

From Europe to the Arctic: Observational Evidence of Aerosol-Induced Heating Gradients and Their Role in Arctic Amplification

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Abstract

The rapid warming of the Arctic—occurring at a rate nearly four times faster than the global average—is a hallmark of climate change known as Arctic Amplification (AA, Rantanen et al. 2022). Despite extensive study, many mechanisms behind AA remain uncertain, particularly those involving long-range energy transport (Previdi et al. 2021). Among these, the role of atmospheric aerosols—specifically Light-Absorbing Aerosols (LAA) such as black carbon, brown carbon, and mineral dust—has emerged as a key but poorly understood driver (Schmale et al. 2021). While modeling studies have hypothesized that aerosol-induced heating at lower latitudes enhances poleward atmospheric energy transport (AET, Shindell and Faluvegi 2009), direct observational evidence has been lacking (Schmale et al. 2021).

This study addresses this gap by presenting novel experimental data collected during four scientific research cruises conducted between 2018 and 2022 aboard the R/V Oceania (Institute of Oceanology, Polish Academy of Sciences). The cruises covered latitudinal transects from mid-latitude Europe (Gdańsk, Poland) to the Arctic Ocean (up to 80 °N), including both summer and winter seasons. Measurements included aerosol absorption coefficients and incident solar radiation, which were used to calculate LAA-induced heating rates (HR) and the associated Atmospheric Power Surplus (APS)—a quantifiable metric of atmospheric energy accumulation.

Our study provides the first direct observational evidence showing how the heating effect of LAA decreases from Europe toward the Arctic. As we moved northward, we observed a clear and consistent drop in the amount of atmospheric warming caused by these aerosols. This pattern was especially visible during summer, with the strongest warming near continental Europe and a sharp decline as we approached the Arctic Ocean. In winter, the warming effect nearly disappeared in high latitudes.

This latitudinal pattern also translated into differences in how much extra energy the atmosphere retained due to LAA. Near Europe, the atmosphere gained significantly more energy compared to the Arctic, where this surplus became minimal. The difference was striking, showing that the energy accumulated in the lower atmosphere near Europe can be more than a hundred times greater than in the far North.

By applying an energy balance model, we found that this difference in energy input could help explain why the Arctic is warming more strongly than mid-latitude regions—even in places where there are no significant local emissions (Shindell and Faluvegi 2009). Our results suggest that aerosols emitted far from the Arctic, especially from mid-latitudes, can still influence Arctic warming by altering the balance of atmospheric energy and enhancing northward energy transport (Sand et al. 2013).

These findings provide valuable experimental confirmation for a theory that has so far relied mainly on modeling studies: that distant pollution sources can affect climate in remote regions like the Arctic (Navarro et al. 2016). Our work highlights the importance of considering the global impact of regional emissions and points to the need for international efforts to reduce emissions of light-absorbing aerosols, particularly black carbon, to protect the fragile Arctic climate system (Laskin et al. 2015).

Acknowledgments. This research was supported by the National Science Center grant SMART (grant no. 2023/49/B/ST10/00513) and the Polish National Agency for Academic Exchange (grant no. BPN/BEK/2024/1/00044).

The manuscript containing the full results of this research has been submitted to Nature Communications and is presently undergoing the review process (Ferrero et al., manuscript assignment NCOMMS-24-48156-T).

References

- Laskin, A., J. Laskin, and S.A. Nizkorodov (2015), Chemistry of atmospheric brown carbon, *Chem. Rev.* **115**, 10, 4335–4382, DOI: 10.1021/cr5006167.
- Navarro, J.C.A., V. Varma, I. Riipinen, Ø. Seland, A. Kirkevåg, H. Struthers, T. Iversen, H.-C. Hansson, and A.M.L. Ekman (2016), Amplification of Arctic warming by past air pollution reductions in Europe, *Nat. Geosci.* **9**, 277–281, DOI: 10.1038/ngeo2673.
- Previdi, M., K.L. Smith, and L.M. Polvani (2021), Arctic amplification of climate change: a review of underlying mechanisms, *Environ. Res. Lett.* **16**, 093003, DOI: 10.1088/1748-9326/ac1c29.

- Rantanen, M., A.Yu. Karpechko, A. Lipponen, K. Nordling, O. Hyvärinen, K. Ruosteenoja, T. Vihma, and A. Laaksonen (2022), The Arctic has warmed nearly four times faster than the globe since 1979, *Commun. Earth Environ.* **3**, 168, DOI: 10.1038/s43247-022-00498-3.
- Sand, M., T.K. Berntsen, J.E. Kay, J.F. Lamarque, Ø. Seland, and A. Kirkevåg (2013), The Arctic response to remote and local forcing of black carbon, *Atmos. Chem. Phys.* **13**, 1, 211–224, DOI: 10.5194/acp-13-211-2013.
- Schmale, J., P. Zieger, and A.M.L. Ekman (2021), Aerosols in current and future Arctic climate, *Nat. Clim. Change* **11**, 95–105, DOI: 10.1038/s41558-020-00969-5.
- Shindell, D., and G. Faluvegi (2009), Climate response to regional radiative forcing during the twentieth century, *Nat. Geosci.* **2**, 294–300, DOI: 10.1038/ngeo473.

Received 15 September 2025

Accepted 20 October 2025