How well do stereo cameras observe shallow cumulus spatial organization?

An evaluation combining atmospheric path-tracing and high-resolution Large-Eddy Simulations (LES)

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Abstract

This poster displays how to **interface high-resolution Large-Eddy-Simulations (LES) with stereo camera observations**. This expertise can be used as an Observing System Simulation Experiment (OSSE) to **optimize camera networks** and **evaluate LES** by their cloud geometry, spacing, movement, and evolution.

1. Introduction

Spatial organization is essential for convection parameterization in numerical weather and climate models. However, spatial organization is challenging to observe. **Most ground-based measurements consist of one-dimensional profile data**, often sampled by lidars or radars. A recently explored new method of obtaining **multi-dimensional information** is to utilize hemispheric images **from networks with multiple cameras**, which observe shallow cumuli in unprecedented spatial detail.

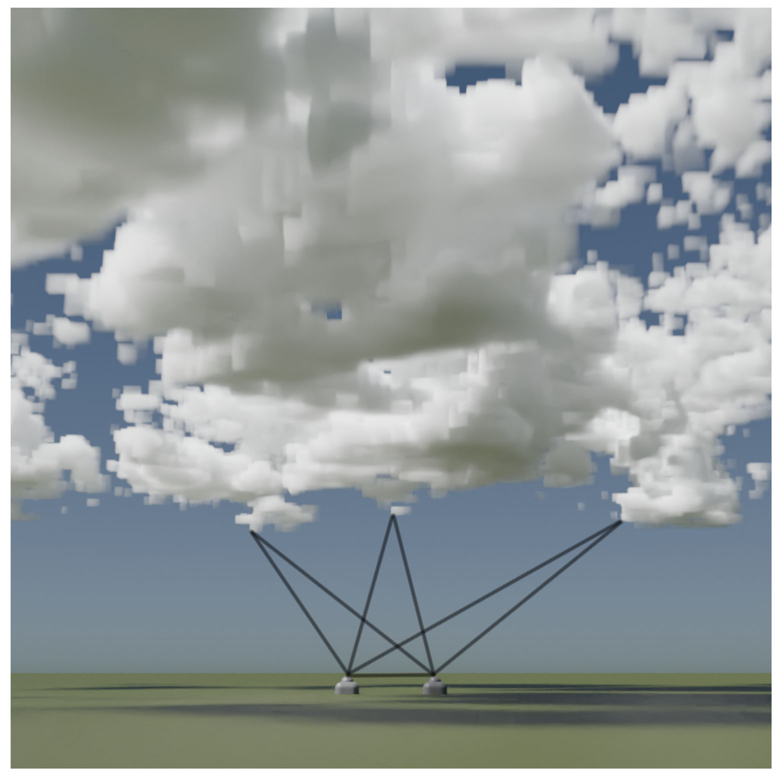

Figure 1: Path-tracing of a Large Eddy Simulation (LES). The black triangles indicate the triangulation process yielding the three-dimensional reconstructions of our setting. The cubic expression reveals the horizontal 50 meters resolution of our simulation.

- Apply **open-source** Monte Carlo **path-tracer** to high-resolution LES (see figure 1)
- **Emulate** a network of multiple **stereo cameras**
- Use three-dimension **LES** cloud fields **as input**
- **Reconstruct** the cloud shells **from** the **emulated** stereo **camera snapshots**
- **Compare** reconstruction **against original LES** cloud field
- Estimate **geometrical error**

The SOCLES project

SOCLES stands for Stereo Observations of Clouds for Large-Eddy Simulation Validation and Sub-scale Cloud Parameterizations[1]. The main idea is to combine high-frequency cloud observations by multiple stereo cameras with high-resolution Large-Eddy simulations (LES) at a mid-latitude continental meteorological supersite to gain insides into fine-scale spatial and temporal structures of cloud populations.

[1] gepris.dfg.de/gepris/projekt/430226822

2. Objectives

- Provide an **interface between simulations and stereo camera observations** based on path-tracing which enables an unprecedented direct comparisons
- Provide Observing System Simulation Experiments (OSSEs) to **optimize stereo camera networks**
- Provide a technique for directly **evaluating cumulus simulations against real-world** three-dimensional **camera data**
- Provide the capability to gain **insights into cloud geometry, spacing, movement, and evolution**

3. Methods

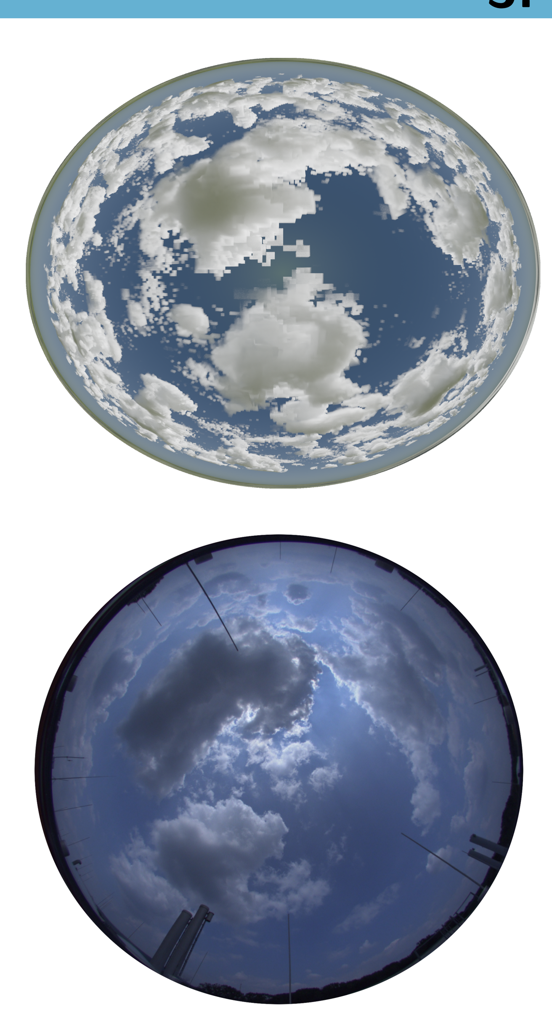

Figure 2: Artificially generated All-Sky Imager emulation of an LES by our path-tracer compared against a real camera image below. Note that the cubic expression reveals the 50 meters horizontal resolution.

DALES

We used the Dutch Atmospheric Large-Eddy Simulation (DALES) model ([Heu+10]) with a 25.6 x 25.6 km^2 domain and a horizontal resolution of 50 m. DALES has been used in many recent intercomparison studies for shallow cumulus days.

Path-Tracer

To emulate the camera network (see figure 2) and create visualizations, we consolidated the idea of [Heu+21] to use the render engine Cycles included in the open-source software blender[1]. Cycles provide GPU rendering via path tracing, which is a Monte Carlo method approximating the solution of the rendering equation.

Stereo Reconstruction

The reconstruction method used for our All-Sky Images is based on [Bee+16]. Note that in contrast to [Bee+16] we run it on images generated from LES data.

[1] www.blender.org

4. Results

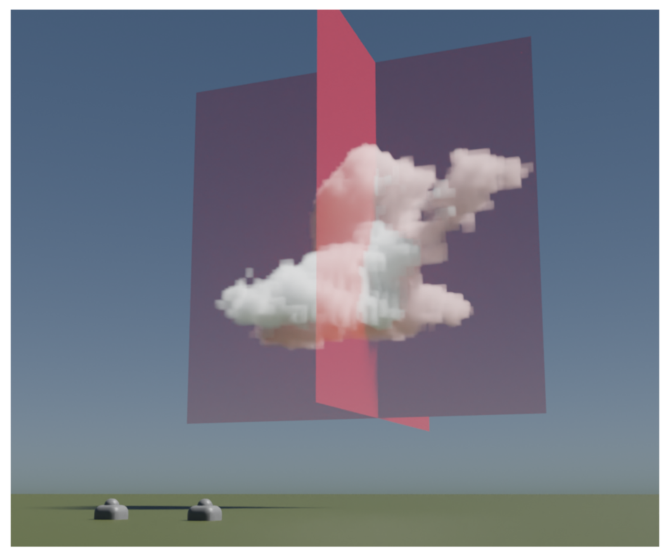

Figure 3: Visualization of an exemplary cumulus cloud done with our path-tracer. The red planes indicate the sections for the figures below.

- Examine **how many grid boxes of cumulus cloud fields are theoretically reconstructable**
- Explore **how many grids are indeed reconstructed** by our stereo algorithm
- Test this by firstly calculating all grid boxes **visible in both camera simultaneously**, see **green boxes** in figure 4

We found that **19.46% of the cloud shells are theoretically reconstructable**, see figure 7. Theoretically reconstructable means that the grids are seen by both cameras simultaneously. An example extract of a **section of the** whole **simulation** is displayed in figure 5. The **grid boxes captured by** our **stereo reconstruction** are as in figure 4 depicted by the **red points**.

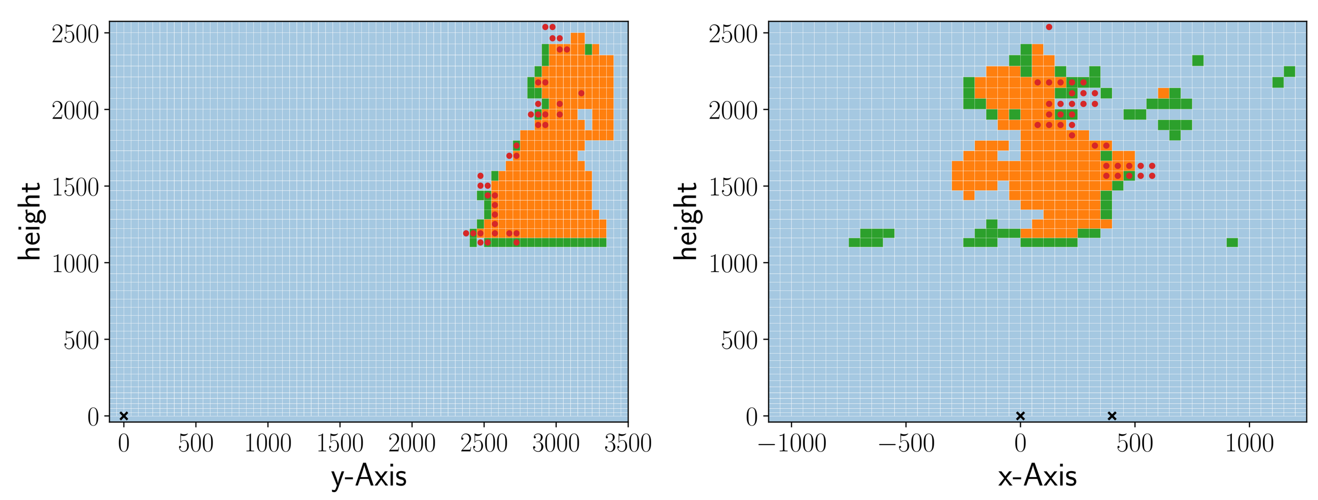

Figure 4: Sections of the cloud above. The orange grid boxes are the cloud with visible grids colored in green. The red points are the captured grid boxes of our stereo reconstruction. The black crosses illustrate the camera positions. On the left, you can see the section pointing into the cloud, and on the right the one going from left to right. Note that the grid boxes displayed here are the same as the 50 meter horizontal resolution grids used in our simulation.

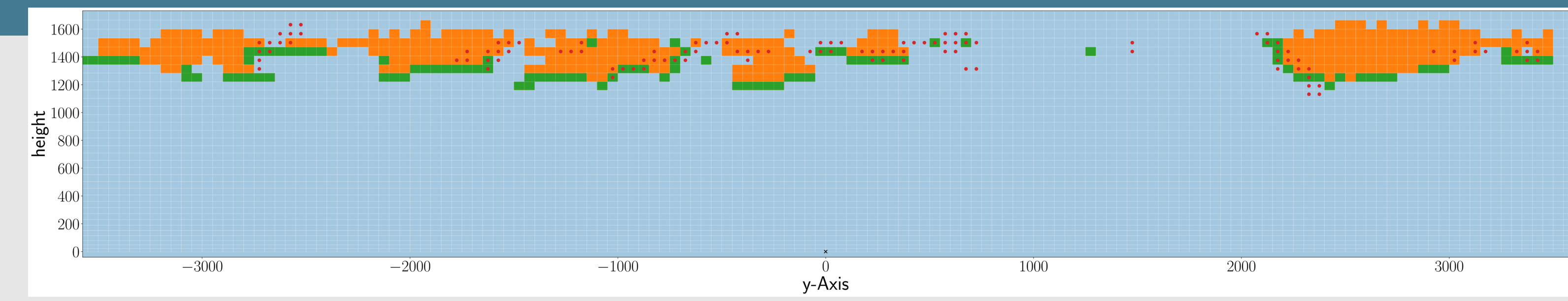

Figure 5: Extraction of a section through the whole simulation. The orange grid boxes are the cloud with visible grids colored in green. The red points are the captured grid boxes of our stereo reconstruction, and black crosses illustrate the camera positions. Note that the grid boxes displayed here are the same as the 50 meter horizontal resolution grids used in our simulation.

5. Statistics

Here, we present the statistics of **how many grid boxes are indeed reconstructed compared to the visible grid** (plotted in green in figure 4 and 5). Therefore, we introduce the "**reconstruction ratio**" which is the ratio of the reconstructed grid divided by the number of visible grids in percentage terms.

- **Violin-box plots** of the reconstruction ratios **for different tolerances** on the right in figure 6
- Reconstruction method does not see grid boxes with very-low liquid water content
- It happens that reconstructed points appear inside of the clouds
- Tolerances are needed for those dependence on liquid water content

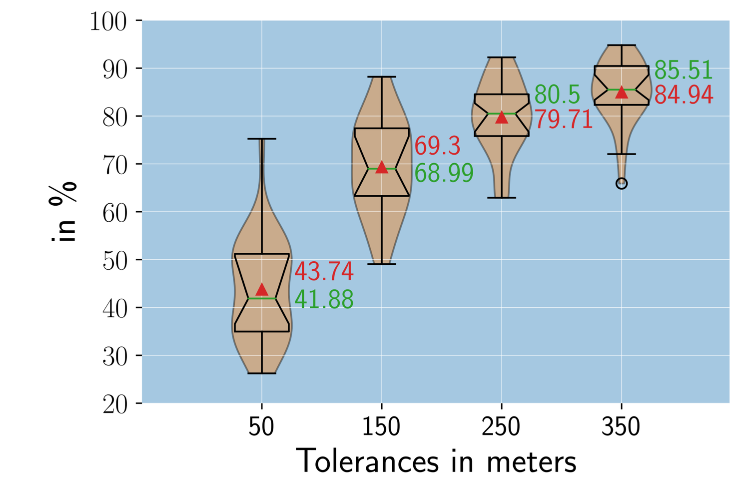

Figure 6: Violin-Box-Plot of the reconstruction ratio, i. e. the percentages of how many grid boxes of the visible grids are indeed reconstructed. The red-filled triangle indicates the mean percentages.

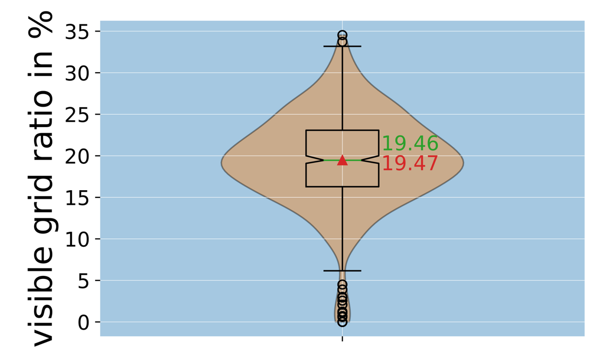

Figure 7: Violin-Box-Plot of the visible grid ratio, i. e. the percentages of how many grid boxes of the single cloud shells are on average visible in both cameras simultaneously. The red-filled triangle indicates the mean percentages.

The violin-looking brown surfaces are the mirrored distributions, the **red-filled triangles** are the **means**, and the **green lines** are the **medians**. The notches around the medians visualize the 95%-confidence interval of these medians. The interquartile ranges are indicated by the boxes, and the whiskers extend this range by 1.5. Data points outside of the whiskers are outliers and plotted as circles.

6. Main points

- We provided an **interface between high-resolution LES and camera observations**.
- The interface **works well both visually** as images **and statistically** by analyzing the grid boxes of the stereo reconstructions from those artificially generated images.
- **19.46%** of a cumulus cloud shell is theoretically reconstructable on average.
- The **stereo reconstruction** works quite well. However, there is still **room for improvement**.
- Our work can be used on the one hand as OSSE to **improve camera networks**. On the other hand, it provides an unprecedented way to **test the geometry of cloud simulations** to real-world camera data.

Outlook

We use our real camera network to furtherly test our methods, evaluate the LES, and gain insights into cloud geometry.

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[Bee+16] Christoph Beekmans et al. "Cloud photogrammetry with dense stereo for fisheye cameras". In: Atmospheric Chemistry and Physics 16.22 (Nov. 16, 2016), pp. 14231–14248.
[Heu+10] T. Heus et al. "Formulation of the Dutch Atmospheric Large-Eddy Simulation (DALES) and overview of its applications". In: Geoscientific Model Development 3.2 (Sept. 30, 2010). Publisher: Copernicus GmbH, pp. 415–444.
[Heu+21] Thijs Heus et al. "Efficient rendering of simulated cloud fields using Blender". In: AGU Fall Meeting 2021. AGU, Dec. 15, 2021. URL: https://agu.confex.com/agu/fm21/meetingapp.cgi/Paper/865504 (visited on 12/29/2021).