

# Impacts of Arctic warming on ice nucleating particles from 1981 to 2020: Distributions and contributions of dust, marine organic aerosols, and bioaerosols

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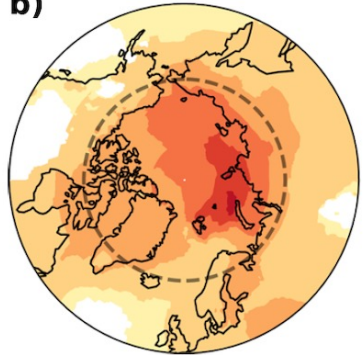
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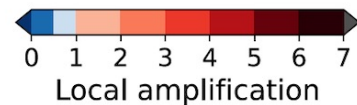
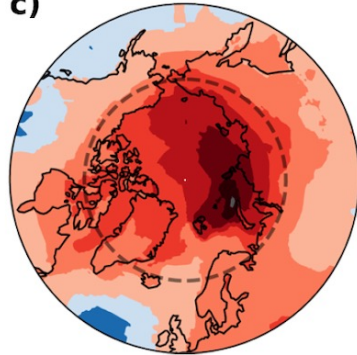
# Arctic Warming

1979 – 2021

b)



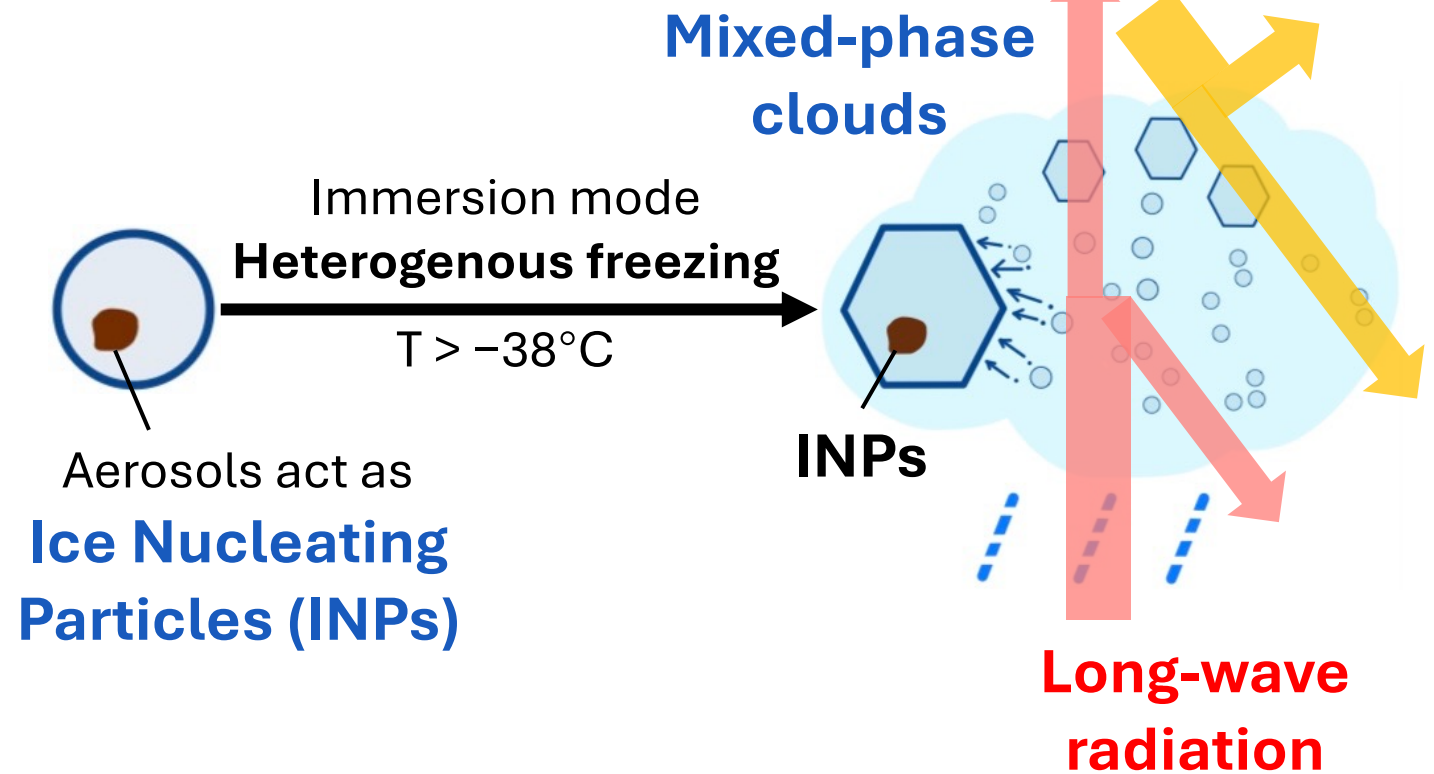
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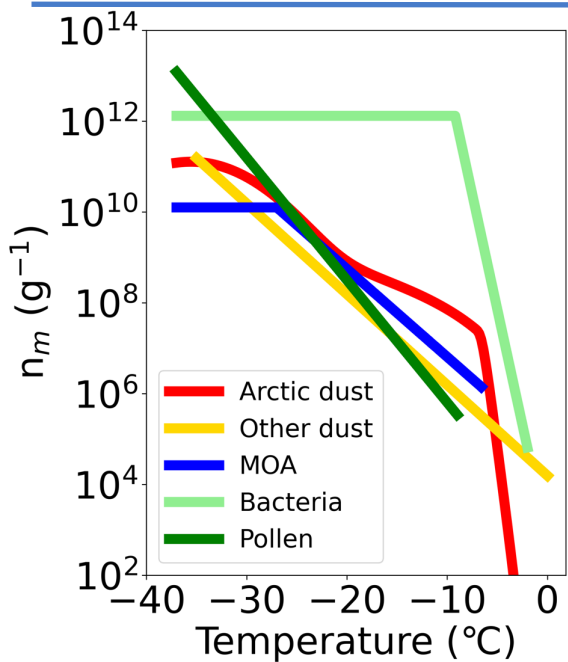


(Arctic warming /  
Global warming)

# Ice Nucleation of clouds by INPs

In the middle and lower  
troposphere at high latitudes





### Ice Nucleating Ability (INA):

The density of ice nucleation active sites per unit mass ( $n_m$ ).

**INA of aerosols**



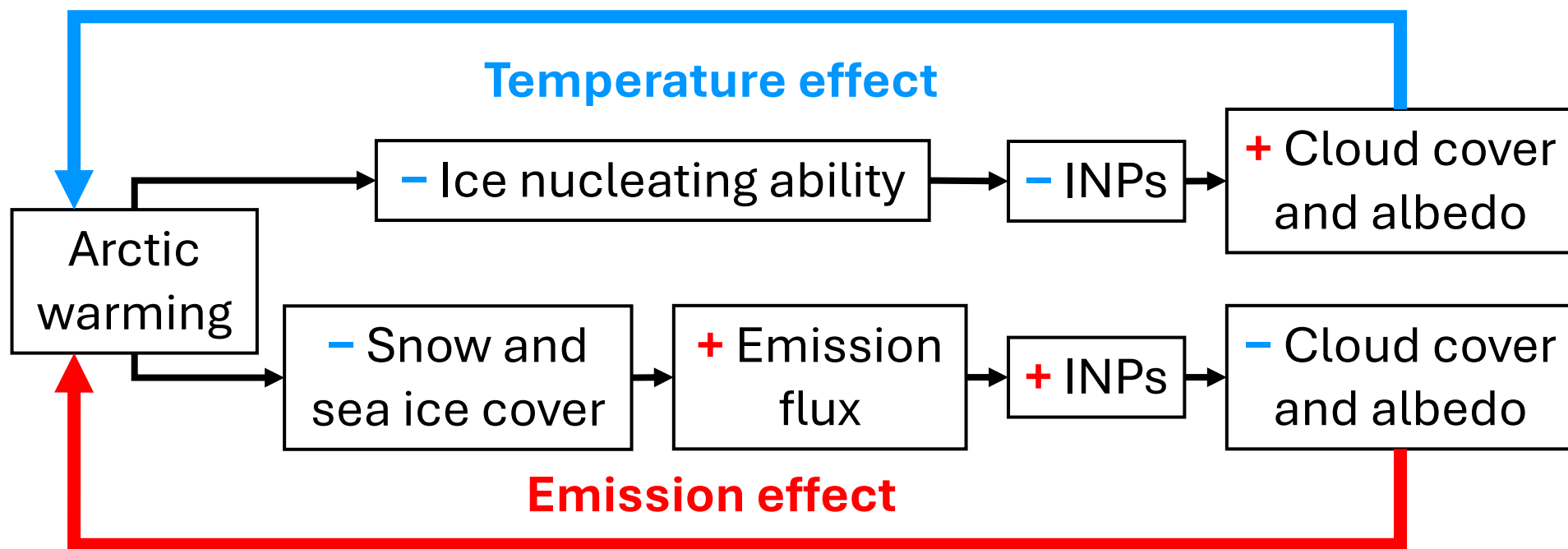
Marine organic aerosol (MOA)

Bioaerosols

Dust

Glacier

**Emission of aerosols**



Land

## Limitations of Previous Studies:

- There are few modeling studies comprehensively consider **INP sources** (dust, MOA and bioaerosols) and their **ice nucleating abilities (INA)**.
- It remains unclear how **INPs respond to Arctic warming**.



**Comprehensively consider multiple aerosol sources and their effects on ice nucleation.**

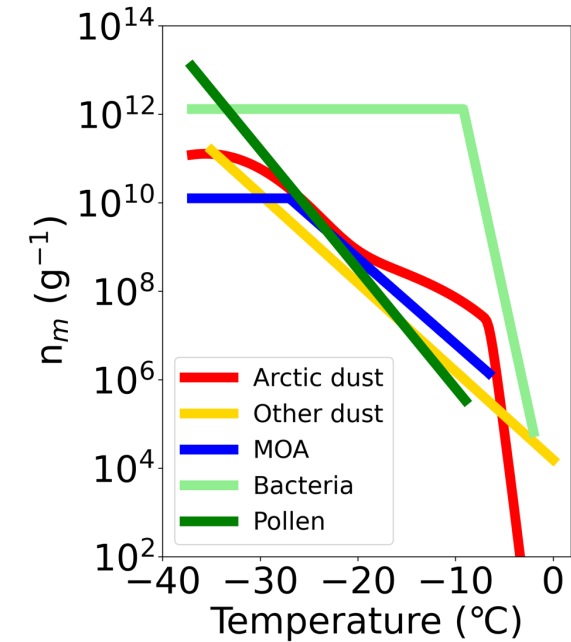
## **Research Objectives**

- To evaluate the **contribution** of individual aerosol species to ice nucleation in Arctic lower-tropospheric clouds.
- To understand the **changes** in aerosols and their effects on ice nucleation in the Arctic by Arctic warming (from 1981 to 2020).

## Models: CAM-ATRAS and CLM in CESM

(Matsui, 2017; Matsui and Mahowald, 2017)

	Emissions	INPs (in clouds)
	Calculated online	
<b>Dust</b>	Calculated from meteorological and surface conditions (e.g., wind speed, snow/ice cover, vegetation cover)	Calculated from aerosol concentrations, INA, temperature and cloud fraction.
<b>MOA</b>		
<b>Bioaerosols</b>		



**Emissions:** Kok, Albani, et al., 2014; Kok, Mahowald, et al., 2014; Burrows et al., 2013; Wilson et al., 2015; Hoose et al., 2010.

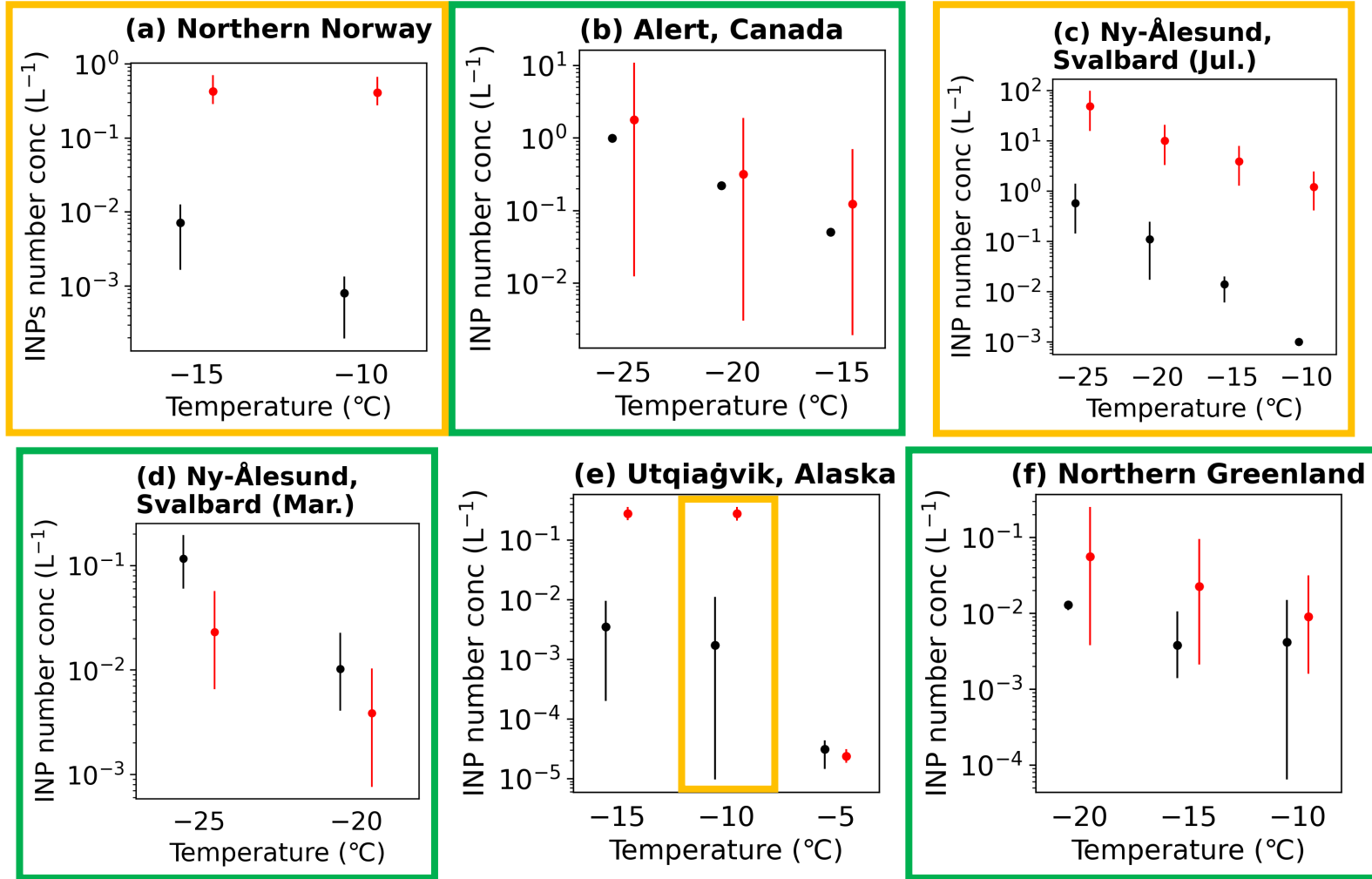
**INPs:** Tobo et al., 2019; Kawai et al. 2023; DeMott et al., 2015; Wilson et al., 2015; Diehl et al., 2015; Hummel et al., 2018.

<b>Arctic aerosols</b>	Aerosols (dust, MOA, and bioaerosols) emitted from the Arctic (>60°N)	➔ <b>Arctic INPs</b>
<b>Non-Arctic aerosols</b>	Aerosols emitted from the non-Arctic region (<60°N)	➔ <b>Non-Arctic INPs</b>
<b>Total aerosols</b>	Aerosols emitted globally (=Arctic aerosols + Non-Arctic aerosols)	➔ <b>Total INPs</b>

Arctic aerosols and non-Arctic aerosols are separately calculated in the model

Observation —

Simulation —

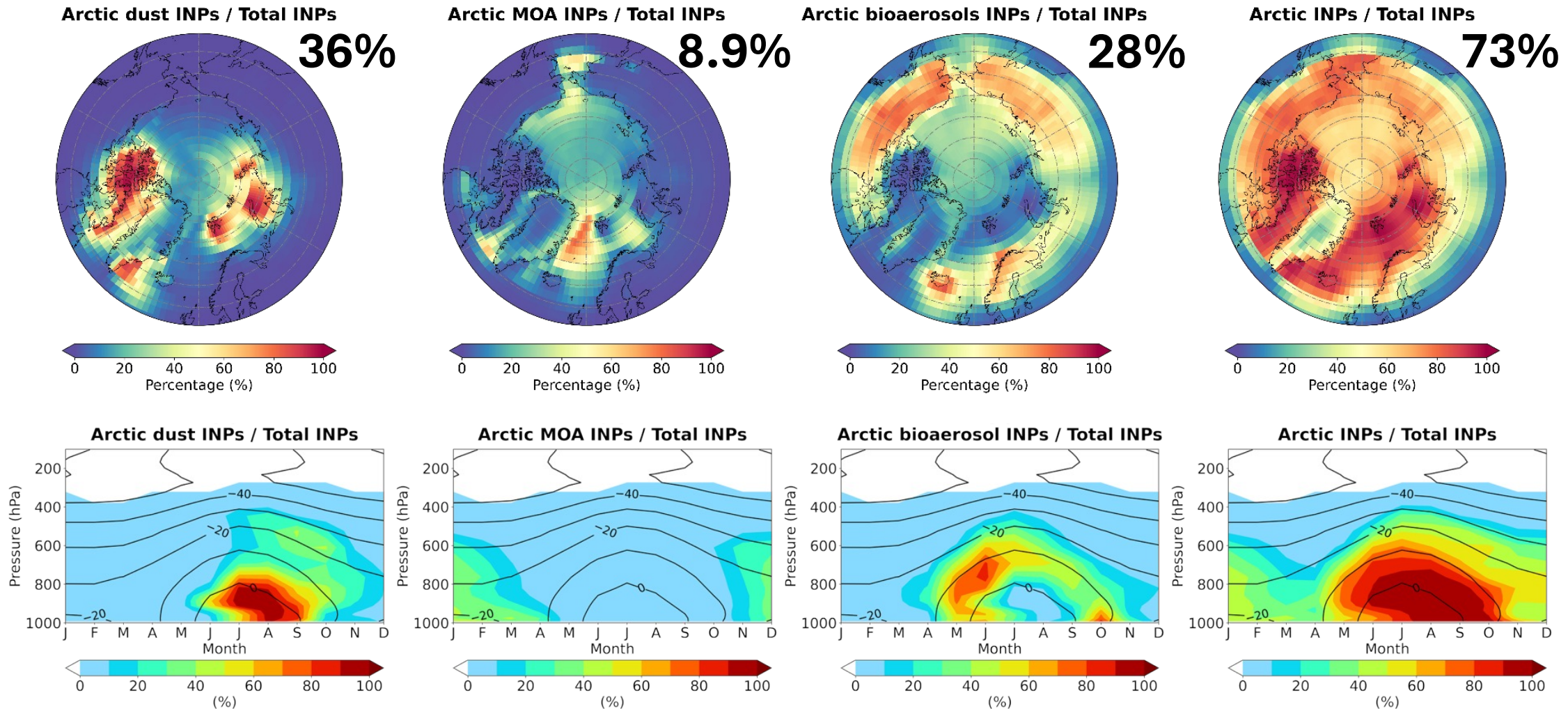


At Alert, Ny-Ålesund (March), and northern Greenland, the model reproduces observed INP concentrations well.

- The model **overestimates** the number concentration of **bacteria INPs** at -15°C and -10°C.
- At Ny-Ålesund (July), the overestimation may be due to the overestimation of dust emissions around the Svalbard (*Kawai et al., 2023*).

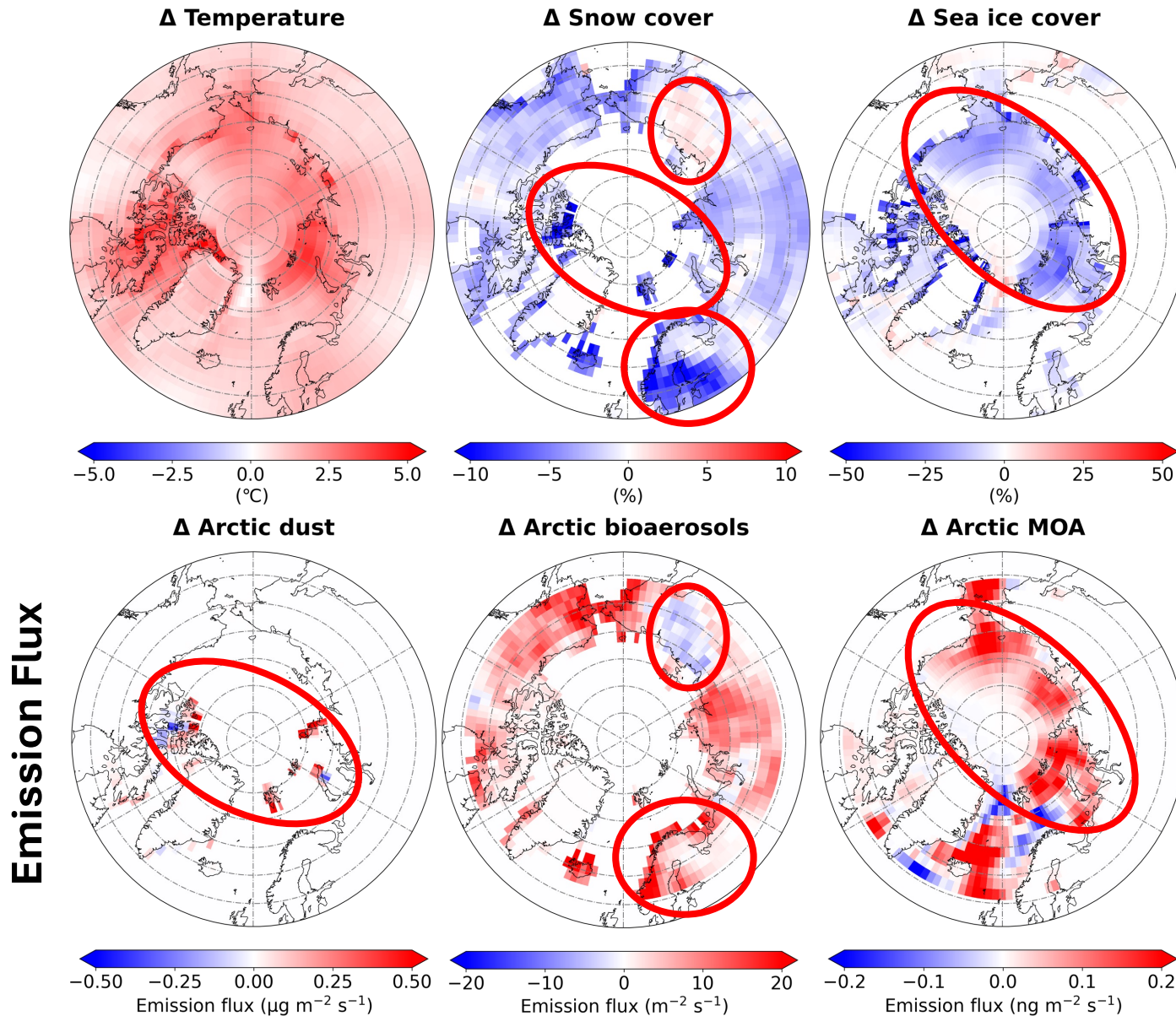
Lower troposphere (&gt;730 hPa)

1981 ~ 2020



- Arctic INPs dominate total INPs in most regions of the lower Arctic troposphere.
- Each species of INPs exhibiting distinct spatial and seasonal patterns.

## Changes from the 1981–1990 average to the 2011–2020 average

Arctic average change

- Temperature: **+ 1.6°C**
- Snow cover: **- 2%**
- Sea ice cover: **- 7%**

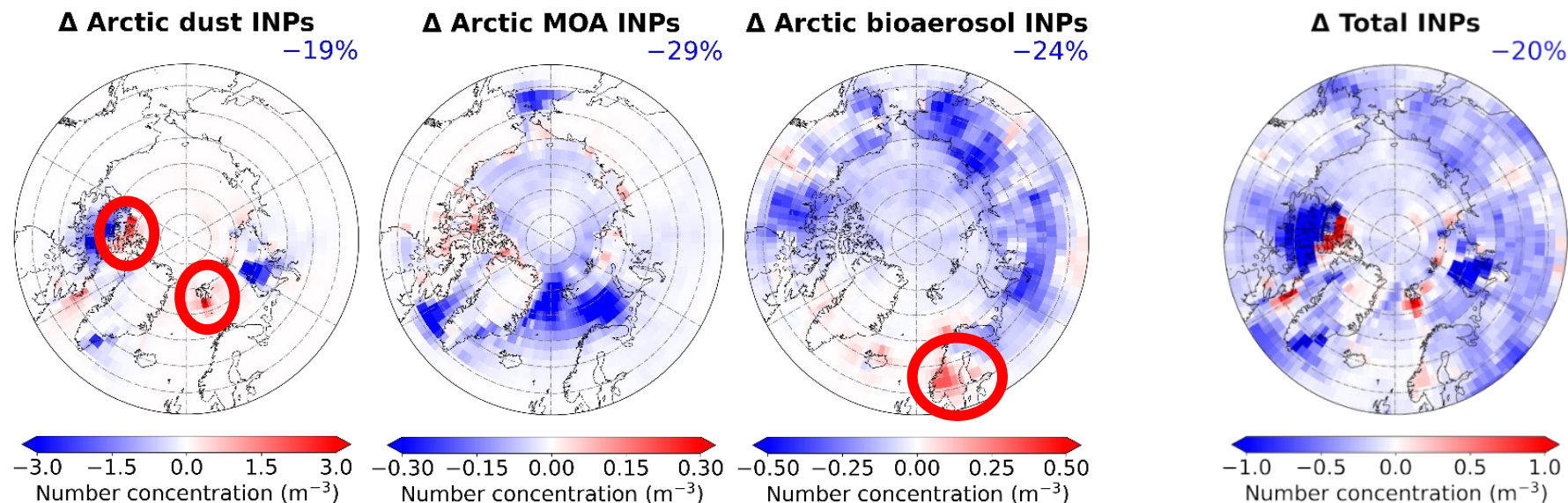
Rate of change

- Arctic dust emission: **+ 18%**
- Arctic bioaerosols emission: **+ 4.7%**
- Arctic MOA emission: **+ 9.4%**

From 1981 to 2020, the **retreat** of snow cover and sea ice driven by Arctic warming has led to **increased** emissions of Arctic dust, Arctic MOA, and Arctic bioaerosols.

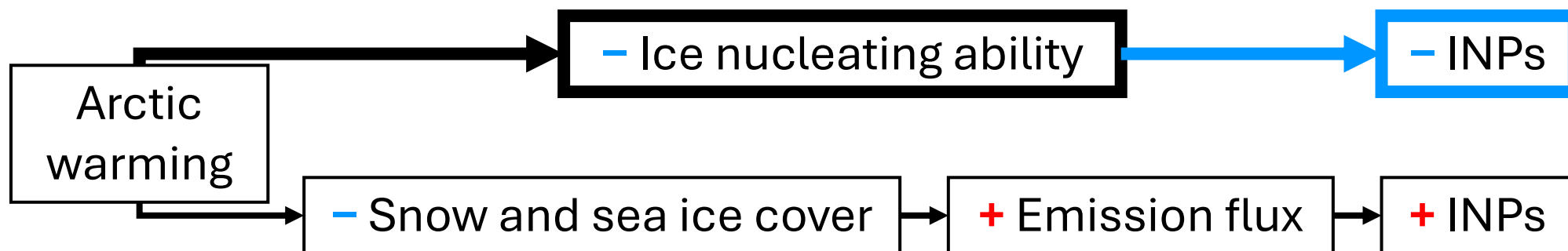
Lower troposphere (>730 hPa)

## Changes from the 1981–1990 average to the 2011–2020 average



### Rate of change

- Arctic dust INPs:  $-19\%$
- Arctic bioaerosols INPs:  $-24\%$
- Arctic MOA INPs:  $-29\%$



INPs show **reductions** in all regions, except in some regions with the largest increase in emissions, where INPs increase.

- **Arctic-sourced INPs** account for more than **70%** of total INPs in the Arctic lower-tropospheric (> 730 hPa) clouds. **Dust** is the largest contributor (**36%**), followed by **bioaerosols** (**28%**) and **MOA** (**9%**), with each species exhibiting **distinct spatial and seasonal patterns**.
- Arctic warming **increases** local **emissions** of all three aerosol species by **4.7–18%** because of the retreat of snow and sea ice. Nevertheless, **INP concentrations** in the Arctic lower-tropospheric clouds **decline** by **19–29%**, primarily because of the lower ice nucleating ability at higher temperatures.

Average in the Arctic lower troposphere (>730 hPa)

Contribution to total INPs

