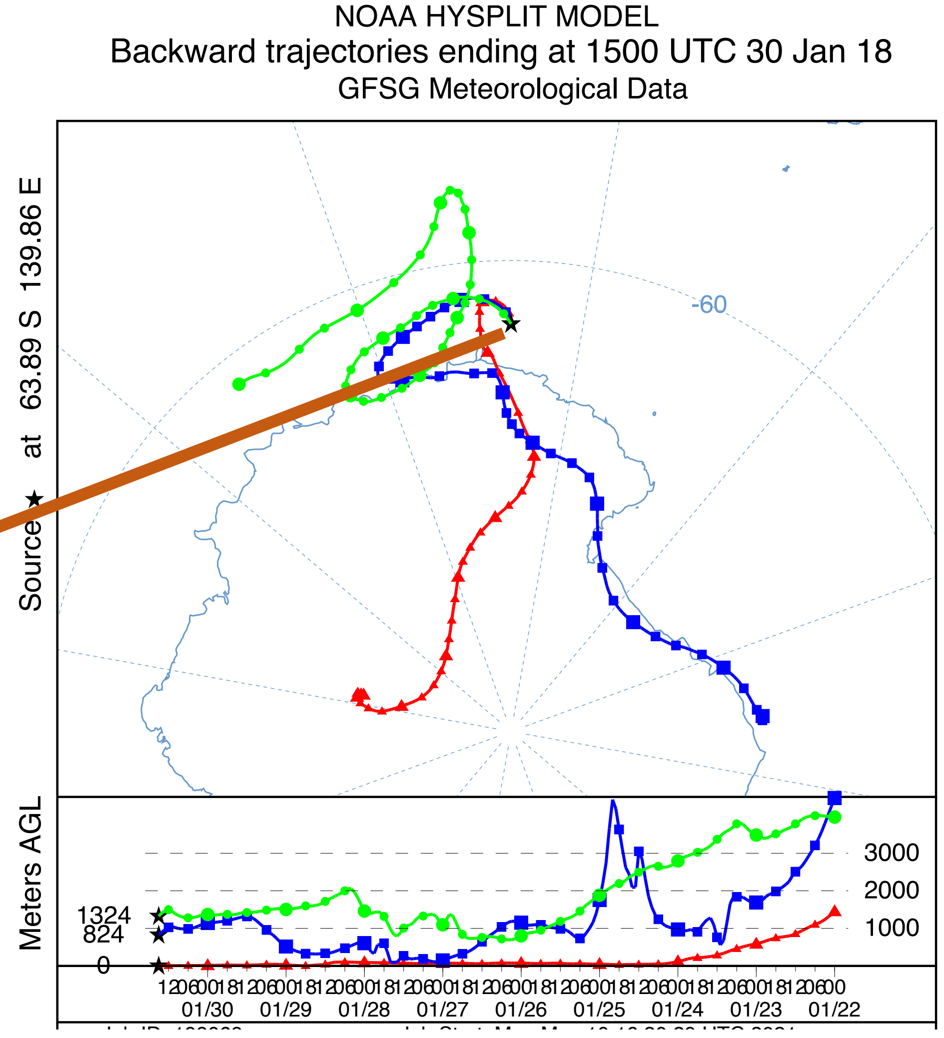
CALIOP used to identify dust in the MBL (<2km) near CAPRICORN-2 measurements

MBL INP Composition



HYSPLIT 10-day back-trajectories for the thickest MBL dust layer originate over Antarctica, and could represent a local source or long-range transport + subsidence





Aerosol iron measurements during CAPRICORN-2 suggest Antarctica may be contributing to the SO dust budget

High concentration and moderate solubility= anthropogenic and fire sources

Low concentration and high solubility= long range transport

High concentration and very low solubility= dust

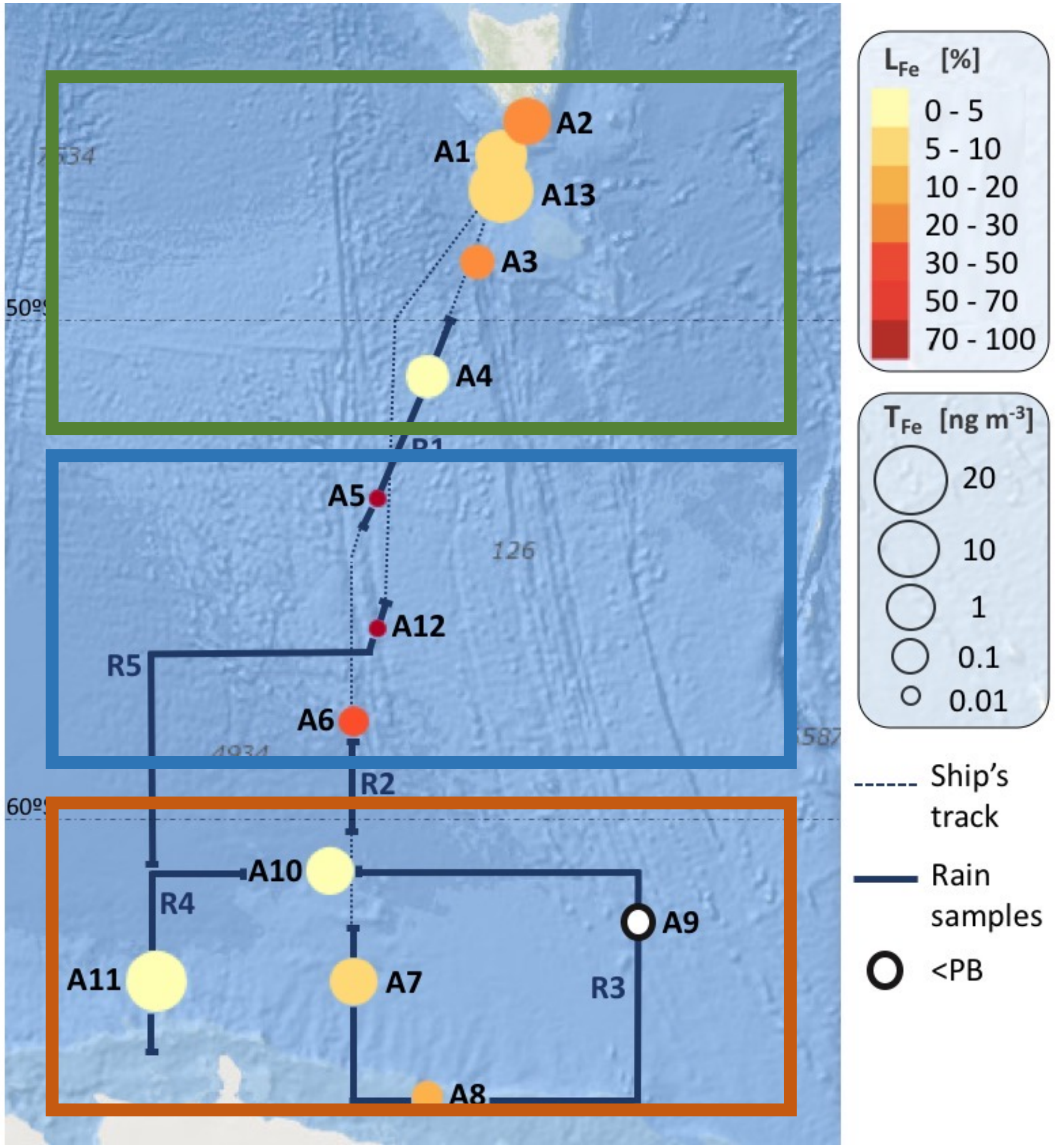
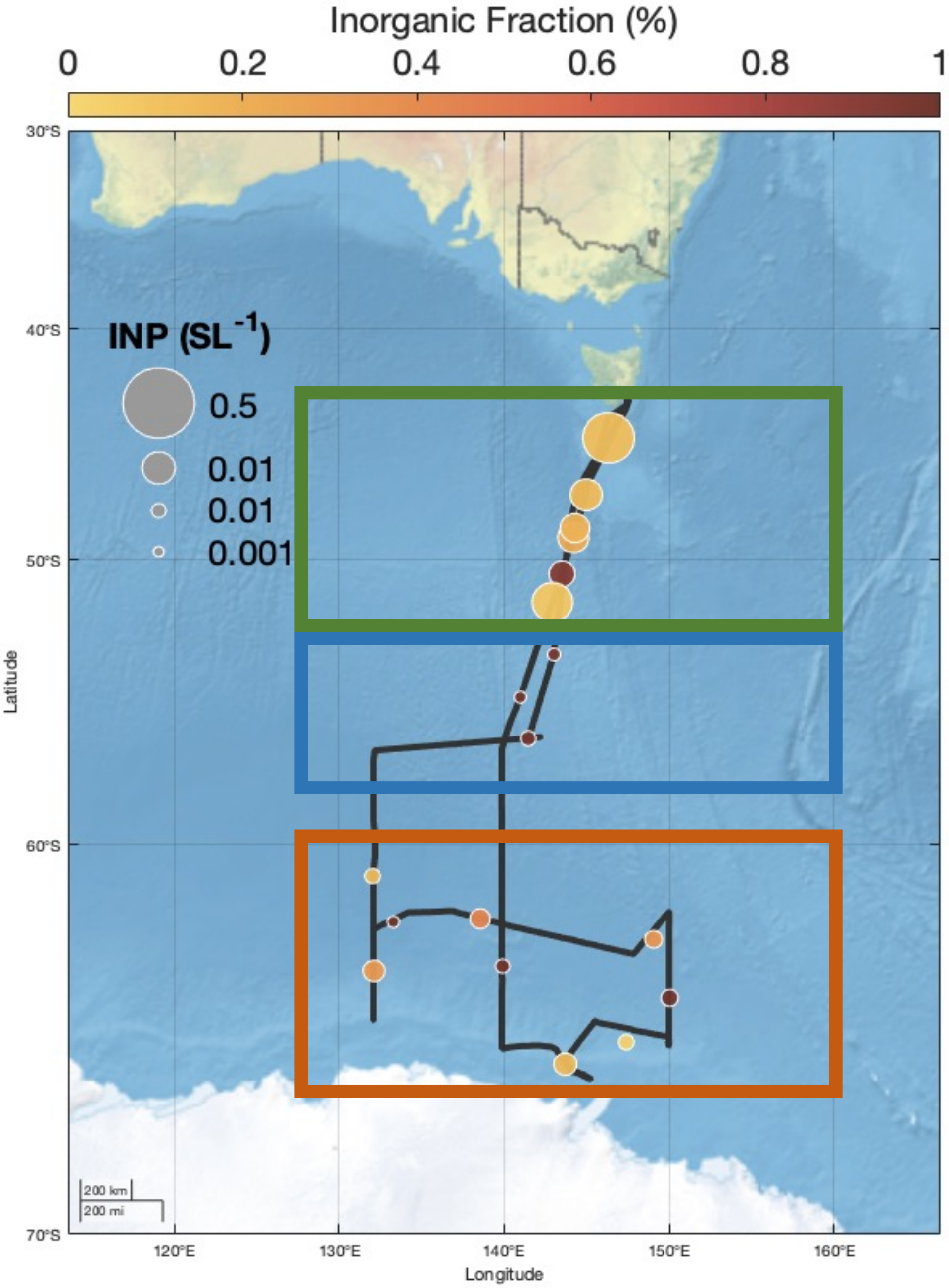


Figure courtesy Morgane Perron (University of Tasmania/Laboratoire des Sciences de l'Environnement Marin (LEMAR) and Andrew Bowie (University of Tasmania)

INP inorganic fraction broadly agrees with patterns seen in aerosol iron



Anthropogenic and fire sources

Long range transport

Dust

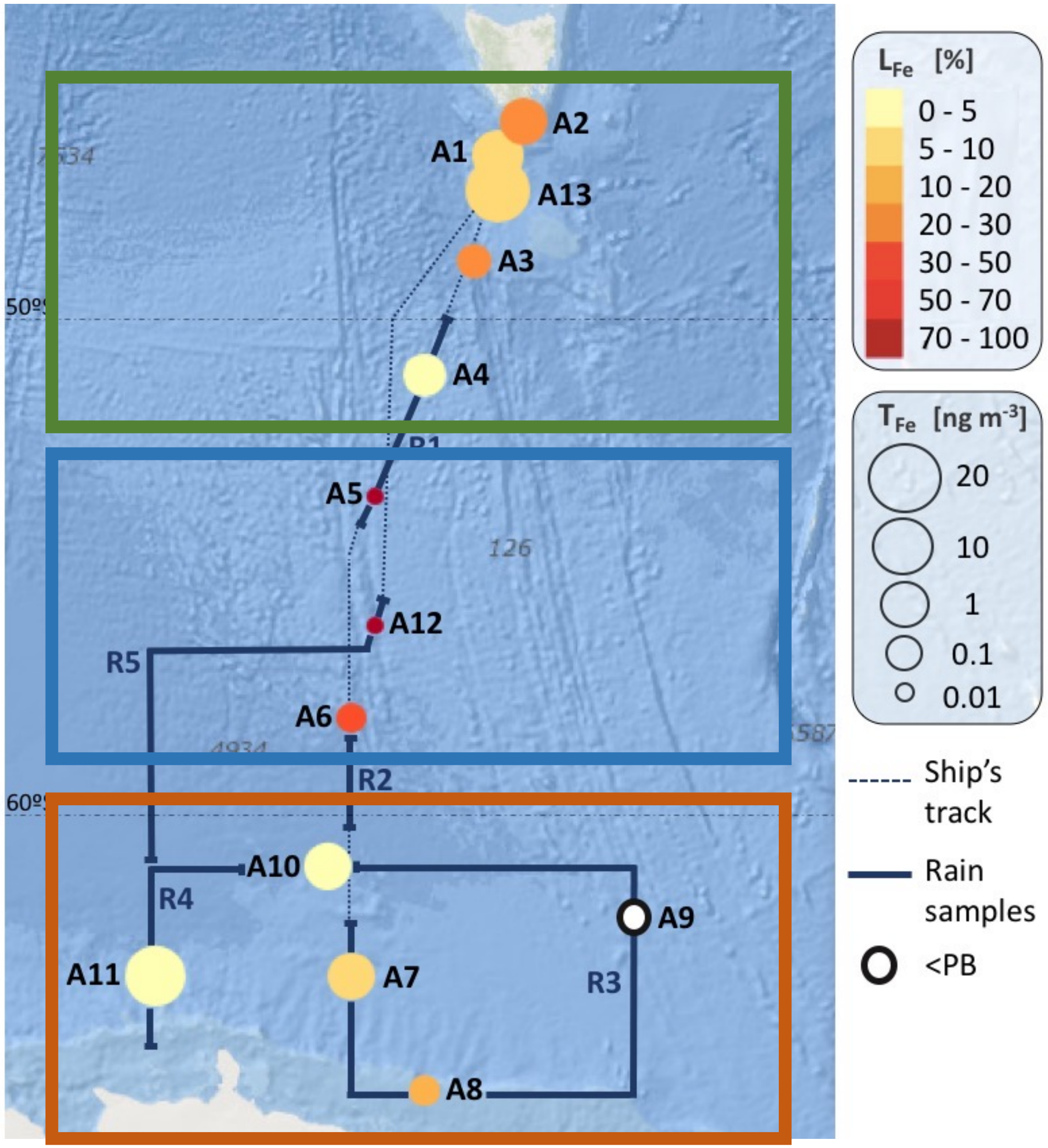


Figure courtesy Morgane Perron (University of Tasmania/Laboratoire des Sciences de l'Environnement Marin (LEMAR) and Andrew Bowie (University of Tasmania)

Summary

SO INPs are from a variety of sources, and vary latitudinally, temporally, and vertically

Unknown mechanism for enhancement of INP concentrations relative to wind speed-driven increases in sea spray aerosol

Amount of dust measured by SOCRATES TEM aerosol collections sufficient to account for INPs measured at all heights

Dust is a highly efficient INP and may influence cloud glaciation in the SO if present in small amounts

Inorganic INP fraction increases at high southern latitudes, consistent with an Antarctic dust source inferred from CALIOP and HYSPLIT

Acknowledgements

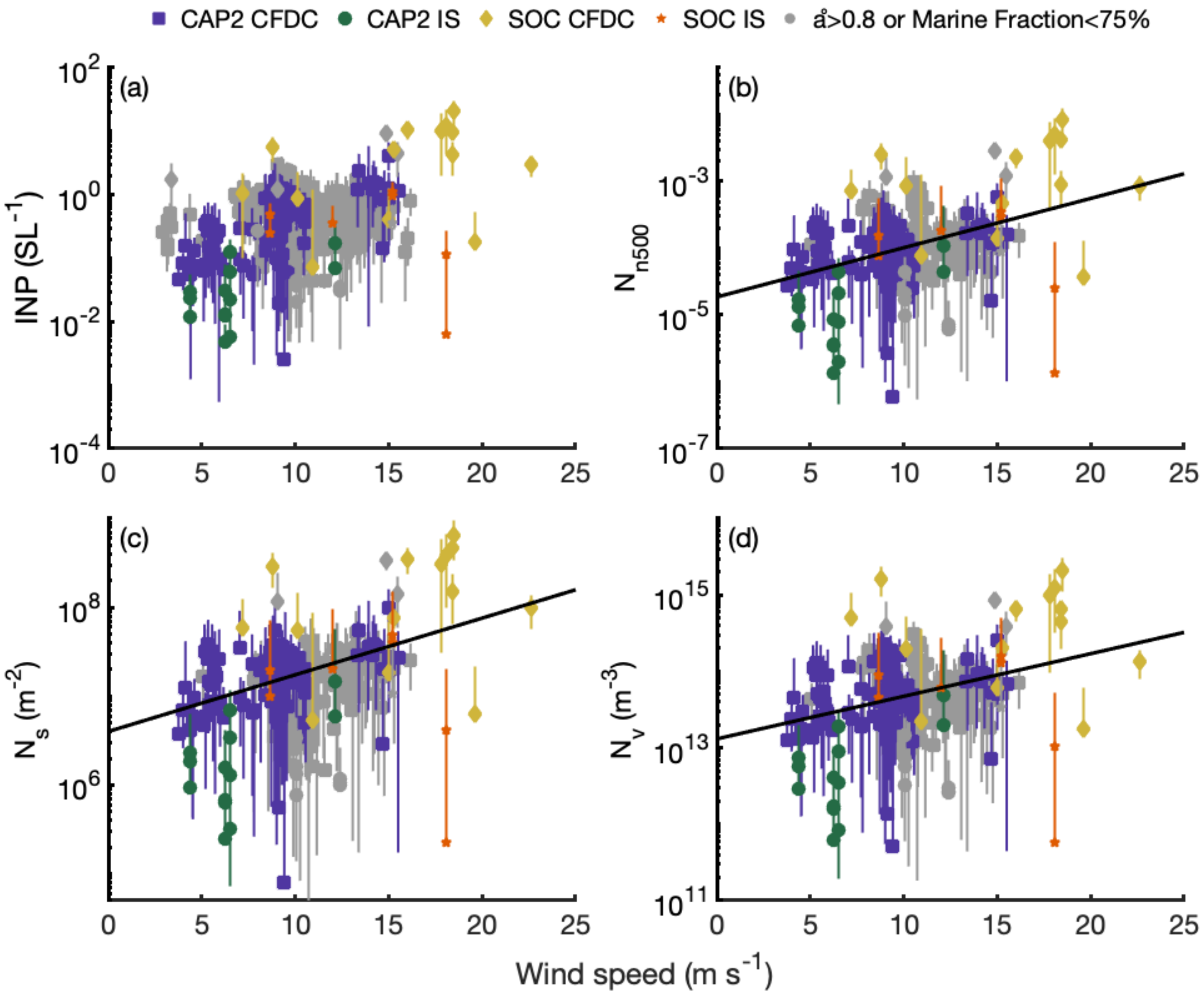
- National Science Foundation AGS-1660486, the SOCRATES Science Team, and the EOL G-V staff and crew
- Department of Energy (DOE), Office of Science, Contract DE-SC0018929
- DOE-ARM Battelle Memorial Institute Contract #339591
- CSIRO, Australian Antarctic Division and the Australian Bureau of Meteorology for support of CAPRICORN, MICRE and MARCUS measurements
- NSF Center for Aerosol Impacts on Chemistry of the Environment, University of California, San Diego, NSF CHE-1801971

Spearman’s rank correlation between INP concentrations and environmental/aerosol metrics

Table S1. Spearman’s rank correlation between environmental variables, aerosol metrics, and concentrations of INPs in multiple temperature ranges. Values in bold represent a significant relation ($p<0.05$).

Factor	**-19:-21 °C**	**-21:-23 °C**	**-32:-25 °C**	**-25:-27 °C**	**-27:-29 °C**	**-29:-31 °C**
Wind speed	-0.1796	**0.7782**	**0.2948**	**0.4339**	**0.6509**	**0.6102**
Altitude	-0.1796	0.2363	**-0.3685**	-0.1353	**0.516**	**0.2689**
Air Temperature	-0.1796	0.2815	0.0076	-0.1557	0.0533	**0.2126**
RH	0.1796	**-0.6006**	-0.0868	0.0752	**-0.678**	0.0783
N_{500}	-0.1796	**0.715**	**0.5117**	**0.4111**	0.0009	**0.5786**
N_{PMA}	-0.1796	**0.7601**	0.2528	**0.3116**	-0.0079	**0.6092**
SA	0.1796	**0.7752**	**0.4918**	**0.4212**	**0.4985**	**0.6546**
SA_{PMA}	-0.1796	0.8595	**0.3856**	**0.4167**	0.2422	**0.6312**
V	-0.898	0.2273	**0.3333**	**0.3513**	0.2073	**0.6358**
V_{PMA}	-0.898	0.3869	**0.346**	**0.3748**	0.32	**0.5934**
AE	-0.1796	0.4260	**-0.3753**	**-0.2727**	**0.6480**	0.0569

Wind speed is a missing variable in explaining Southern Ocean INP concentrations



Normalization by aerosol concentration has no effect at any temperature

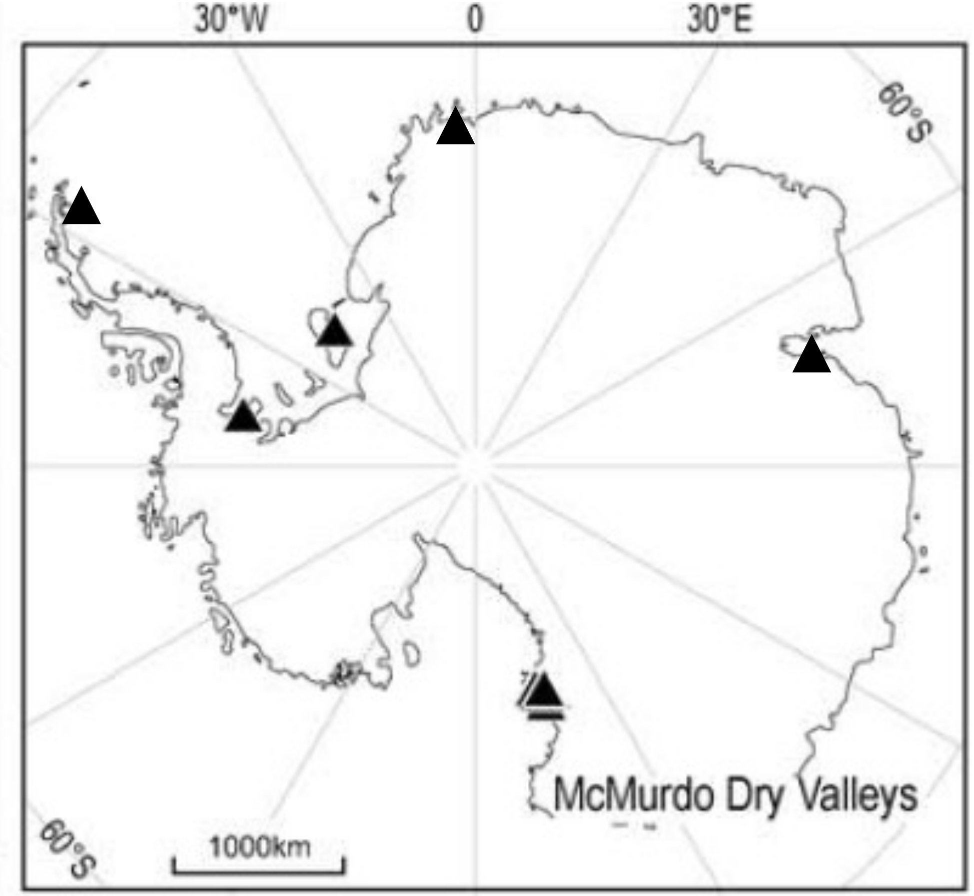
Does Antarctica emit dust?

High-latitude dust sources can be significant, but are often overlooked

Katabatic winds thought to be responsible for dust emission- not parameterized in models

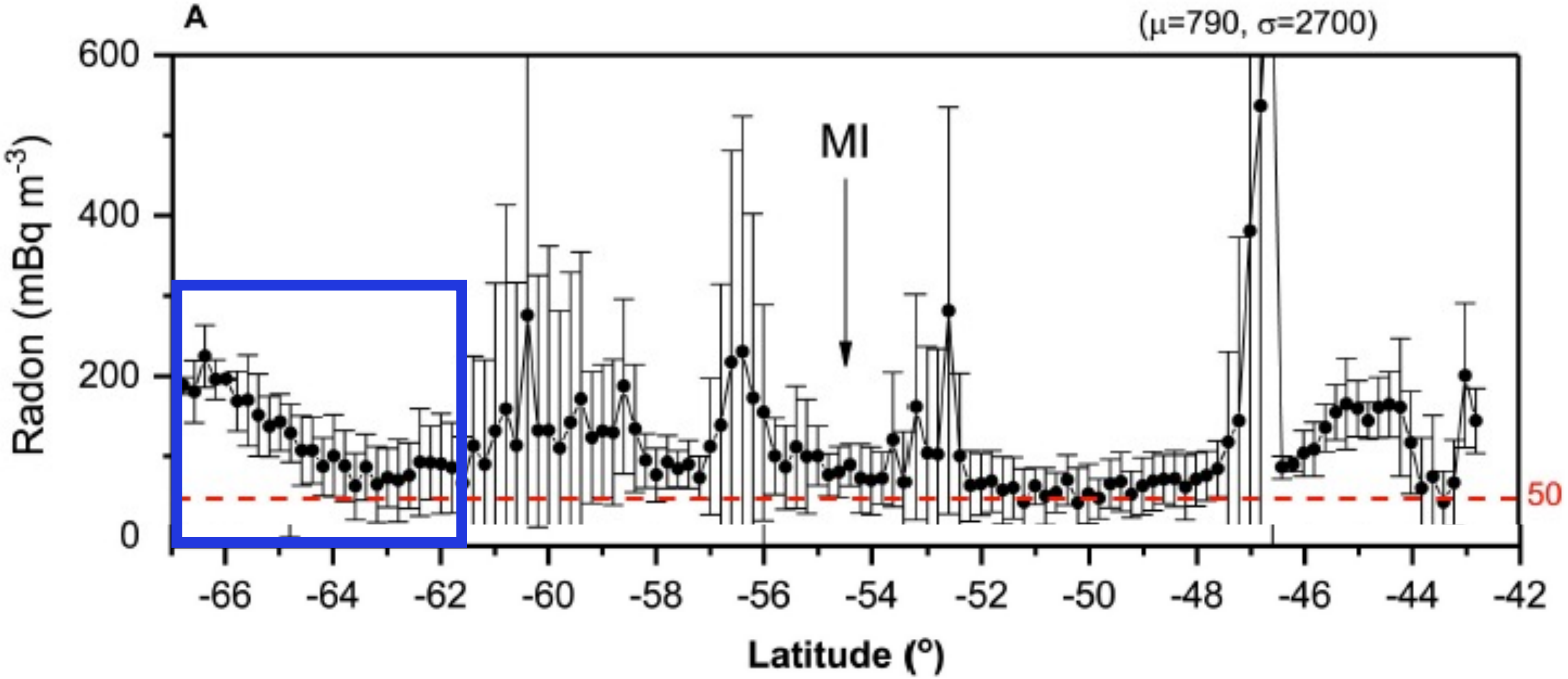
Mass of emissions completely unconstrained

Dust is a highly efficient INP, so small concentrations can have a large impact on cloud phase



Bullard et al., 2016; Kavan et al.

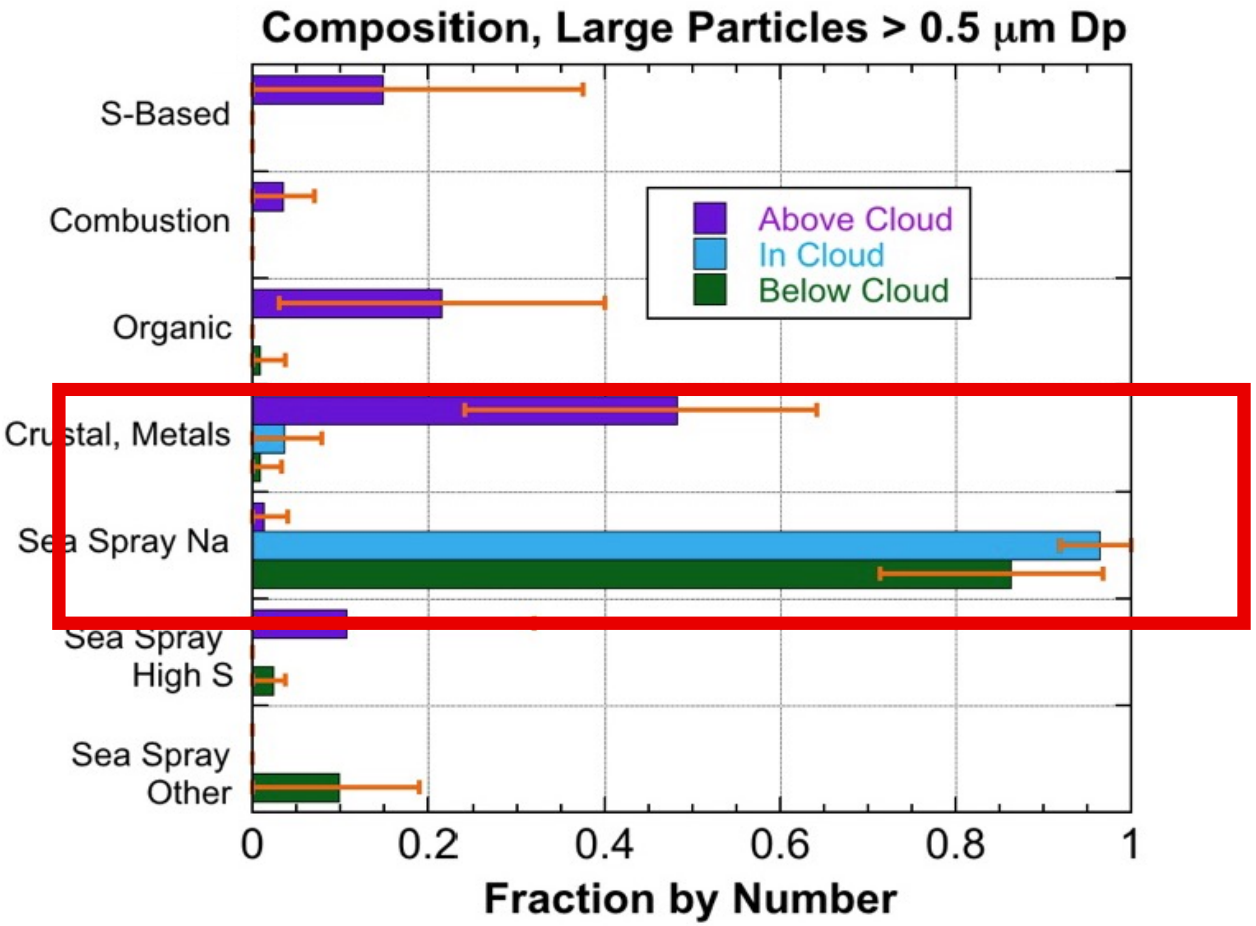
Radon measurements demonstrate Antarctic katabatic outflow reaches hundreds of km offshore



Antarctic katabatic outflow identified from radon measurements influences trace gas and aerosol properties hundreds of km offshore

Chambers et al. 2018

TEM particle composition from SOCRATES flights



Particle composition inferred from TEM results of all particles can be used to inform CFDC parameterizations

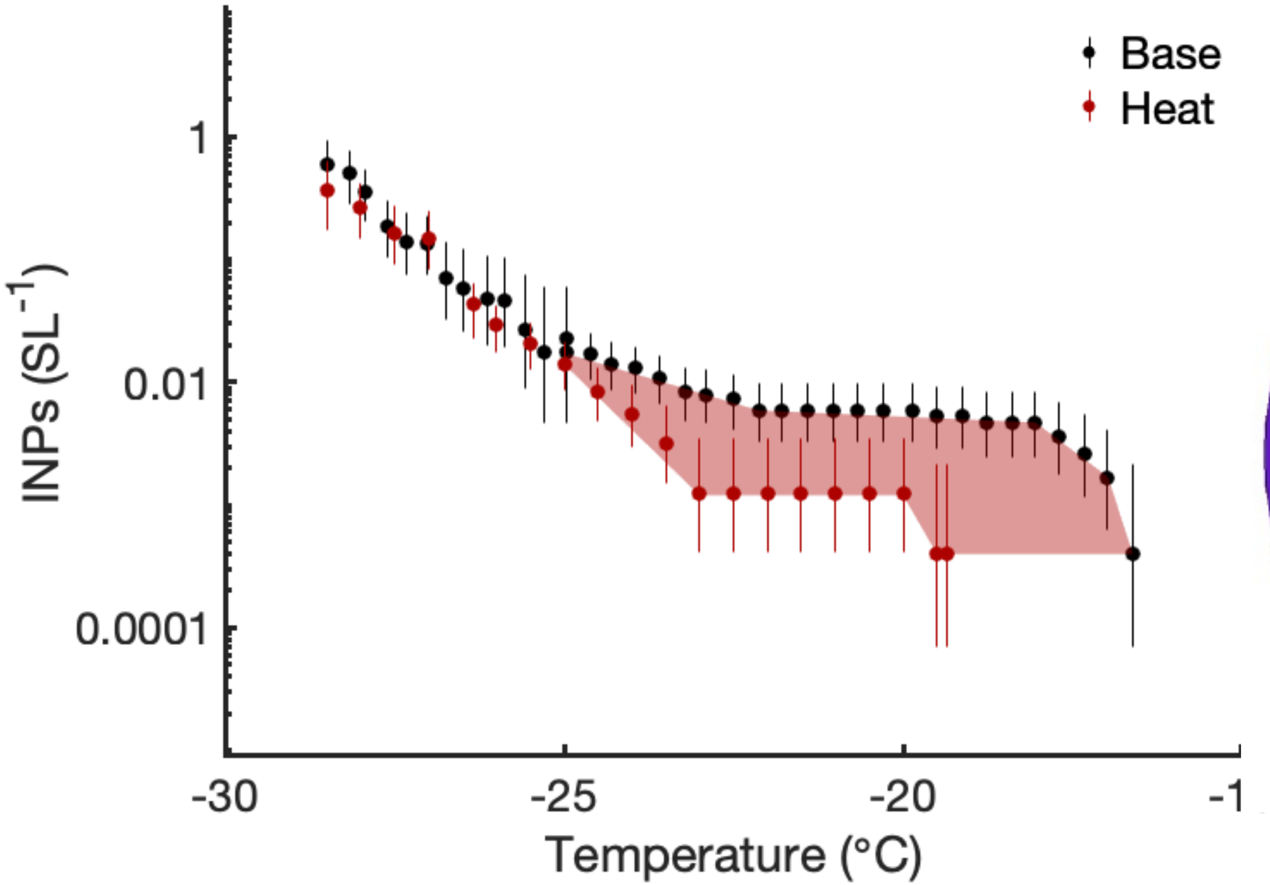
$$n_n(T) = \frac{n_{INPs}(T)}{n_{aerosol>500nm}}$$

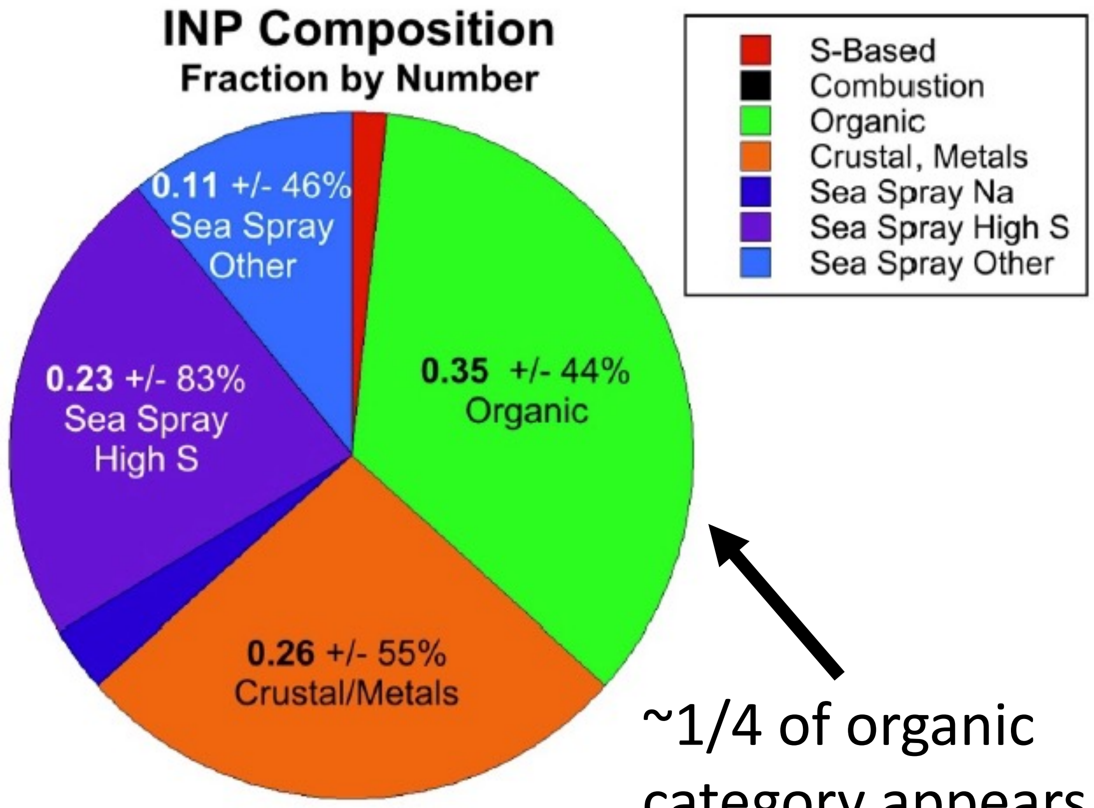
From TEM:
Dust fraction in MBL= 2%
Dust fraction above cloud=50%

Twohy et al., 2021

CAPRICORN-2 INPs show biological, dust, and marine inorganic signatures

Extras- INP Composition



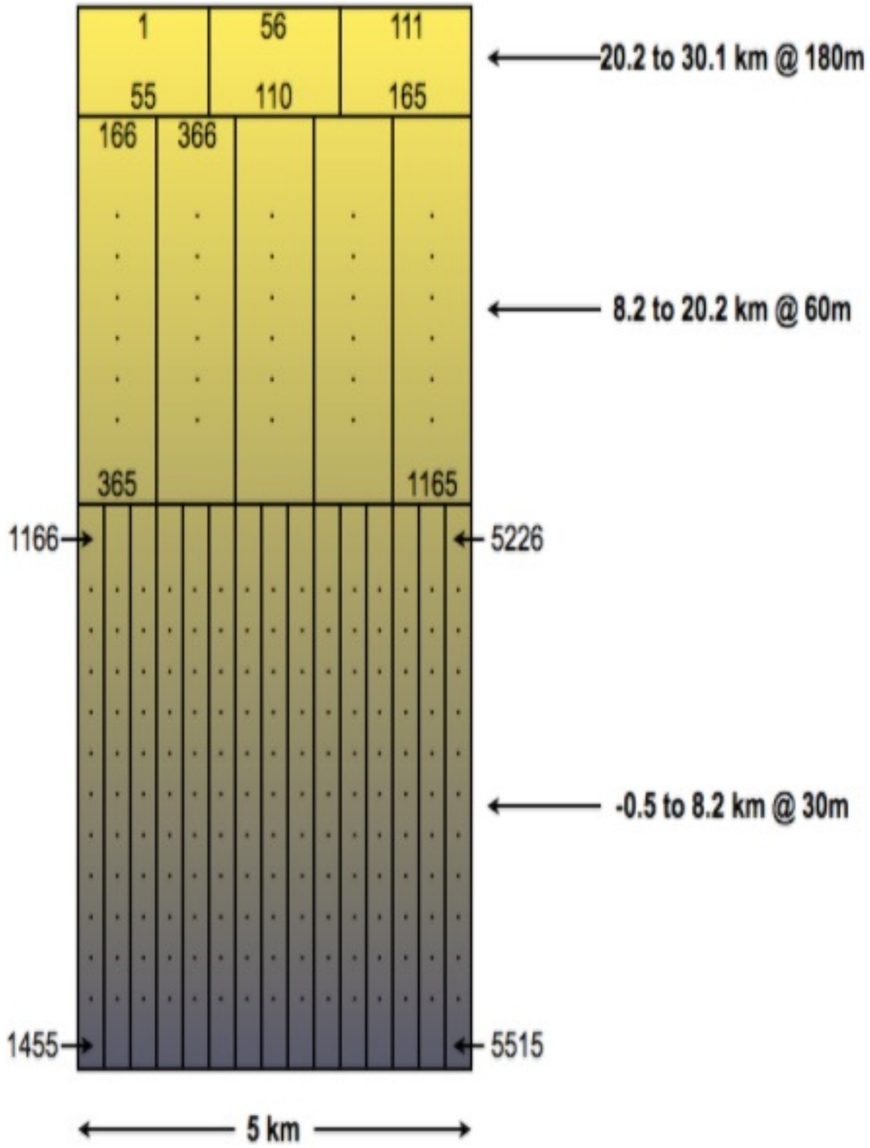


~1/4 of organic category appears biological

Twohy et al., 2021

The CALIOP LIDAR on CALIPSO provides vertical profiles of aerosols and identification of aerosol sub-types.

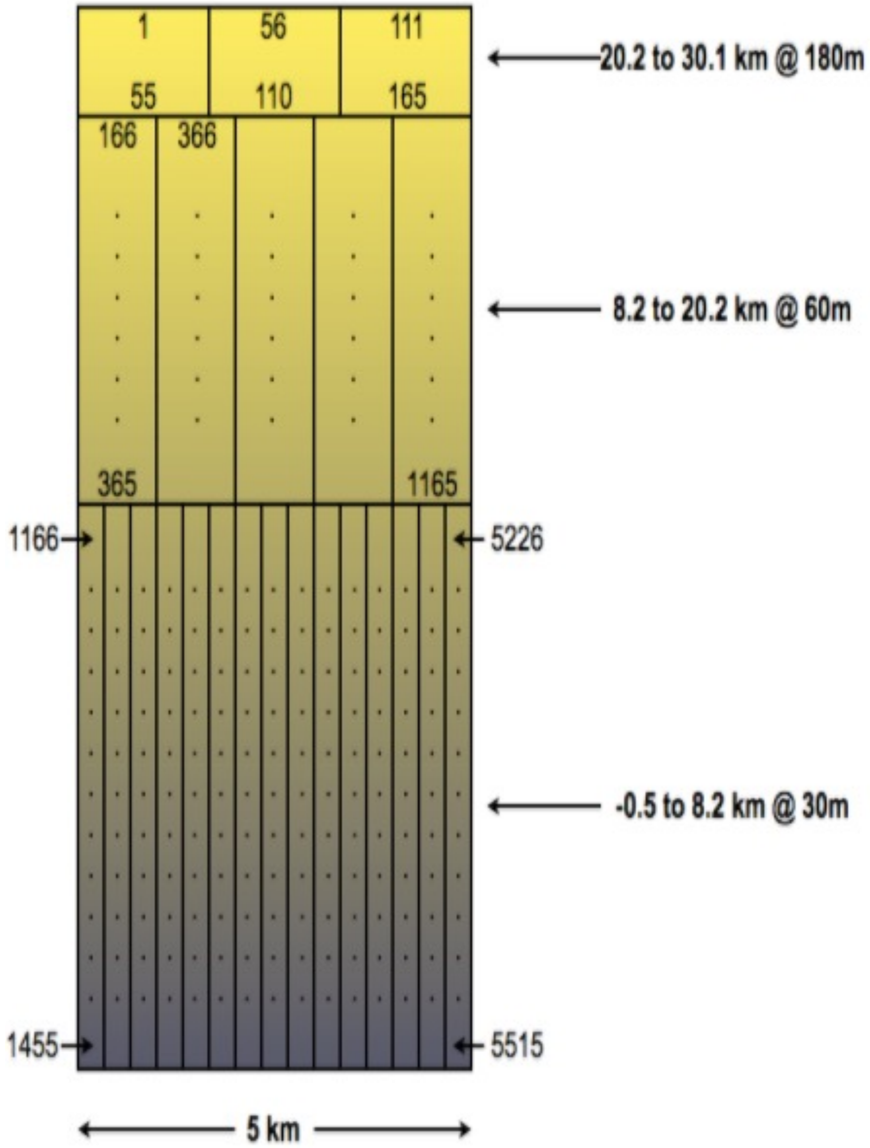
- CALIOP vertical feature mask (VFM)
  - $532_{\parallel}$ nm, $532_{\perp}$ nm, 1064 nm
  - Spectral dependence used to distinguish clouds from aerosols
- Backscatter, volume depolarization ratio, altitude, and surface used to identify subtypes
- Limitations:
  - Very narrow swath width: 5 km
  - No coverage under clouds
  - More sensitive to larger aerosols
- Pros:
  - High vertical resolution
  - Cloud and aerosol subtype identification



Extras- CALIOP lidar

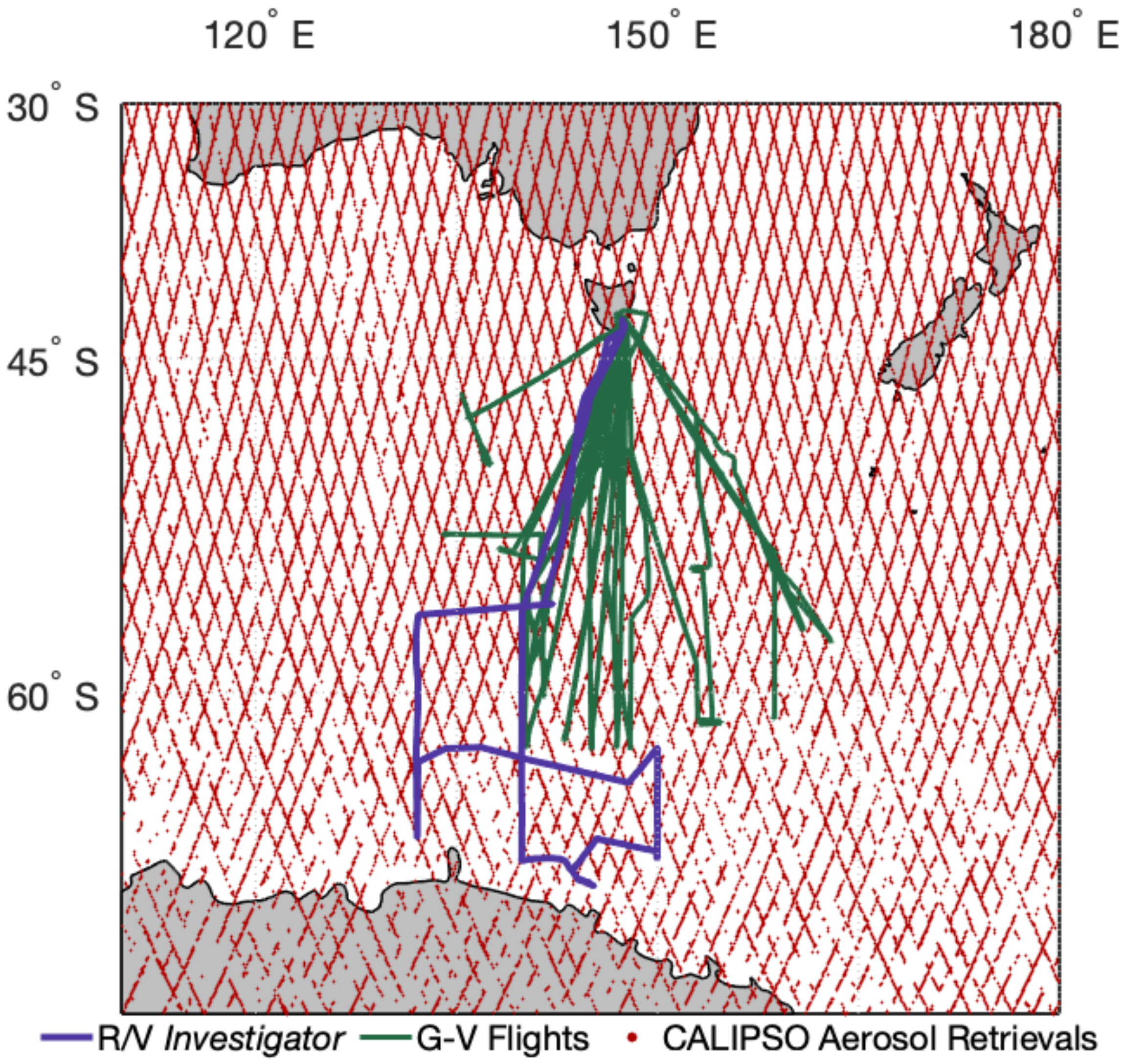
The CALIOP LIDAR on CALIPSO provides vertical profiles of aerosols and identification of aerosol sub-types.

- Only VFM features <8.2 km in altitude were considered
    - 1/3 km horizontal resolution
    - 30 m vertical resolution
    - Each “box” was considered one “sample”
    - Samples with unidentified aerosol types (0) were ignored
- No data affected by low laser energy was included
- Day and night data both used



Extras- CALIOP lidar

CALIOP LIDAR (CALIPSO) VFM was used to analyze aerosol composition during CAPRICORN-2



CALIOP VFM data that overlapped CAPRICORN-2 and SOCRATES was selected:

- Jan. 1 to Feb. 28, 2018
- -70 to -30 °S, 110 to 180 °E

Data separated by altitude:

- Marine Boundary Layer (MBL): 0-2 km
- Free Troposphere (FT) and above: 2-8.2 km

Backscatter, volume depolarization ratio, altitude, and surface used to identify subtypes