ATARRI: Dust effects on clouds

ATARRI

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BSC and ICREA

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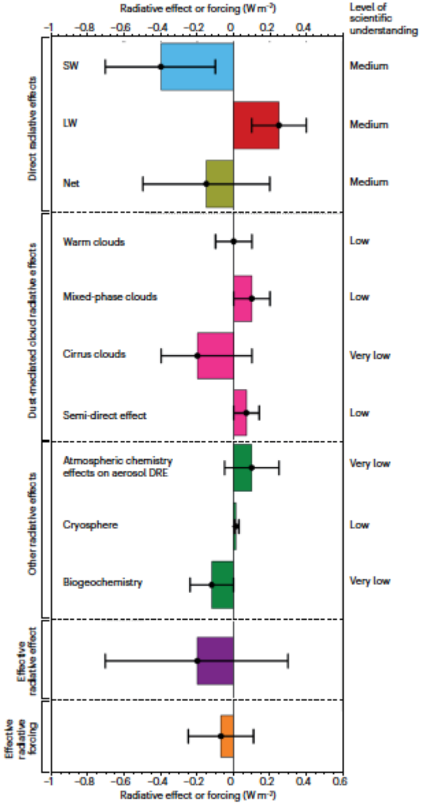
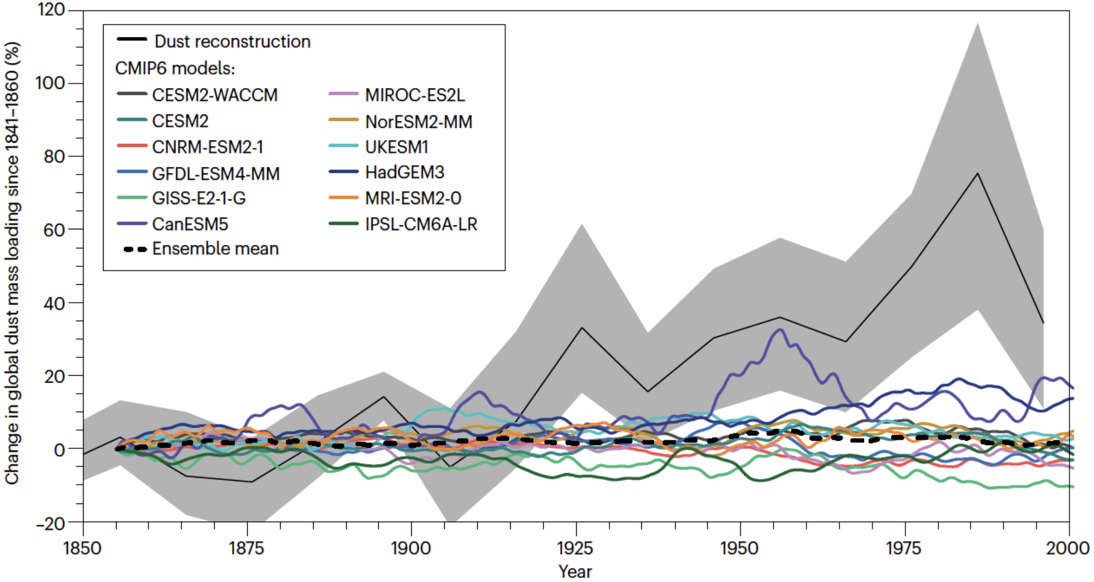
Outline of this session

- An introduction to the effects of dust on clouds and climate
- Focus on mixed-phase and cold clouds
- Dust in the context of other INP
- Key mechanisms for ice nucleation
- Global modeling of dust as INP
- Current status, challenges and opportunities

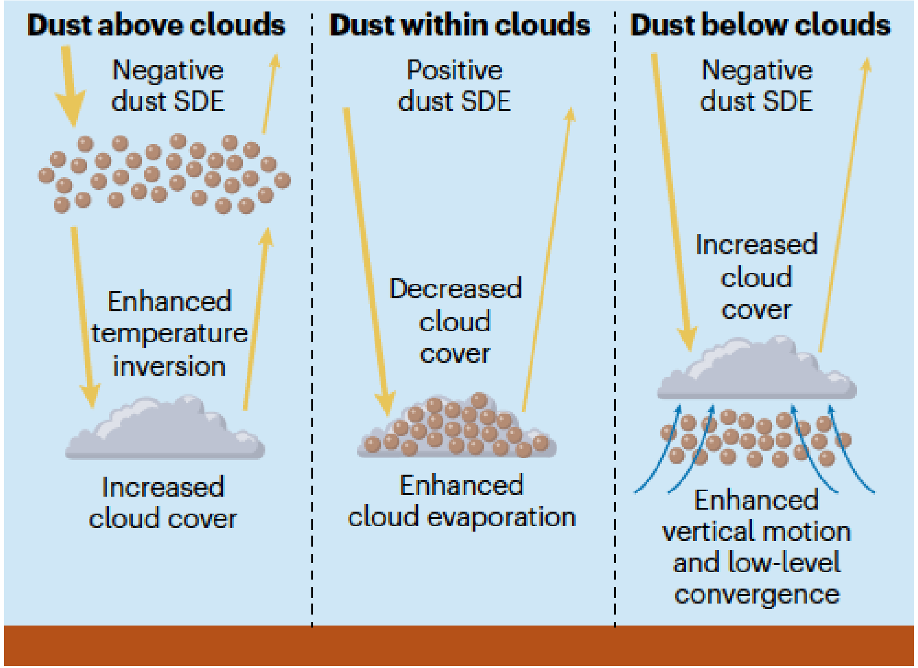
Global radiative effect and forcing





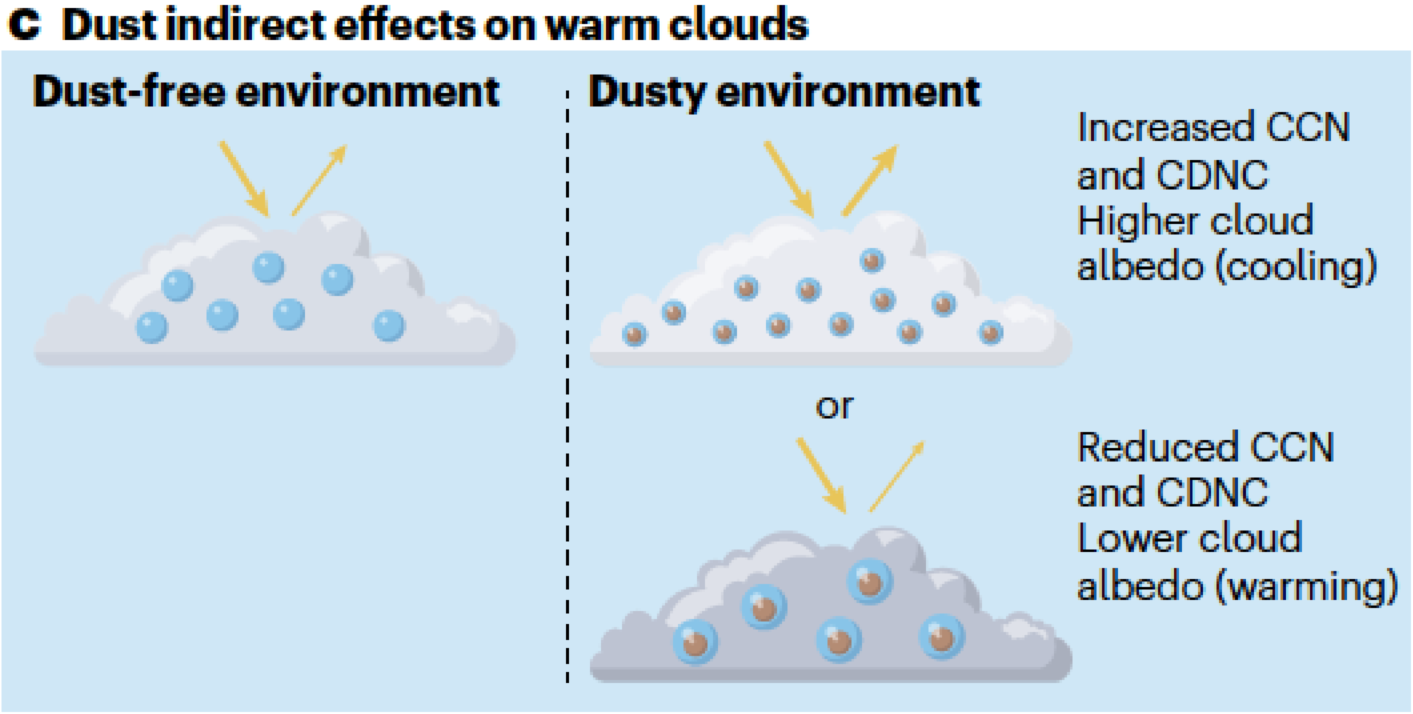
Dust semi-direct effects on low clouds

f **Dust semi-direct effects on low clouds**

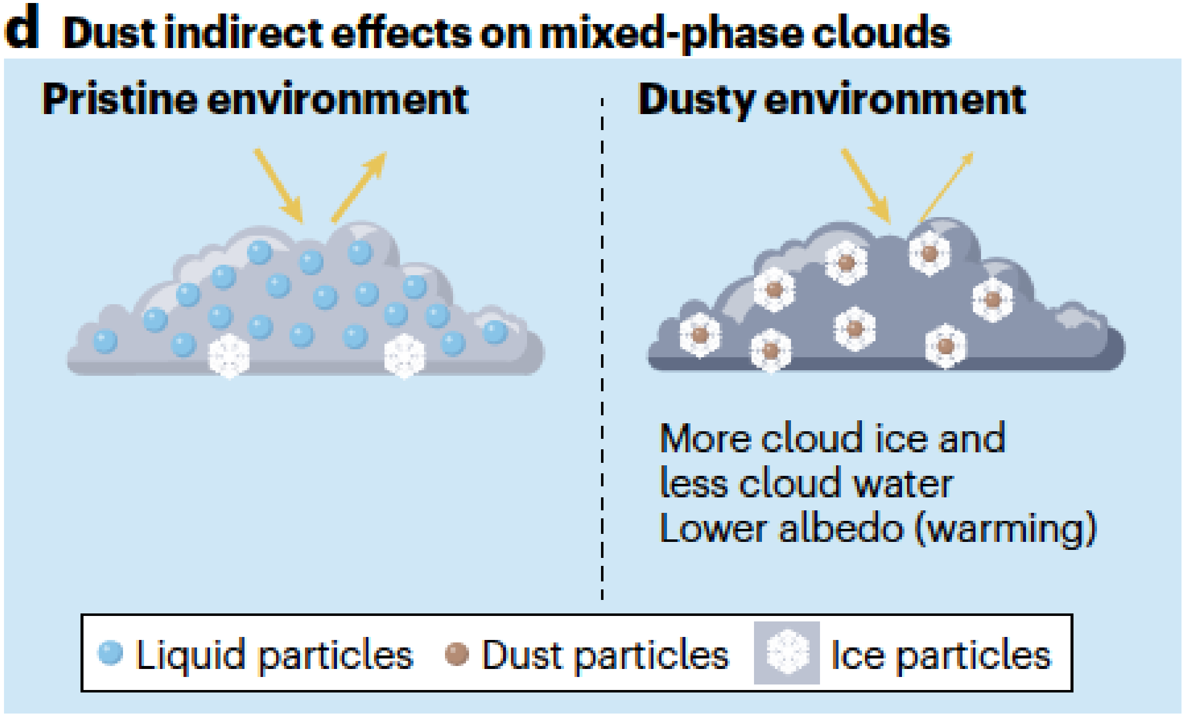


- Depends on the the relative position of the dust and cloud layers within the atmospheric column and the amount of radiation absorbed by the dust layer
- Note this assumes that dust radiative warming from SW absorption dominates over cooling from LW emission
- However, the amount of coarse dust, which emits LW radiation more strongly than fine dust, has likely been underestimated

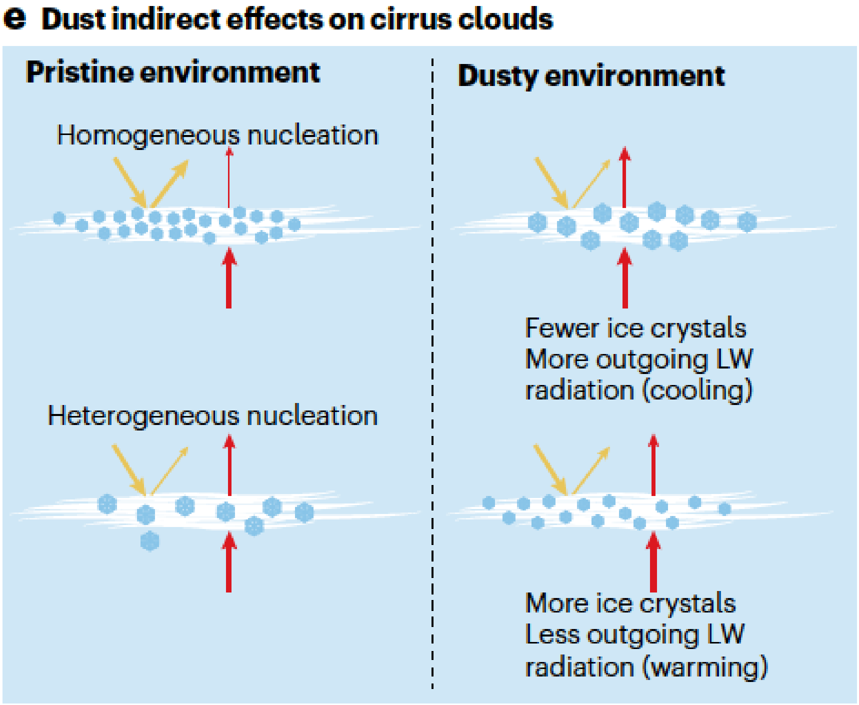
Dust indirect effects on warm clouds



Dust indirect effects on mixed-phase clouds



Dust indirect effects on cirrus clouds



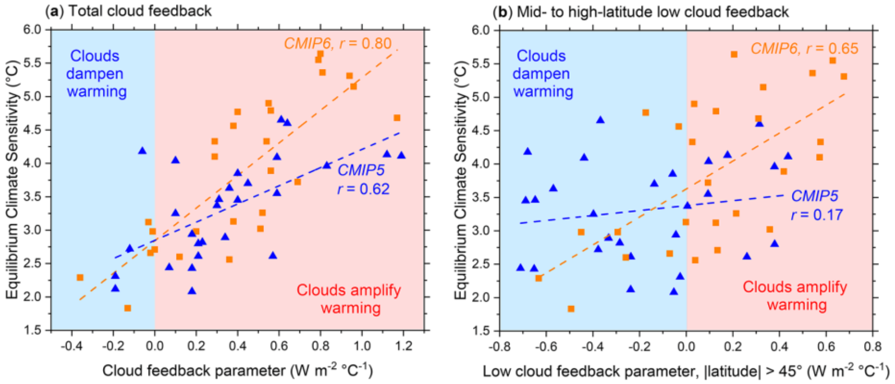
- Cirrus clouds reduce emission of LW radiation to space more effectively than they reflect SW radiation and thus have a net warming effect

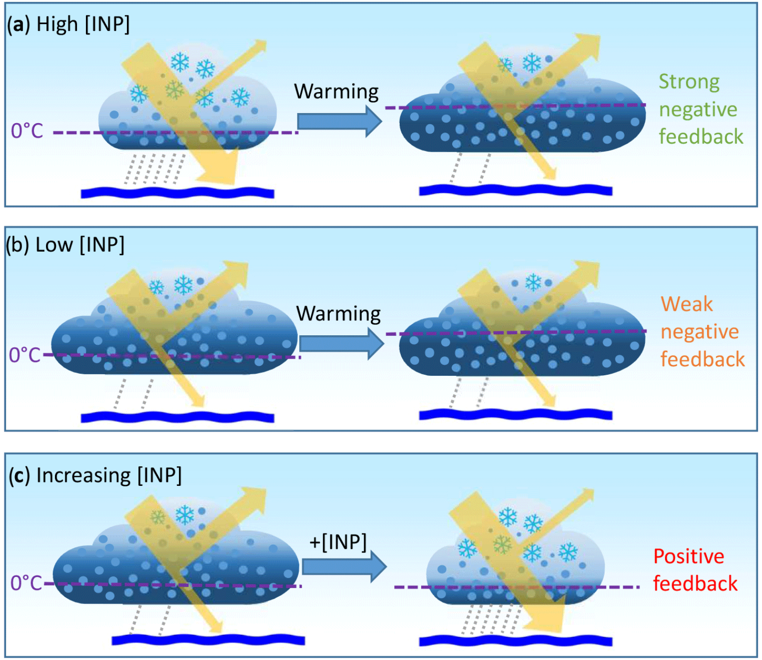
- In pristine environment, heterogeneous nucleation reduces ice crystal number and increases ice cristal size -> optical thining (cooling)

- In dusty conditions, more dust may increase ice crystal number and reduce ice crystal size -> (warming)

Changing INPs in a warming climate

Magnitude of the negative cloud-phase feedback component depends on the amount and nature of the small fraction of aerosol particles that can nucleate ice crystals



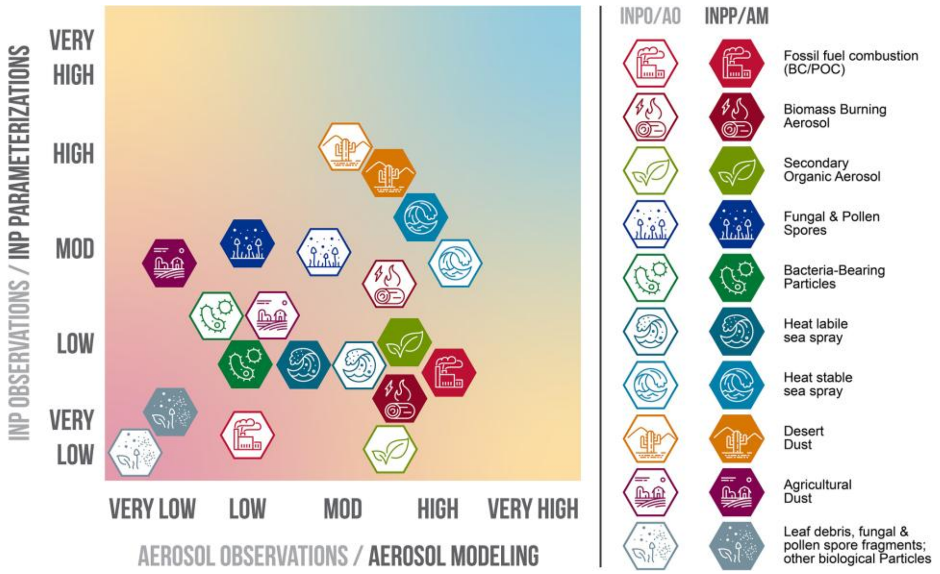


Murray et al. (2021)

Importance and relative level of understanding of dust INP

- Desert dust is considered one of the best known INPs

- However, dust is a dominant source of INP and many uncertainties remain

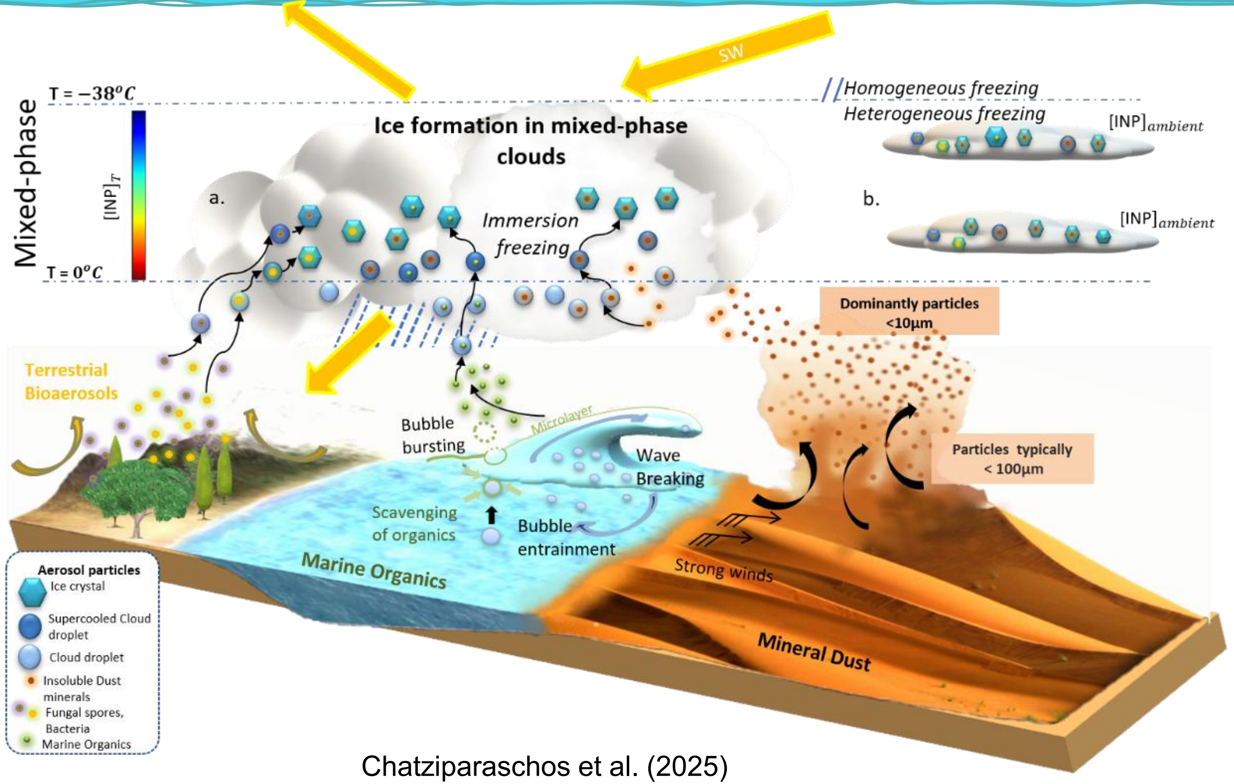


Burrows et al. (2022)

The global contribution of dust to INP concentrations

- Many species may contribute to INP concentrations

- Among those, dust, marine organics (MPOA) and PBAP are currently thought to be the key global scale contributors

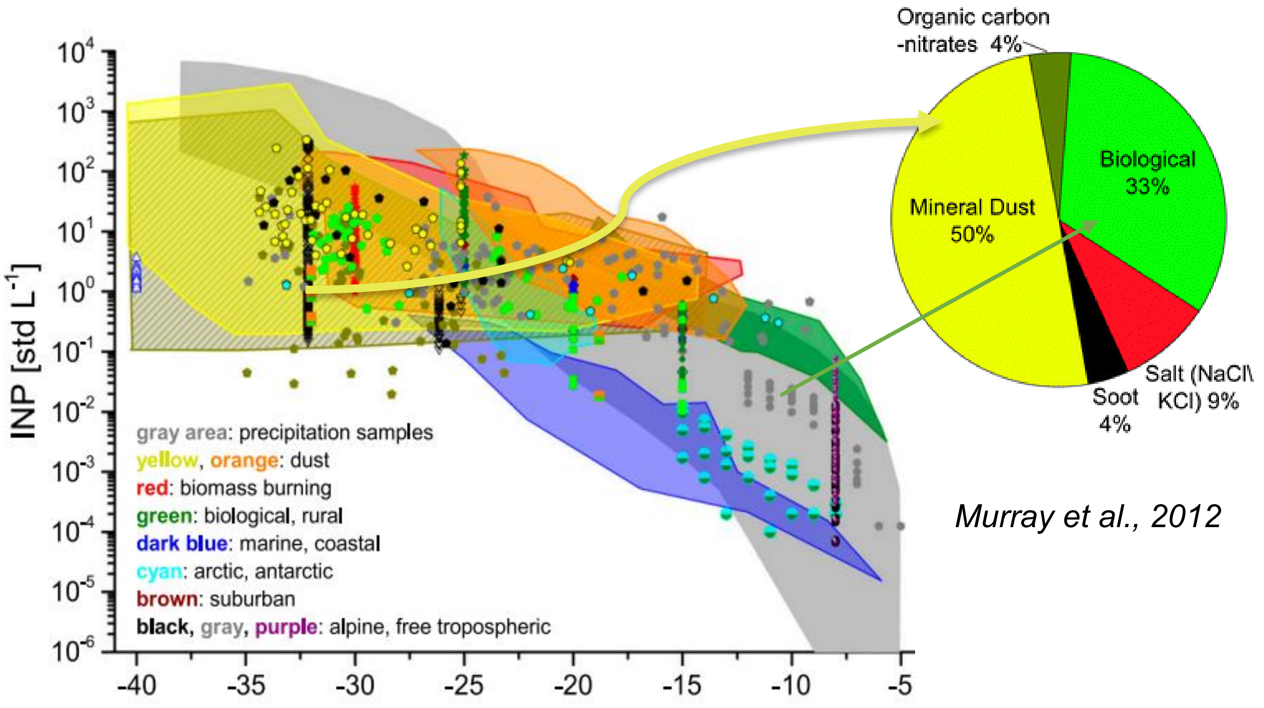


Chatziparaschos et al. (2025)

Dust effects on clouds: Ice nucleation ability

•At **colder temperatures (≈ –20 to –35 °C)** the **yellow/orange [dust] reaches the highest INP number concentrations**, up to ~10^3–10^4 std L^{-1}.

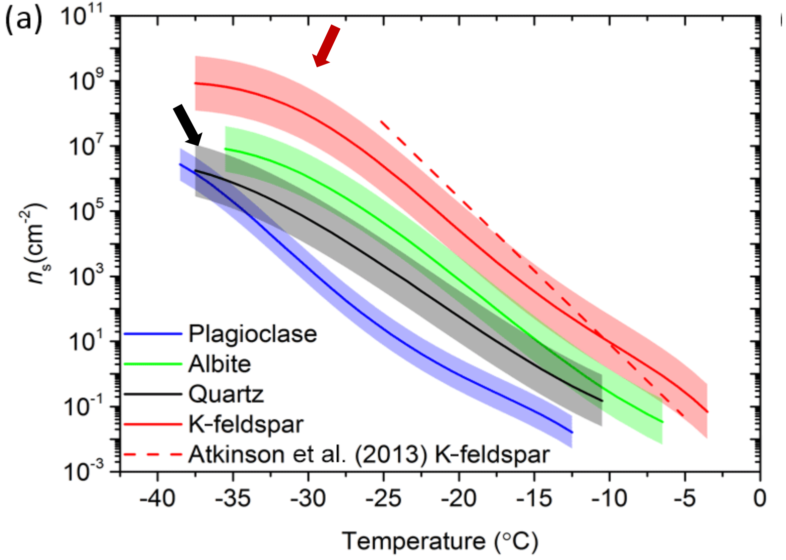
•**mineral dust is the main precursor of INPs in lower temperatures**, compared to marine, biological, or suburban sources, which sit mostly at lower concentrations.



Kanji et al., 2017

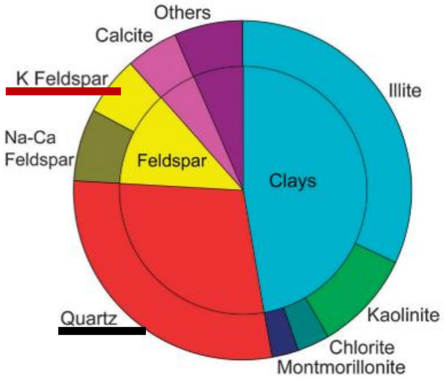
Murray et al., 2012

Ice nucleation and mineralogy

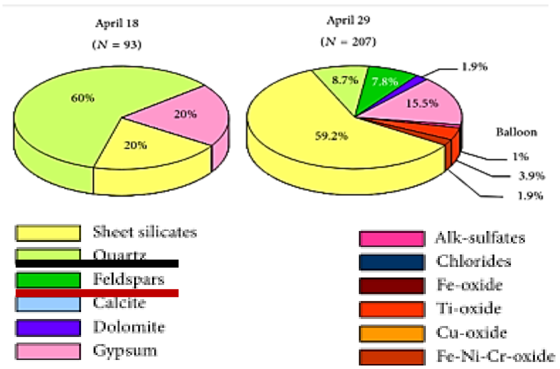


Harrison et al. (2019) immersion freezing

Average of atmospheric dust composition



Murray et al., 2012



Moroni et al., 2015

Feldspar (especially K-feldspar) and quartz are the main precursors of ice-nucleating particles (INPs) within mineral dust, *this relatively small mineral fraction largely controls the INP activity of dust plumes.*

Why K-Feldspar is so ice-active

•**Crystalline template:** K-feldspar surfaces expose lattice planes with spacings similar to hexagonal ice, which helps orient water molecules and **lowers the energy barrier for ice formation**.

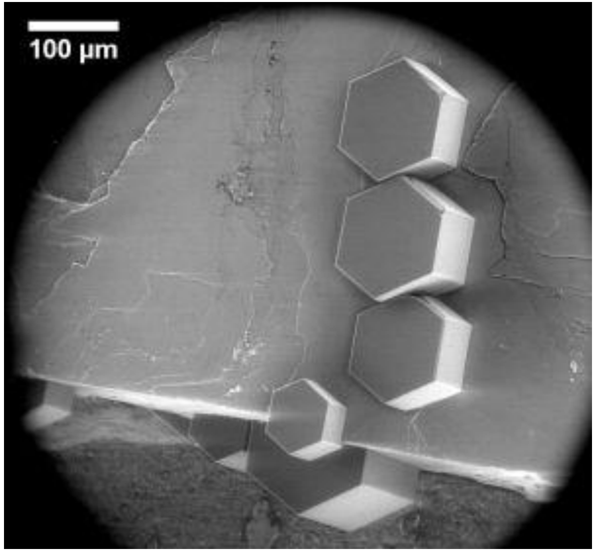
•**Active surface sites:** Defects, steps, cracks and chemically altered areas on the feldspar surface create a small number of **highly active nucleation sites** where ice first forms.

•**Water structuring:** Hydrophilic surface groups and dissolved ions (K^+, Na^+, Ca^{2+}) organize adjacent water into semi-ordered layers, making it easier for that layer to transform into ice.

•**Relevant freezing modes:** Feldspar grains are especially effective INPs in **immersion and condensation freezing**, triggering ice at mixed-phase cloud temperatures (roughly –10 to –30 °C).

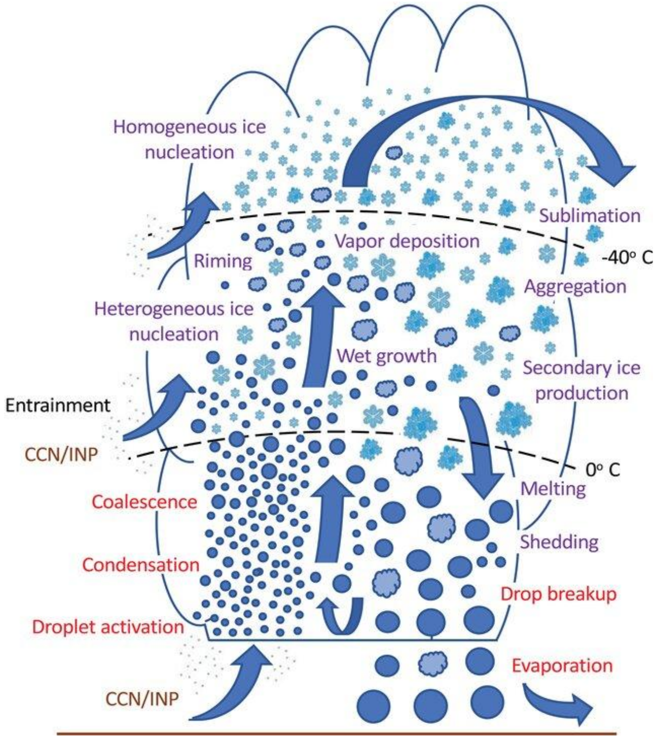
•**Mineralogy dependence: K-feldspar is much more ice-active than most other feldspars and quartz**, so even a modest K-feldspar fraction in dust can dominate its overall INP activity.

K-feldspar



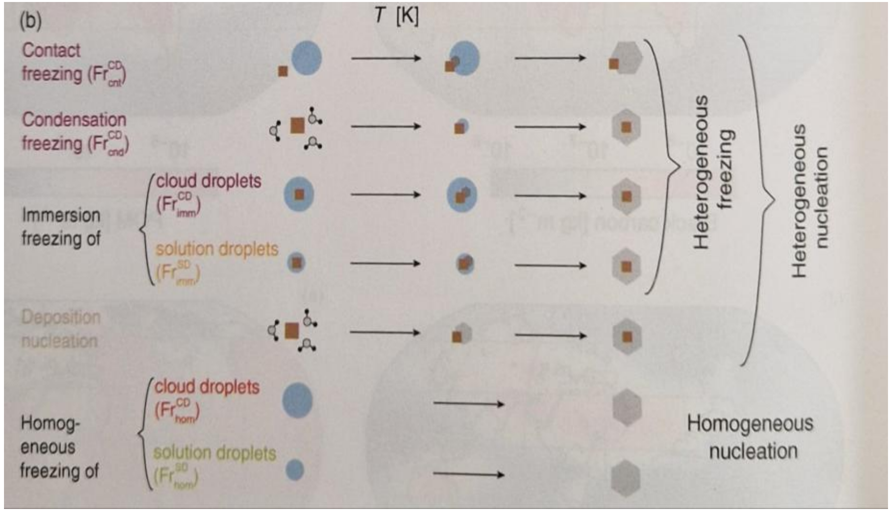
(Photo: Alexei Kiselev and Dagmar Gerthsen, KIT)

Complexity of cloud microphysics



Morrison, et al. (2020)

Ice Nucleation mechanisms

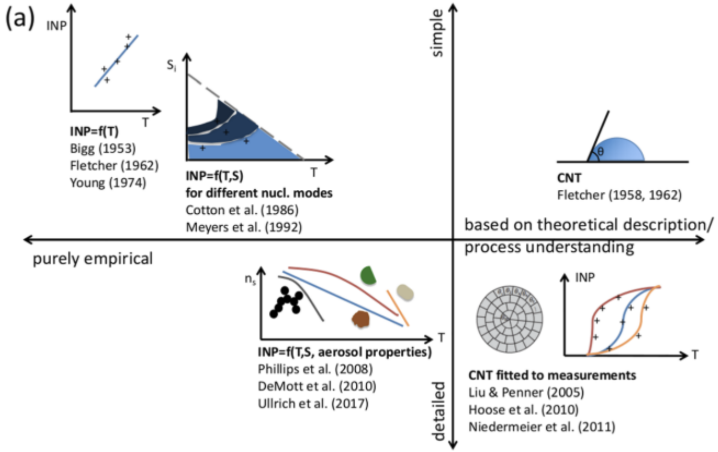


Lohmann, et al. (2016)

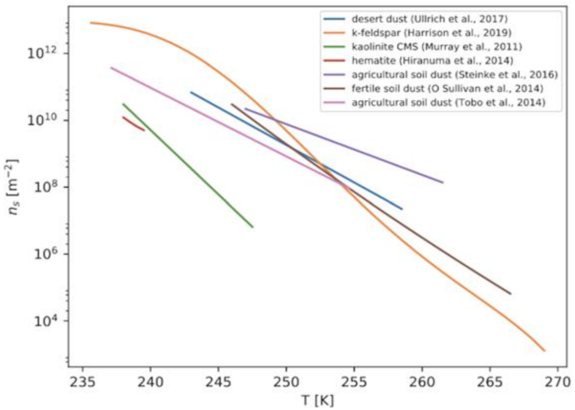
Representation of nucleation in models

Microphysical processes in cold clouds

Heterogeneous ice nucleation parameterizations with different complexities

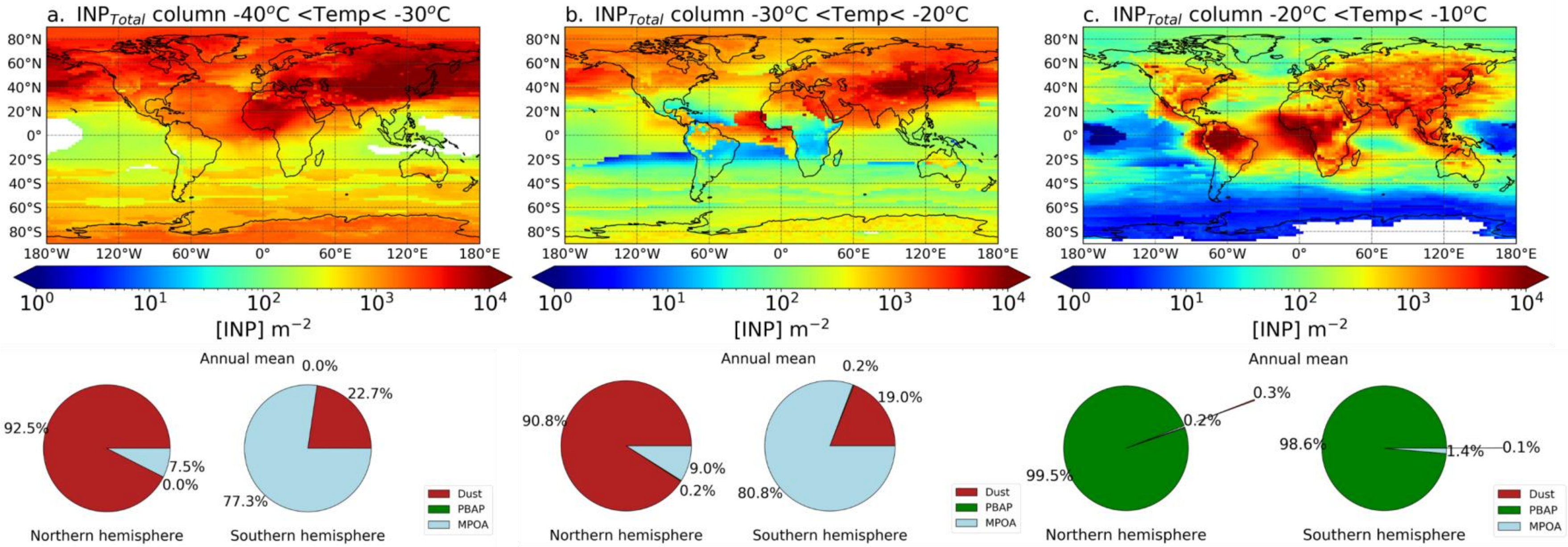


Recent empirical INP parameterizations as a funtion of temperature normalized by aerosol surface area for different types of mineals, desert dust, and soil dust.



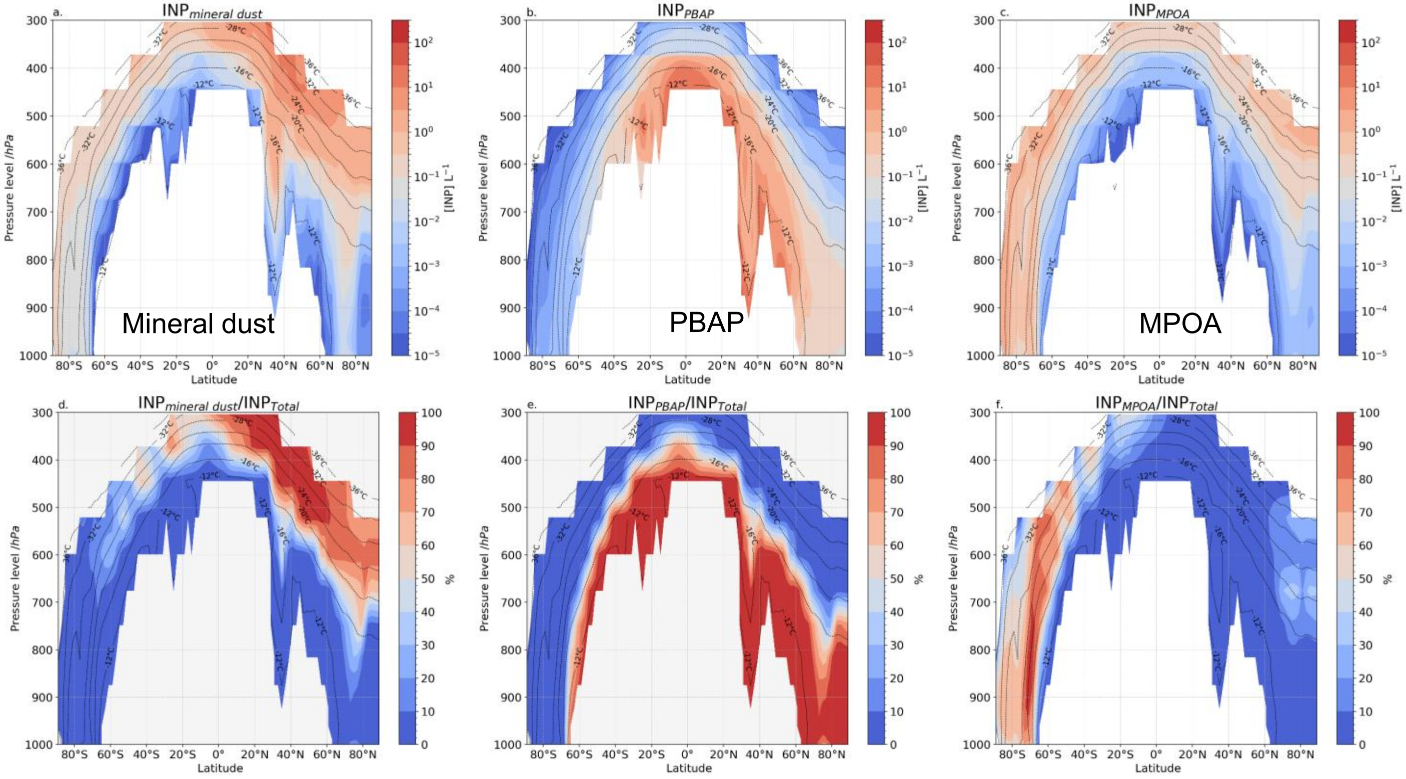
Morrison, et al. (2020)

The global contribution of dust to INP concentrations



Chatziparaschos et al. (2025)

The global contribution of dust to INP concentrations



Chatziparaschos et al. (2025)

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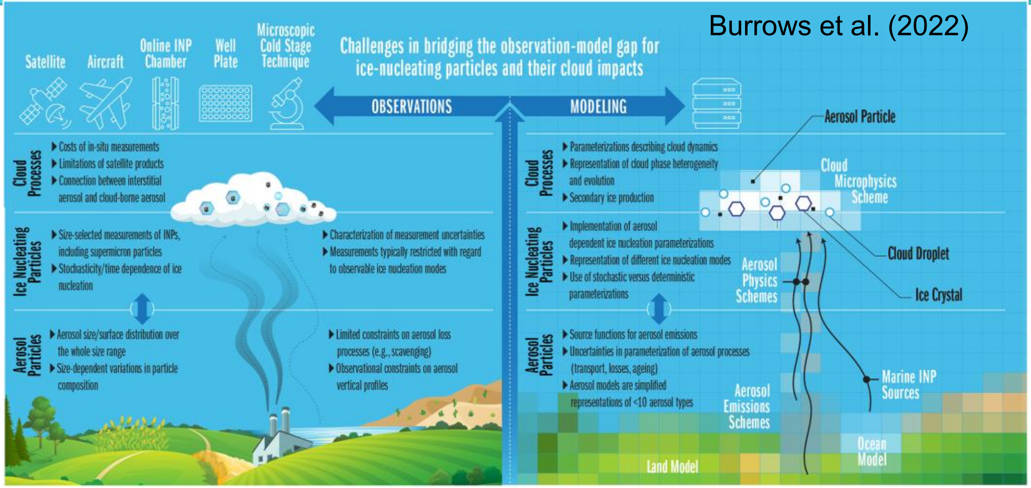
Key challenges

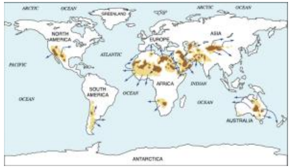
- How can we tackle some of (not all!) uncertainties related to effect of dust on mixed-phase and cold clouds and associated radiative forcing?

- From emission to INP concentrations



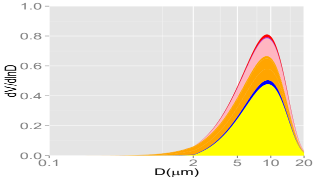
Burrows et al. (2022)

Dust sources and emission

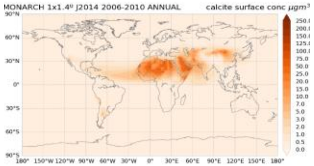


Soil mineralogy

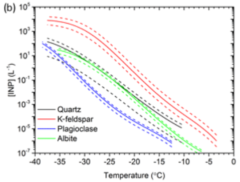
Emitted PSD and mixing state of minerals



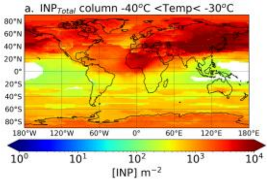
Transport and ageing of minerals



Mineralogy sensitive INP schemes



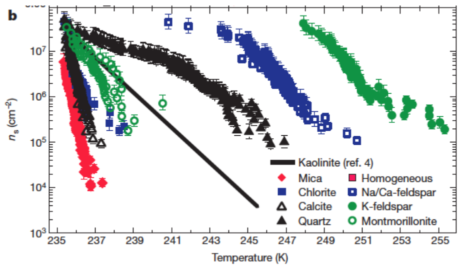
3D INP concentration



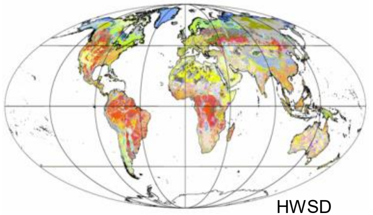
Soil mineralogy

Current status and challenges

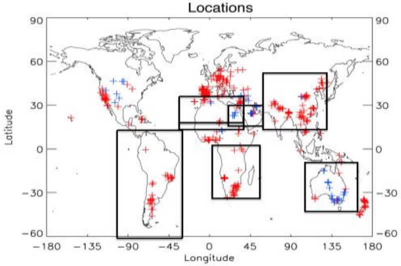
- Dust INP efficiency depends upon mineralogy: (K-)feldspar stands out and quartz to a lesser extent
- The majority of climate models omit variations in mineralogy
- Those experimentally including mineralogy use Claquin et al. (1999) or Journet et al. (2014)
- These maps use massive extrapolation based on soil unit/type and a number of assumptions to overcome the lack of data



Atkinson et al. (2017)



FAO soil types

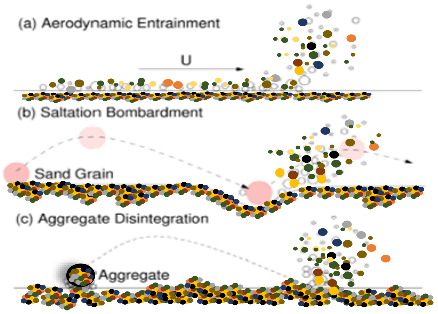


Mineral maps constrained with few observations

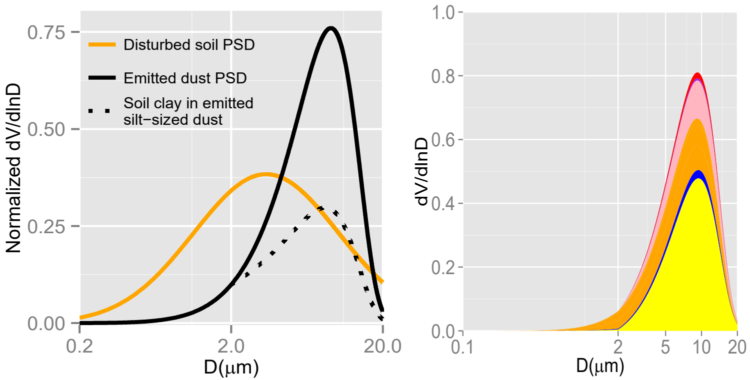
Emitted PSD and mixing state of minerals

Current status and challenges

- Lack of experimental studies tackling the relationship of the emitted PSD and soil-surface mineralogy
- Soil analysis based upon wet sieving disturbs the soil samples
- General lack of quantitative knowledge of mixing state of minerals
- PSD of emitted minerals in models currently based on Brittle Fragmentation theory



Adapted from Shao (2008)

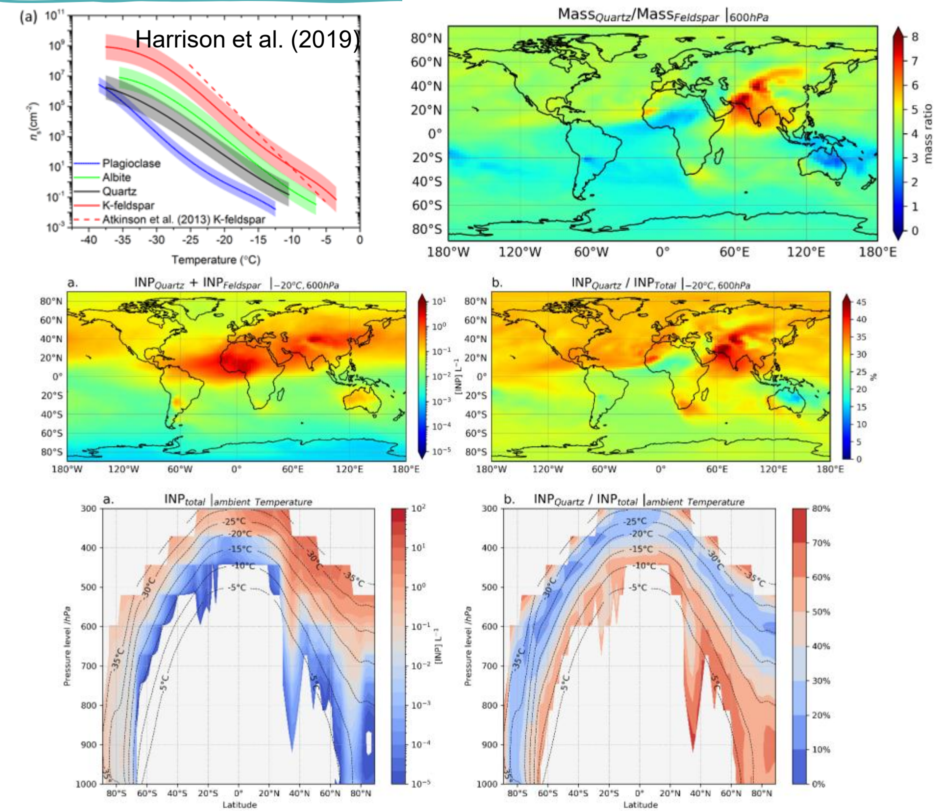


Kok, 2011 ; Perlwitz et al. 2015

Current status of K-Feldspar/quartz contributions to global dust INP

Current status

- Quartz particles have lower ice-active density but are much more abundant in airborne dust than K-feldspar
- K-feldspar remains the most important contributor to INP concentrations globally,
- The contribution of quartz can also be significant, particularly at lower altitudes.

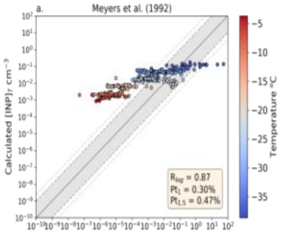


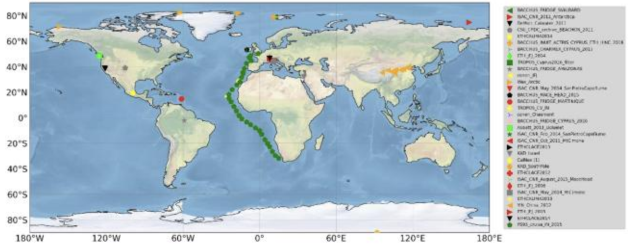
Chatziparaschos et al. (2023)

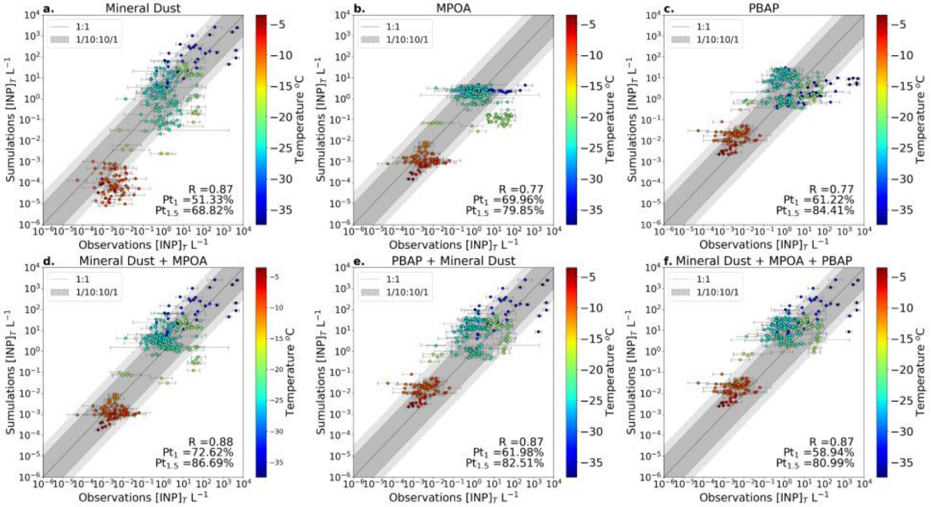
Evaluation against INP observations (together with other relevant INP)

Current status

- Aerosol sensitive scheme outperforms temperature-only sensitive schemes
- Dust (K-feldspar, quartz) and MPOA performs best compared with observations
- PBAP INPs contrubute to overestimation of INP in our model





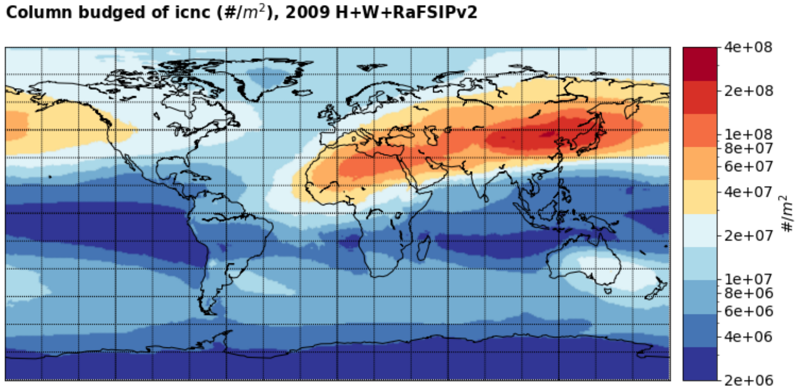


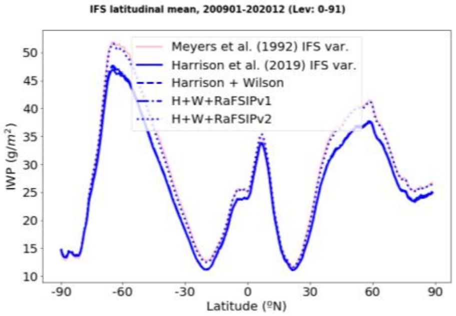
Chatziparaschos et al. (2025)

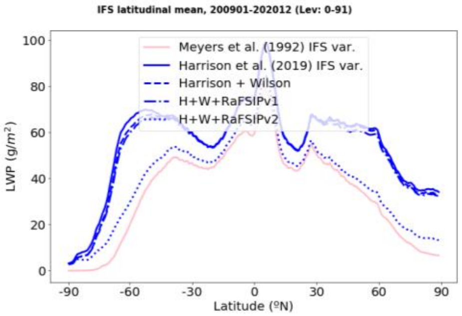
ICNC, IWP and LWP with current aerosol-sensitive INP schemes

Current status

- Results in EC-Earth3: ICNC distributions when considering dust, and MPOA and secondary ice production
- We can achieve relatively similar results than the temperature-only scheme for IWP and LWP only when we consider secondary ice production





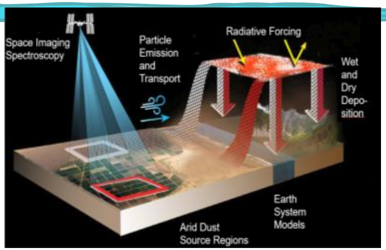


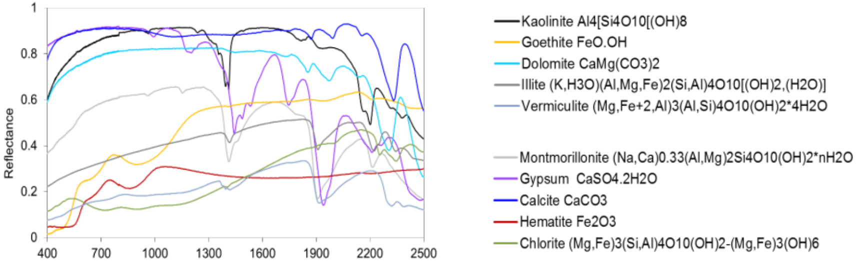
Costa-Surós et al. (2025 in review)

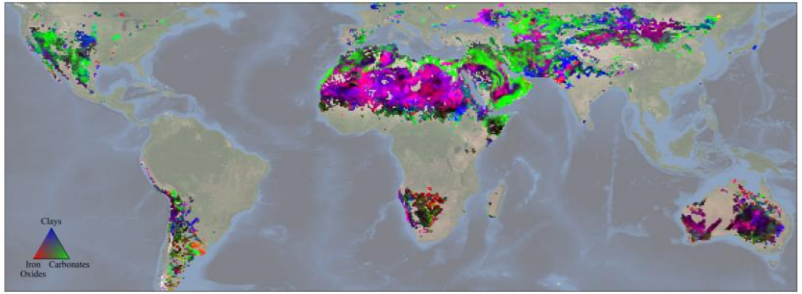
Soil mineralogy

Opportunities

- EMIT began measuring from the ISS in July 2022
- EMIT uses imaging spectroscopy and identifies soil dust minerals due to their distinct spectral signatures (60m resolution)
- First release of global maps for ESMs done.
- *Deriving abundances requires some modeling and estimates of mineral sizes*
- *Limitation: VSWIR only, therefore quartz and feldspar not directly observed, and only infered.*







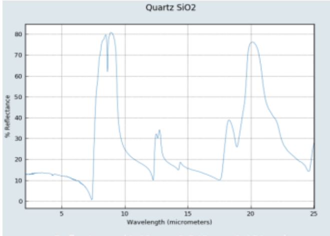
Green et al. (2022), Thompson et al. (2024), Clark et al. 2024
And more

Soil mineralogy

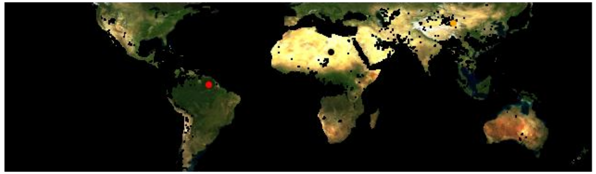
Opportunities

- Hybrid MODIS and ASTER - (0.05 deg)
- Combined VSWIR and TIR
- Tailored to quartz and feldspar fractions
- To be combined with EMIT

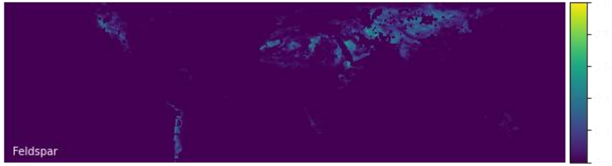
Full Range ECOSTRESS/USGS Spectral Library
(VSWIR and TIR resampled at MODIS spectral resolution)

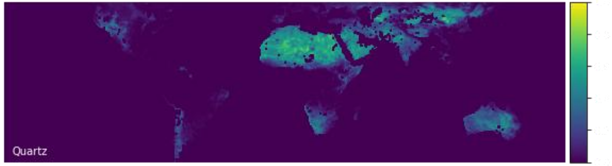


Hybrid MODIS and ASTER Remotely Sensed Data



Quartz and Feldspar Fractions & Uncertainties



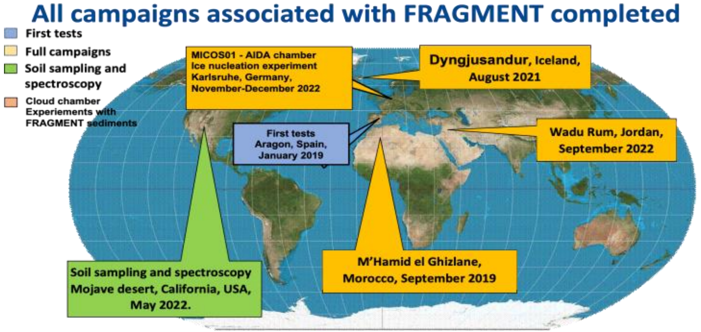


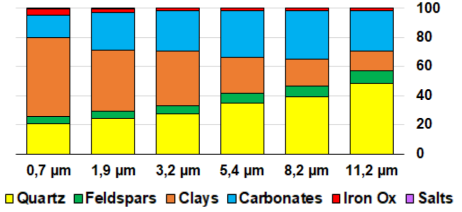
Grant et al. (2025 in review)

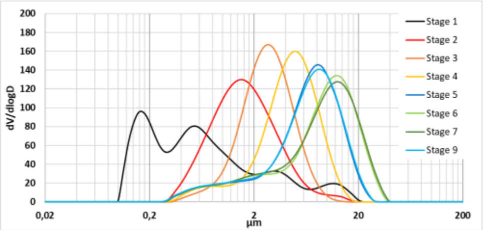
Soil mineralogy

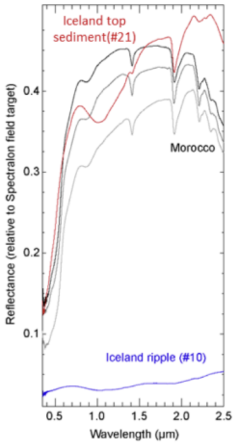
Opportunities

- Evaluation and improvement of soil mineral maps
- Tailored soil sampling campaigns in the context of the FRAGMENT Project
- More than 350 samples analyzed including dry and wet PSD analyses, XRD mineralogy, iron mode of occurrence
- Analysis size-segregated sub-samples
- Combined with in-situ and lab spectroscopy









Gonzalez-Romero et al. (2023, 2024)

Emitted PSD and mixing state of minerals

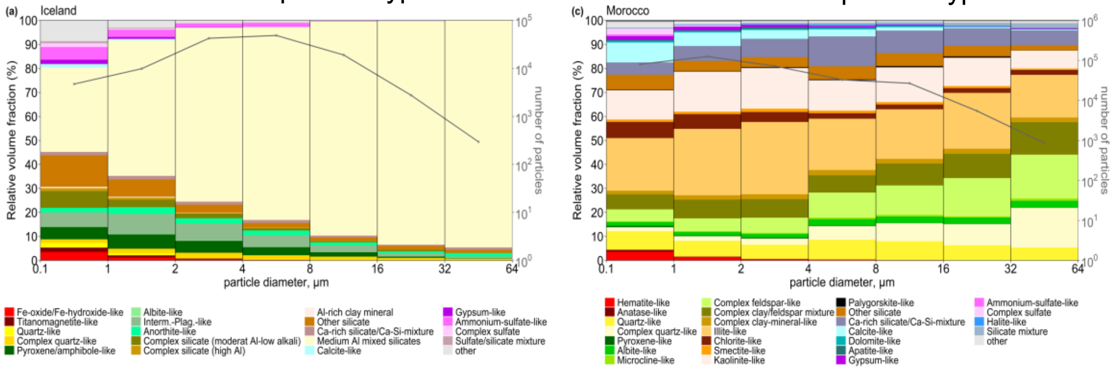
Opportunities

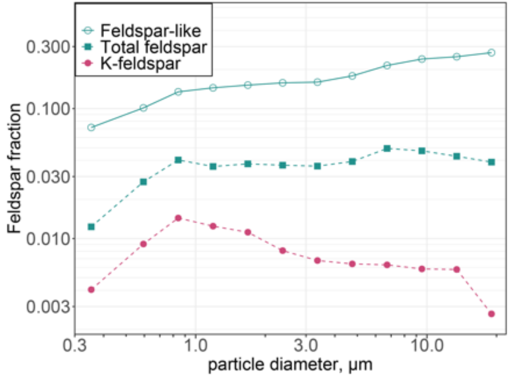
- New constraints on the emitted PSD of minerals based on SEM of freshly emitted dust

- New constraints on size-dependent mixing state of K-feldspar

Iceland particle types

Morocco particle types

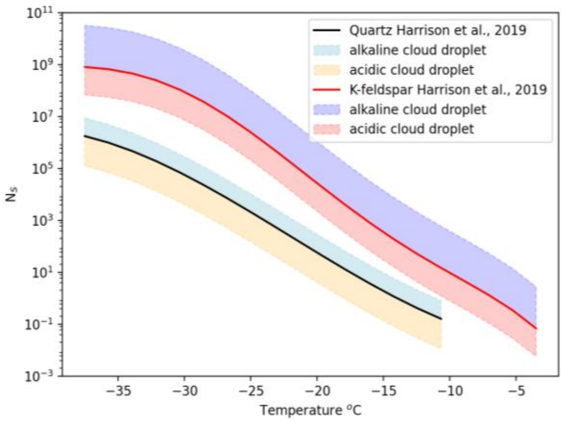




Panta et al. (2023) and Panta et al. (2025)

Mineralogy, size (and ageing) sensitive schemes

- Very few experimental studies on ageing, mixing state and particle size effects upon INP efficiency.
- Lack of modeling studies
- Studies tend to show enhancement under alkaline conditions and suppression under acidic conditions (although highly uncertain)
- We need more data and knowledge but simple schemes that are consistent with the few observations we have could be tested in modeling sensitivity studies to understand its potential significance



Potential simple scheme ($n_s = \ln(1 - FF)\,/A$) with FF dependent on ratio of ammonium to sulfate in cloud droplets (Courtesy M. Chatziparaschos)

Dust effects on clouds: Bibliography

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