

General comments:

In this paper, the authors present a comprehensive study on simulating the global distribution of dust and marine ice-nucleating particles (INPs) using the UK Earth System Model (UKESM1). They incorporate two important INP types, namely dust and marine organic aerosols, into the model and evaluate the simulations against an expanded global dataset of INP measurements. Furthermore, they found that soil dust might be an important INP source which was not considered in the current model. The paper is well-structured and clearly written. The methodology is sound, and the results are presented in a logical and convincing manner. The study makes a significant contribution to understanding the global distribution of INPs and identifying potential gaps in current INP representations in climate models. The paper is a valuable contribution to the field and provides useful insights into the gaps in our understanding of INP sources and their representation in climate models. I recommend publication after addressing the following comments:

Model evaluation using satellite observations:

The authors demonstrate the model's skill in capturing the spatial and temporal variability of INP concentrations through a thorough comparison with observations from diverse geographical locations and seasons. However, as the authors acknowledge, the current INP observations are primarily short-term campaign measurements, lacking long-term continuous time series. Relying solely on these ground-based INP observations may not be sufficient for a comprehensive evaluation of the model's performance. To address this limitation, I suggest that the authors consider utilizing satellite remote sensing data to further validate their model results. Satellites can provide valuable information on cloud phase and cloud-top temperature, which can be used to infer the threshold temperature for immersion freezing INPs (Carlsen et al., 2022). This satellite-based diagnostic approach can help identify potential INP sources on a global scale, complementing the ground-based observations. The authors should discuss the advantages and limitations of using satellite data for model validation in their discussion section.

Potential role of anthropogenic pollution in the Northern Hemisphere mid to high latitudes:

The most intriguing finding of this study is the discrepancy between the observed and modeled ice-nucleating particle (INP) concentrations in the mid to high latitudes of the Northern Hemisphere, particularly at higher temperatures. The authors suggest that soil dust may be an overlooked source of INPs in these regions. This insight opens up a new avenue for investigation and highlights the need to better understand the role of different INP sources in the global context. However, it is important to note that the mid to high latitudes of the Northern Hemisphere are also heavily influenced by anthropogenic pollution. While the contribution of anthropogenic pollutants to INP concentrations is still a matter of ongoing research and debate, there is evidence from satellite observations and field measurements that cannot be ignored. Satellite-based studies have shown that polluted regions tend to exhibit higher ice nucleation threshold temperatures, indicating a potential impact of anthropogenic emissions on ice formation processes (Zhao et al., 2019). Additionally, some recent observation found that organic aerosols in anthropogenically influenced areas can importantly contribute to INP

concentrations (Tian et al., 2022). These studies should be referenced for more comprehensive explanations of your results.

Given these findings, I suggest that the authors consider the potential role of anthropogenic pollution in their analysis and discussion. While soil dust may indeed be an important and overlooked source of INPs, the influence of anthropogenic pollutants should not be dismissed, especially in regions where their concentrations are high. The authors could strengthen their argument by addressing this aspect and discussing how the relative contributions of soil dust and anthropogenic pollutants to INP concentrations might vary spatially and temporally. By considering the potential role of anthropogenic pollution alongside soil dust, the authors can provide a more comprehensive analysis of the factors contributing to the observed discrepancies in INP concentrations in the Northern Hemisphere mid to high latitudes.

Reference:

Carlsen, T., & David, R. O. (2022). Spaceborne evidence that ice-nucleating particles influence high-latitude cloud phase. *Geophysical Research Letters*, 49, e2022GL098041. <https://doi.org/10.1029/2022GL098041>.

Zhao, B., Wang, Y., Gu, Y. et al. Ice nucleation by aerosols from anthropogenic pollution. *Nat. Geosci.* 12, 602–607 (2019). <https://doi.org/10.1038/s41561-019-0389-4>

Tian, P., Liu, D., Bi, K., Huang, M., Wu, Y., Hu, K., et al. (2022). Evidence for anthropogenic organic aerosols contributing to ice nucleation. *Geophysical Research Letters*, 49, e2022GL099990. <https://doi.org/10.1029/2022GL099990>