Large-eddy simulations of Arctic turbulence and clouds as observed during MOSAiC

Prof. Roel A. J. Neggers (neggers@meteo.uni-koeln.de)

The Arctic climate is warming at a rate that is unprecedented in human history. Given the large impact on society and nature of this ongoing phenomenon, the underlying causes and mechanisms are intensely researched at the moment. While various feedback mechanisms between components of the Arctic climate system have successfully been identified, much about them is still poorly understood. The persistent lack of reliable observational data at high latitudes is a prime cause for this problem. Available datasets are typically collected at only a few stations, and often lack spatial and temporal coverage. As a result of this data gap, the performance of atmospheric models suffers in the Arctic. While the uncertainty in Arctic climate predictions is well known, even reanalyses suffer from persistent biases, despite observational data being assimilated.

The ongoing DFG-funded SFB TransRegio project 172 titled "$(AC)^3$" is designed to overcome these challenges in better understanding climate at high latitudes (http://www.ac3-tr.de/). Various recent $(AC)^3$ field campaigns have contributed to filling the existing data gap. In addition, the project includes a strong, integrated modeling component, consisting of various codes and configurations. These range from global climate simulations via regional nested flow-resolving simulations down to turbulence-resolving Large-Eddy Simulations (LES). With the $(AC)^3$ project going into its third (final) phase, the overall strategy is to now fully employ the model capabilities in the project to optimize the scientific outcome of the observational datasets as collected during the first two phases. This effort necessitates and prioritizes the use of High Performance Computing (HPC) systems.

Within the $(AC)^3$ project, the InScAPE research group at the University of Cologne (https://atmos.meteo.uni-koeln.de/inscape/doku.php) is responsibile for delivering the high-resolution simulations. Among others, we operate the DALES code (Heus et al, 2010) at resolutions high enough to resolve Arctic turbulence and clouds. While the code has been thoroughly tested for Arctic conditions, recent work based on earlier Polarstern missions has given us demonstrable expertise in configuring such experiments (PASCAL, Neggers et al 2019; Egerer et al., 2021). Typically, LES experiments are performed for relatively small domains surrounding the observational platforms. Measurements of atmospheric state variables are used to initialize and constrain the simulations, while independent data on turbulence and clouds are used to evaluate the model results and critically test their realism. The four-dimensional model datasets thus generated are employed as a virtual laboratory to better understand Arctic climate at process level, thus filling a critical data gap that current meteorological instrumentation can not yet cover.

To further support our LES work in the context of the $(AC)^3$ project, with this proposal we apply for computation time on the Levante High-Performance Computing (HPC) system of the DKRZ. Our specific goal in this project is to perform daily LES experiments to accompany the MOSAiC Arctic Ocean drift experiment in 2019-2020 (Shupe et al., 2022).

The project has the following overarching science objectives:

1. To simulate the atmospheric domain surrounding the MOSAiC measurement platforms at high turbulence- and cloud-resolving resolutions;
2. To boost statistical significance by covering every day during the year-long drift with LES experiments;
3. To thus augment and support the observations made during the field campaign;
4. To use big data analysis techniques to scan the joint observed-simulated high-resolution dataset thus generated for physics-based emergent constraints on Arctic Amplification.

With this approach we combine various developments in our field that have yielded promising scientific results in recent years. Firstly, our LES codes are now good enough to reliably simulate observed turbulence and clouds in the Arctic. Secondly, the routine generation of daily LES at meteorological sites for periods lasting multiple years has proven to be feasible and has become a well established scientific tool (Neggers et al., 2012; Gustafson et al, 2020; Schemann et al., 2020). Thirdly, the combination of state-of-the-art measurements with high resolution LES in the Arctic has become well established, and has yielded insights that would not have been possible by using either of them separately (Neggers et al., 2019; Egerer et al., 2021; Chylik et al, 2022). Finally, the concept of "emergent constraints" (e.g. Nijsse and Dijkstra, 2018) has been shown to be an effective method for using present-day observations to understand what factors control climate change. Such empirical relations also provide a confidence interval for interpreting climate models. We hypothesize that the availability of daily LES for MOSAiC will facilitate the identification of new, yet unknown emergent constraints in Arctic climate, in particular those in which small-scale fast-acting atmospheric physics play a role. Machine learning techniques will be adopted to this purpose.

In practice, our suite of numerical experiments on Levante will consist of both control runs and sensitivity experiments. For each day during the 2019-2020 MOSAiC drift of the Polarstern Research Vessel at least a few experiments will be generated, calibrated against radiosonde profiles. Perturbed runs from this control setup will be performed to give insight in how boundary layer physics respond to changes in the background state. The storage of model output will be significant but manageable. The DALES code has been demonstrated to have satisfactory scaling behavior on various HPC platforms, including SuperMUC (Munich) and JUWELS (Jülich). For visualization purposes we have adopted the open-source Blender tool (https://www.blender.org/), which relies on ray-tracing and can be operated on GPUs (see Figure 1 as an example).

References

Chylik et al., 2022: https://doi.org/10.5194/acp-2021-888
Egerer et al., 2021: https://doi.org/10.5194/acp-2020-584
Gustafson et al., 2020: https://doi.org/10.1175/BAMS-D-19-0065.1
Heus et al., 2010: https://doi.org/10.5194/gmd-3-415-2010
Neggers et al 2012: https://doi.org/10.1175/BAMS-D-11-00162.1
Neggers et al., 2019: https://doi.org/10.1029/2019MS001671
Nijsse and Dijkstra, 2018: https://esd.copernicus.org/articles/9/999/2018/
Schemann et al, 2020: https://doi.org/10.1029/2020MS002209
Shupe et al., 2022: https://doi.org/10.1525/elementa.2021.00060

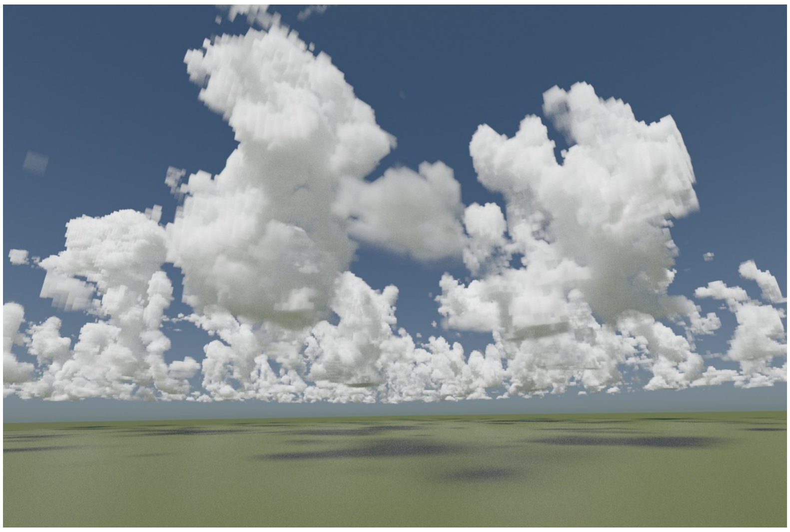

Figure 1: Ray-tracing volume rendering of cumulus clouds in a DALES simulation of the weather observed at the Jülich meteorological site on 24 June 2014.