FY23 Topic Areas Research and Technology Development (TRTD)

Breaking the Complexity Barrier in 3D Cloud Remote Sensing with Deep Machine Learning and Large-Eddy Simulation

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Strategic Focus Area: Climate Science

Objectives: The science driver of our research in advanced cloud remote sensing is that convectively-driven clouds such as cumulus congestus are poorly served by current operational retrievals, which are based on a grossly simplifying assumption about cloud structure: that they are plane-parallel slabs, hence an algorithm using 1D radiative transfer (RT). In this RTD project, our objective is to develop a ground-breaking passive shortwave technique for 3D cloud remote sensing adapted specifically to vertically developed clouds in shallow convective regimes. In contrast with existing 3D cloud property retrievals using tomographic techniques, ours will be applicable to data from multi-angle *satellite* imaging sensors, with their larger pixels and larger swaths. We will thus be able to reconstruct clouds over a larger range of overall sizes, including ones where warm precipitation processes have been initiated.

Our main deliverable is code that takes as input multi-angle imagery of clouds fields at VNIR and SWIR wavelengths, e.g., MISR+MODIS/Terra, and outputs an unbiased estimate of a cloud's outer shape and internal structure. This inversion is performed efficiently enough to make the tool *practical* in applications, e.g., to analyze the statistical properties that matter for cloud-climate interaction for entire cloud fields observed during past and future field campaigns.

Background: Computed tomography of 3D clouds departs radically from operational 1D (uni-directional, pixel-by-pixel) remote sensing methods. It uses multi-pixel/multi-angle/multi-spectral data in a holistic fashion. Previous demos of computed cloud tomography (CCT) have been built on a physics-based forward model that predicts the multi-angle images, which are compared to the measured data in an optimal estimation scheme. That methodology is limited to relatively small pixels—hence relatively small (~1 km) clouds. Moreover, the optimization is slow (~hours to days per cloud).

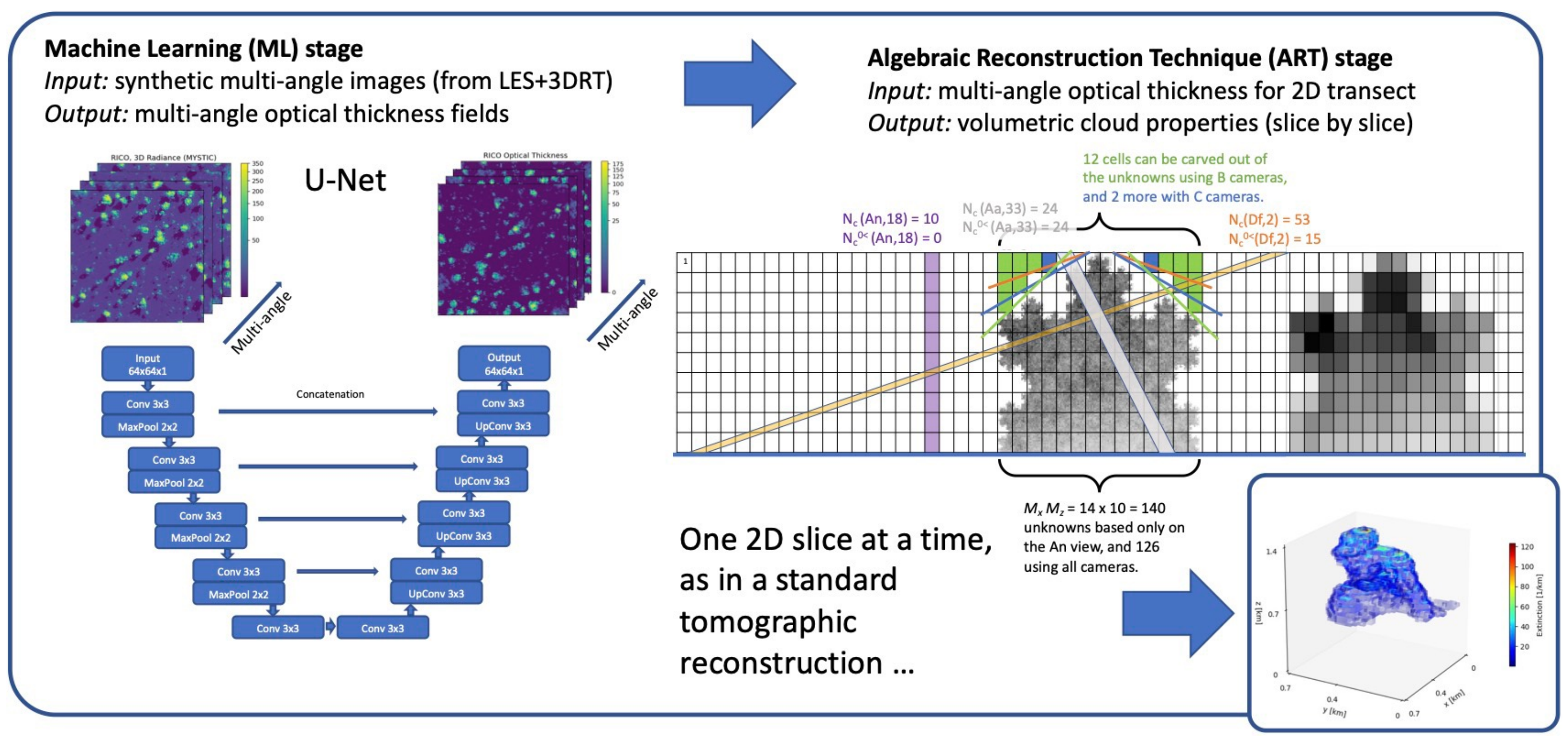
Approach and Results: Our approach overcomes these limitations by replacing the inverse problem using the costly 3D RT and minimization of a standard cost function with a two-stage methodology (cf. Fig. 1). The first stage uses a machine-learning (ML) model to convert the multi-angle imagery into cloud optical thickness at every pixel, not just along the vertical but along every direction (we focus on MISR's angular sampling). The ML model is trained on many synthetic multi-angle image data based on a high-fidelity forward 3D RT model for rendering a 3D cumulus cloud field generated with the JPL Large-Eddy Simulation (LES) model (cf. Fig. 2). We use synoptic conditions representative of the RICO (Rain in Shallow Cumulus Over the Ocean) field campaign to drive the LES cloud dynamics. The LES clouds provide both training data and ground truth for the ML model (cf. Fig. 3), as well as for the full two-step CCT.

Progress in FY23 brings the ML+(LES & 3D RT) thrust to the point where MISR's VNIR multi-angle input will be augmented with collocated uni-directional MODIS' SWIR images, thus gaining sensitivity to cloud-top microphysics (hence more cloud property output, in a form TBD). The ART thrust will proceed with inversion and regularization based on the definition of the cloud's "veiled core" [1]. At that point, publications are warranted for both thrusts. They will then be ready for integration into the full two-stage CCT algorithm, to be tested on LES ground truth and demonstrated on real-world MISR+MODIS data. This will result in two more publications: one on the computational technicalities; one emphasizing Climate applications.

Significance/Benefits to JPL and NASA: The immediate impact of this T-RTD research is to consolidate JPL as a world-leader in multi-angle cloud remote sensing, and as pioneer of CCT—the future-looking approach to passive cloud sensing in the VNIR-SWIR spectrum. Looking back, selected MISR+MODIS data can be processed using CCT to benefit Climate Science. Looking forward, there will be MAIA, PACE and AOS. These new multi-angle sensors all have polarimetric capability in addition to SWIR channels, which opens another path toward cloud-top microphysics in the ML training to be explored in the future.

Reference

[1] Linda Forster, Anthony B. Davis, Bernhard Mayer, and David J. Diner, "Toward Cloud Tomography From Space Using MISR and MODIS: Locating the 'Veiled Core' in Opaque Convective Clouds," J. Atmos. Sci. 78 (2021): pp. 155-66.



Machine Learning (ML) stage
Input: synthetic multi-angle images (from LES+3DRT)
Output: multi-angle optical thickness fields

Algebraic Reconstruction Technique (ART) stage
Input: multi-angle optical thickness for 2D transect
Output: volumetric cloud properties (slice by slice)

One 2D slice at a time, as in a standard tomographic reconstruction …

Figure 1: Schematic overview of our two-stage 3D cloud reconstruction algorithm.

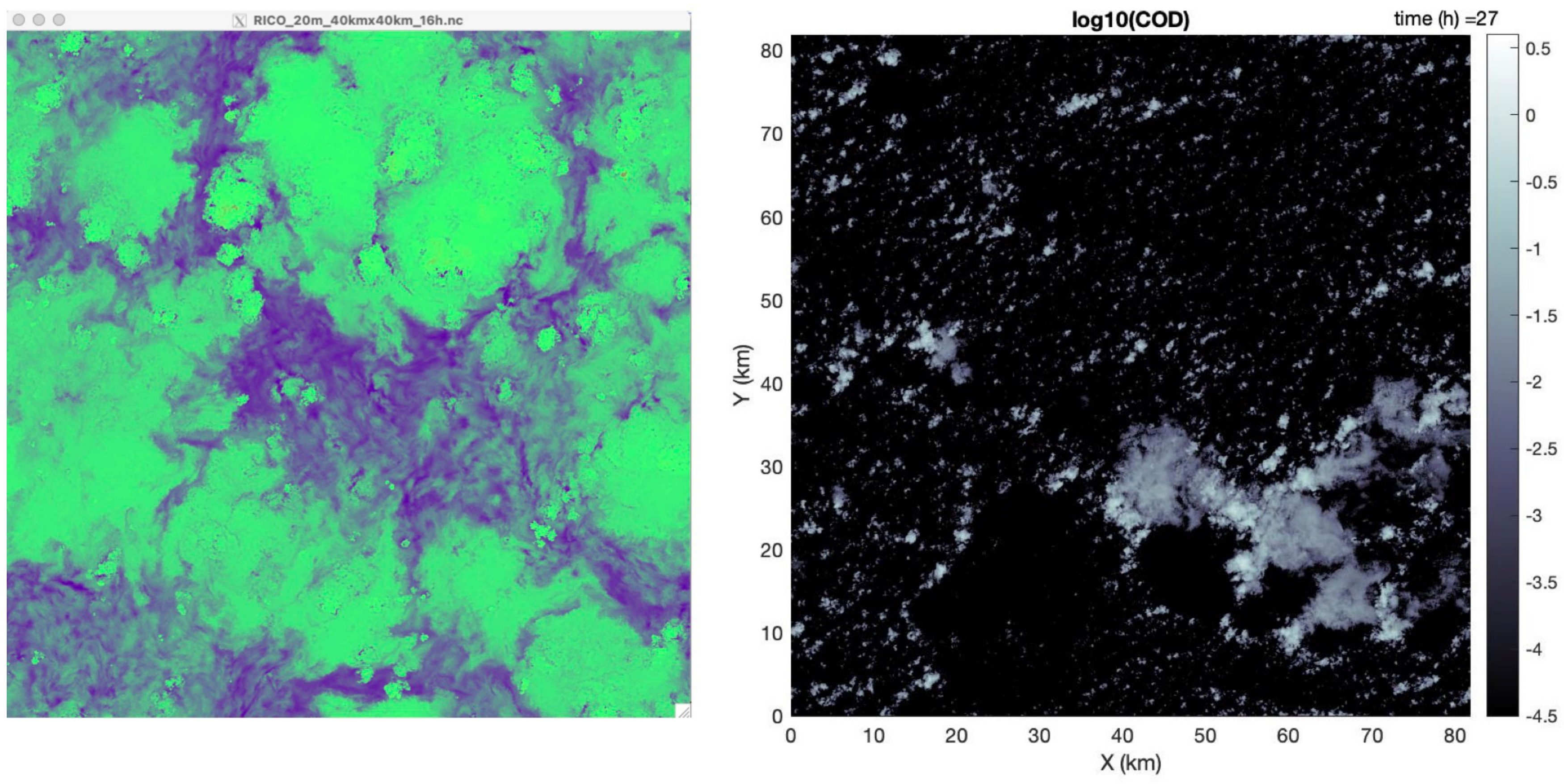
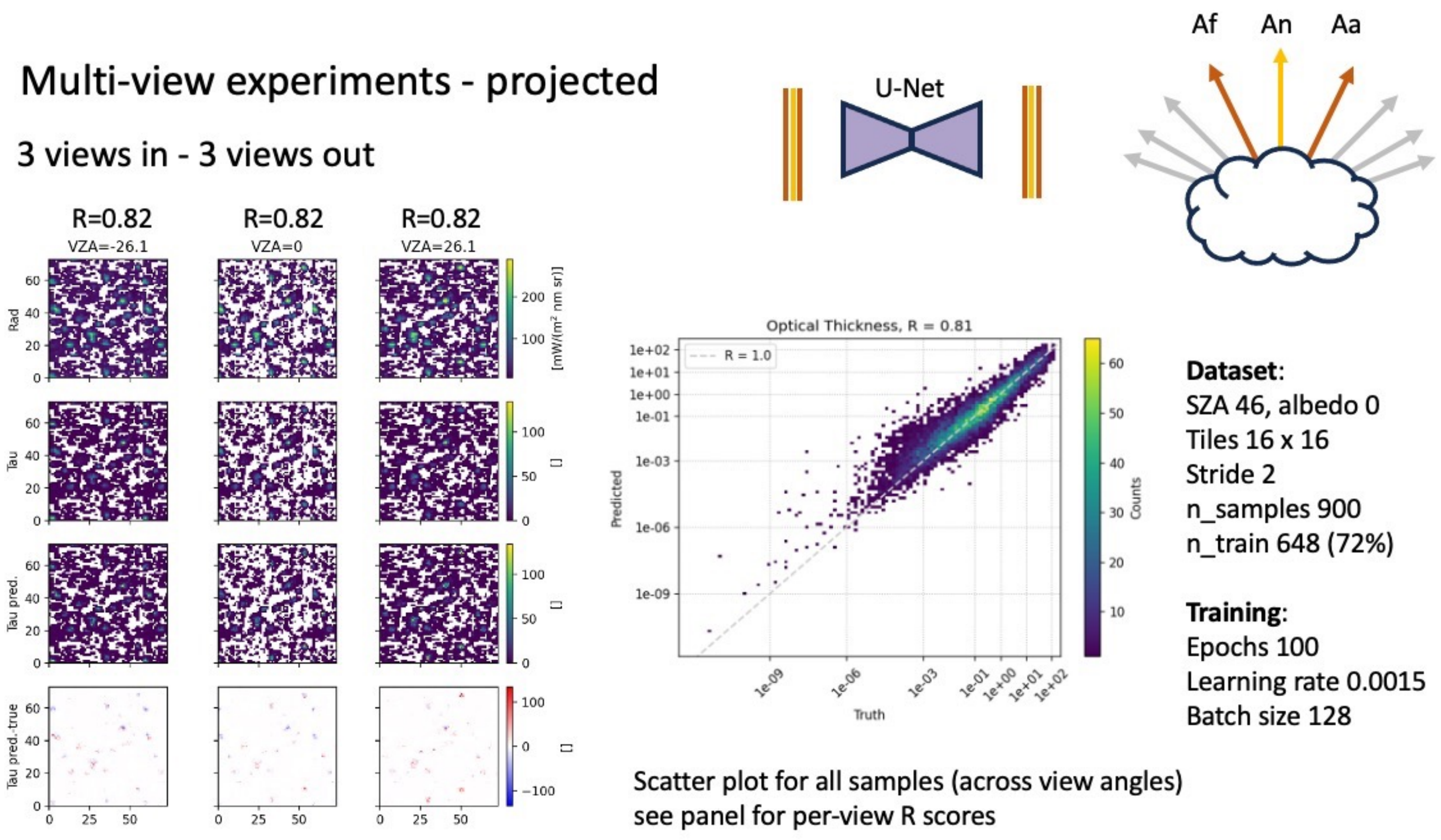


Figure 2: High-resolution LES cloud scenes over a RICO-like subtropical ocean. The scene represents shallow convection with cloud tops reaching ~3 km. We simulated two cases. **Left**: 20 m resolution on a 40x40 km^2 domain showing water vapor at 2 km above the surface after 16 hours for steady-state conditions. **Right**: full-diurnal cycle (40 m resolution) on an 80x80 km^2 domain showing column-integrated cloud liquid water after 27 hours on a log scale. The latter scenario produces a larger and more realistic variability of cloud shapes and clusters due to interactions with precipitation and both LW and SW radiation.



Multi-view experiments - projected

3 views in - 3 views out

Dataset:
SZA 46, albedo 0
Tiles 16 x 16
Stride 2
n_samples 900
n_train 648 (72%)

Training:
Epochs 100
Learning rate 0.0015
Batch size 128

Scatter plot for all samples (across view angles)
see panel for per-view R scores

Figure 3: The best performance so far of a trained CCN model for a a scenario with vanishing surface albedo and a solar zenith angle (SZA) of 46o is to limit the CCN to three viewing zenith angles (VZAs) in both input and output. The target is optical thickness is along the vertical and the closest two VZAs (±26^o). The only images used to predict them from the multi-angle imagery using ML are nadir and those two closest VZAs. The regression parameter R is displayed for all three VZAs. Optimized CNN hyper- parameters are stated on the right.

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