How ships affect atmospheric observations in their vicinity

Large-eddy simulation study on the wake of RV Polarstern and its effects on in-situ observations during MOSAiC

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In Short

- Turbulence- and ship-resolving simulations based on the yearlong Arctic MOSAiC expedition
- Statistical analysis and comparison between simulations and observations
- Investigation of the ship's interaction with the atmospheric flow and its wake's structure

The Arctic atmospheric boundary layer (ABL) affects current and future Arctic warming, which, in turn, is an early warning system for climate change [1]. Persistent atmospheric conditions and the lack of complex topography and diurnal cycles cause the Arctic ABL to provide many distinct and nearly idealized cases for analysis and investigation. Despite these favorable conditions, corresponding field studies are sparse compared to lower latitudes—mainly due to its remote location and harsh weather, especially during the Arctic winter. In 2019 and 2020, the MOSAiC expedition took place to inject our understanding of Arctic warming, including the Arctic ABL. Therefore, the research vessel *Polarstern* drifted for one year attached to an ice shell through the Arctic ocean [2,5].

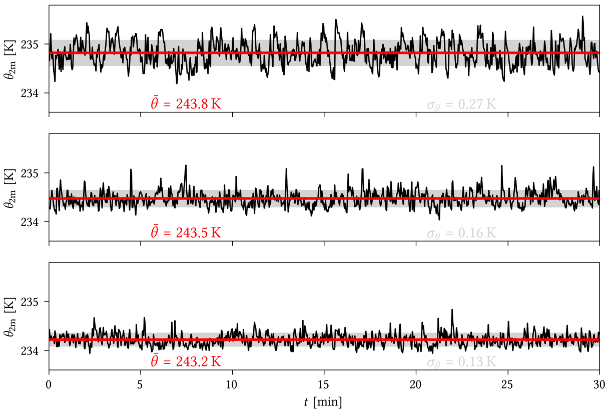

***Figure 1:** Virtual observational atmospheric tower data of potential temperature $\theta_{2\mathrm{m}}$ at 2 m height. The actual virtual measurements are presented via black lines. The grey shadings and the red lines visualize their standard deviations and means. From top to bottom, the atmospheric towers are placed 250 m and 500 m downstream and 250 m upstream of* Polarstern.

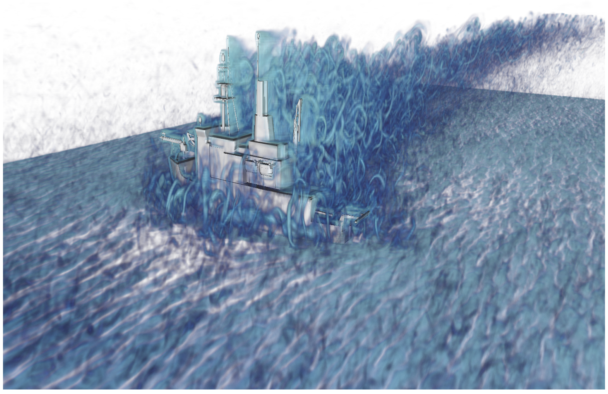

***Figure 2:** Three-dimensional visualization of voricity (blue) in* Polarstern*'s vicinity. Vorticity can be used to quantify turbulence intensity. Higher values of vorticity are tied to darker colors. The mean atmospheric flow acts from bottom-left to top-right. Created utilizing VAPOR [4].*

Considering logistical challenges and the number of involved scientists and countries, the MOSAiC expedition was the largest in history. During the Arctic drift, scientists gathered vast biological, chemical, oceanic, and atmospheric data. One systematic uncertainty of observational data in *Polarstern*'s vicinity is its effects on these data. For atmospheric data, *Polarstern*'s interactions with the atmospheric flow are of crucial importance. *Polarstern* acts as an obstacle to the flow. Thus, observations performed in its wake are anticipated to vary from unperturbed ones. Therefore, the necessary presence of *Polarstern* complicates the analysis and usage of the gathered data.

This project aims to investigate how *Polarstern* affects the atmospheric flow and atmospheric observational data in its vicinity. Analysis and quantification of these effects are not only critical to ensure the MOSAiC data quality. Indeed, the project's results additionally support data analysis, the planning of future expeditions, and can improve observational strategies. We utilize the PALM model [3] for our research and perform highly resolved large-eddy simulations (LESs) for selected weather conditions during the MOSAiC expedition. Computational grids with resolutions less than one meter allow us to explicitly represent *Polarstern*'s envelope and sufficiently simulate strongly stratified ABLs, the most common type of Arctic ABLs (Fig. 2).

PALM's virtual measurement module enables our LESs to create arbitrary amounts of synthetic observational data. Each simulation produces thousands

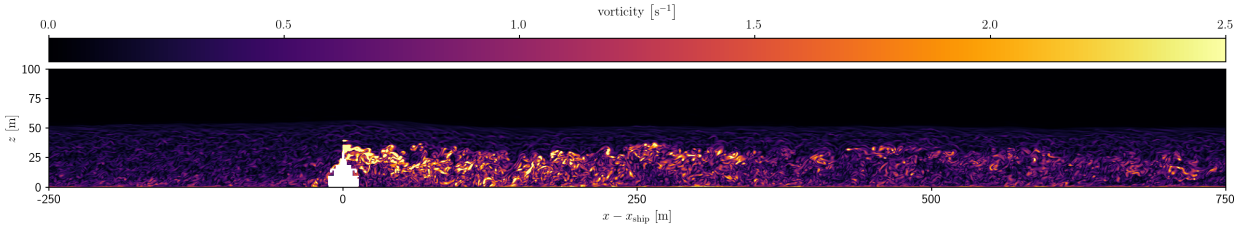

Figure 3: *Vertical snapshot of vorticity, a measure to quantify turbulence, close to* Polarstern*. The white shilouette represents* Polarstern*'s shape at the considered xz-slice. The mean atmospheric flow acts from left to right.*

of hours of synthetic observational data per variable. This data results from meteorological towers and idealized and performed unmanned aerial vehicle flights. The virtual measurements are performed all over the simulated domain. Therefore, comparing perturbed and unperturbed synthetic observational data allows the estimate of *Polarstern*'s influence on surrounding measurements.

Fig. 1 visualizes virtual measurements of potential temperature at three different locations. The presented values indicate that *Polarstern* affects observations over several hundreds of meters by triggering turbulence (Fig. 3). For example, at 500 m distance, the 30-minute averaged observed potential temperature increases by 0.3 K in *Polarstern*'s wake compared to unperturbed observations. This increase, by far, exceeds the accuracy of corresponding instruments and is more intense at closer distances. Higher-order atmospheric measures tend to be affected even more. Although we only present observations of potential temperature, similar effects are present in most variables. Furthermore, we find out that similar effects on observational data are not only tied to *Polarstern*'s wake. Indeed, *Polarstern* induces gravity waves and upstream stagnation pressure. Depending on the atmospheric measure, both phenomena have the potential to influence observational data far in excess of corresponding instrument accuracies.

As stated above, our simulations' results are not only helpful for estimating *Polarstern*'s effects on surrounding measurements. Indeed, implementation of additional virtual measurements (e. g. improved flight patterns) demands only negligible additional computational costs. Thus, our LESs allow us to test various observation strategies—even ones that are only theoretically possible. Contrary, such tests are of greater cost and demand excessive logistical planning in actual field trips. Additionally, applying mitigation strategies to the synthetical observational data allows us to analyze their effects on data analysis and forecast their benefits on future expeditions ahead of them.

So far, we only considered homogeneous surfaces. However, in reality, the surface was only rarely as flat as assumed in our simulations. Indeed, scientists reported ice ridges spanning tens to hundreds of meters. These ridges were up to a few meters high. Leads or aggregated ice piles additionally occurred frequently around *Polarstern* as some observation site buildings. All these inhomogeneous structures are known to trigger near-surface turbulence and, therefore, affect the atmospheric flow. Although *Polarstern* is the dominating dynamic obstacle, it is unknown how the other structures affect *Polarstern*'s wake or the general atmospheric flow. We focus with the upcoming simulations on such heterogeneous surfaces and analyze their effects, especially compared to homogeneous surfaces.

WWW

`https://www.meteo.uni-hannover.de/de/forschung/grenzschichtmeteorologie`

More Information

[1] Wendisch et al., *Eos* **98**, 22–26 (2017). doi:10.1029/2017EO064803.

[2] Shupe et al. (2022), *Elem. Sci. Anth.* **10** (1). doi:10.1525/elementa.2021.00060.

[3] Maronga et al. (2020), *Geosci. Model Dev.* **13** (3). doi:10.5194/gmd-13-1335-2020.

[4] https://www.vapor.ucar.edu

[5] https://mosaic-expedition.org

Project Partners

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