Final Technical Report
of Research Funded by DoE/ASR

Award Number: DE-FOA-0018000
sponsored by ASR Program
PI Name: Alexander Khain, Professor of the Hebrew University of Jerusalem
Project Title: ARM shortwave spectrometers to study the clear-cloud transition zone and mixing processes
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This project is a joint research activity between NASA/GSFC and the Hebrew University of Jerusalem. The NASA/GSFC team is led by Dr. Alexander Marshak.

Executive Summary

The transition (or interface) zone between cloudy and clear air is a region of strong aerosol-cloud interactions where aerosol CCN humidify and swell when approaching the cloud, while cloud drops evaporate and shrink when moving away from the cloud. The transition zone is typically around 10 km. Cloud edges in the transition zone are an important region to study aerosol-cloud interactions and cloud turbulence mixing processes. Homogeneous and inhomogeneous mixing are two limiting cases for cloud mixing processes (Fig. 1 left panel). However, the real cloud mixing processes remain not well understood. Theoretical studies suggest that cloud edges are special regions for studying cloud mixing processes (Fig. 1 right panel). We proposed to study the clear-cloud transition zone and mixing processes. The proposed research is a collaborative effort between NASA/Goddard Space Flight Center and the Hebrew University of Jerusalem. While the NASA team focused on analyzing ground-based hyper-spectral radiance observations to understand cloud edge properties and their connection to mixing processes, the Hebrew University team tackled the problem through cloud modeling activities. By approximating the shortwave spectra in the cloud-clear transition zone as a linear combination of purely clear and purely cloudy spectra we can characterize the variations of cloud optical thickness and cloud droplet effective radius in the transition zone. When applying this method to the measurements of a ground-based shortwave spectroradiometer at the ARM's SGP site, representing continental conditions, and MAGIC field campaign between Log Angeles, California and Honolulu, Hawaii, representing maritime scenarios, we found that cloud optical depth consistently decreases in both cases, but droplet size decreases much more substantially for the continental regime, suggesting different mixing processes for the continental and maritime conditions.

The investigation and measurements of radiation clouds were coupled with a unique cloud modeling. A novel spectral bin microphysics was developed and implemented to the System of Atmospheric Modeling (SAM). In order to resolve cloud transition zones with high spatial gradients of microphysical variables a unique high resolution (10 m) was used in simulations. The model calculates droplet size distributions in each grid point. The model output was transferred to the NASA/GSFC team for utilization in radiative calculations and testing of both radiative algorithm and model representation.

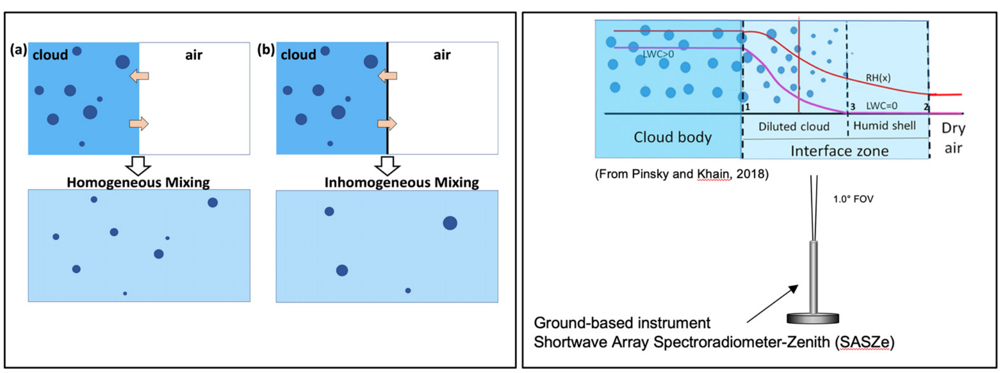

Figure 1. Left**:** Schematic illustration of two limiting scenarios of the air entrainment and mixing processes: (a) the homogeneous mixing reduces the size of all droplets but does not substantially change the number of cloud droplets due to quick mixing of cloud and drier air; (b) the inhomogeneous mixing reduces the droplet number concentration for droplets of all sizes but does not change the droplet size spectrum as a result of cloud droplets evaporation before dry air penetrates to the entirety of the cloud. Right**:** The scheme of changes of microphysical variables within the interface zone near cloud edge and the remote measurements of the interface zone with SASZe.

Review of project activities (references to cited paper are given in [])

We proposed to study the variation of droplet size in the transition zone and understand cloud mixing processes by analyzing ground-based ARM spectroradiometer observations and through cloud modeling activities. The proposed research is a collaborative effort of NASA/GSFC team focusing on analyzing ARM spectroradiometer data and the Hebrew University of Jerusalem team focusing on high-resolution cloud modeling. The two teams engaged in close collaboration tackling the same challenging problem from different aspects in the whole ASR funded time period. The goal of proposed research is improving understanding aerosol-cloud interactions in the transaction zone and cloud mixing processes.

Aerosol optical depth and particle size in partly cloudy regions [6]. We studied aerosol-cloud interactions by examining statistical relationships between aerosol properties and nearby low-altitude cloudiness using observational data. The analysis reveals that the positive correlation between cloudiness and aerosol optical depth (AOD) reported in earlier studies is strong for all aerosol types considered: dust, sulfate, carbon, and sea salt. The observations also indicated that in the presence of nearby clouds, aerosol size distributions tend to shift toward smaller particles. This is consistent with a greater cloud related increase in the AOD of fine-mode than of coarse-mode particles. The greater increase in fine mode AOD implies that the cloudiness-AOD correlation does not come predominantly from cloud detection uncertainties. Additionally, the results show that aerosol particle size increases near clouds even in regions where it decreases with increasing cloudiness. This suggests that the decrease with cloudiness comes mainly from changes in large-scale environment, rather than from clouds increasing the number or the size of fine-mode aerosols.

Cloud edge properties measured by the ARM shortwave spectrometer over ocean and land [20].

We used the spectrally invariant method to study the variability of cloud optical thickness and droplet effective radius in transition zones between the cloudy and clear-sky columns observed by ARM shortwave spectroradiometers at the SGP (C1) and during the MAGIC field campaign. The spectrally invariant method approximates the spectra in the transition zone as a linear combination of definitely clear and definitely cloudy spectra. The slope and intercept of the linear relations characterize variations of cloud optical thickness and droplet effective radius in the transition region (Fig. 2). We have analyzed 22 cloud edge cases from the SGP and MAGIC. Each case of shortwave spectroradiometer observation was carefully examined by checking the image from ARM's total sky imager (TSI) and ceilometer observations and cloud base and cloud top data products to screen SASZe measurements, making sure that all selected SASZe observations are from non-drizzling single layer water clouds. (Examples of zenith radiance variation and corresponding TSI image are shown in Fig. 3.)

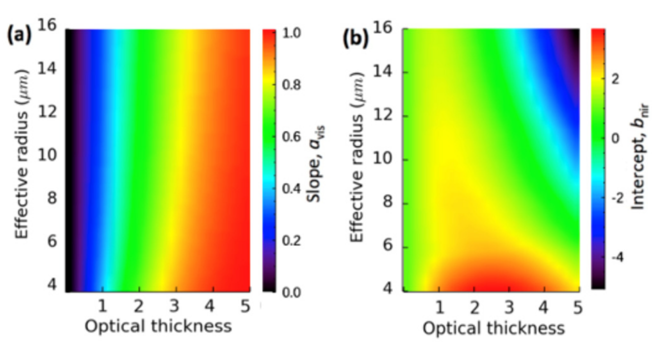

Figure 2. Radiative transfer model simulations for (a) visible slope and (b) near-infrared intercept as a function of cloud droplet effective radius and cloud optical depth over vegetated areas of mid-latitude regions for the SGP for the solar zenith angle of 45° and aerosol optical depth of 0.2 (from Yang et al., 2019).

We found that that in the transition between cloudy and clear sky *(a)* the slopes of the visible band decrease, indicating the decrease of optical thickness toward cloud edges, and *(b)* the intercepts of the near-infrared band show a much more significant increase at the SGP than from the MAGIC.

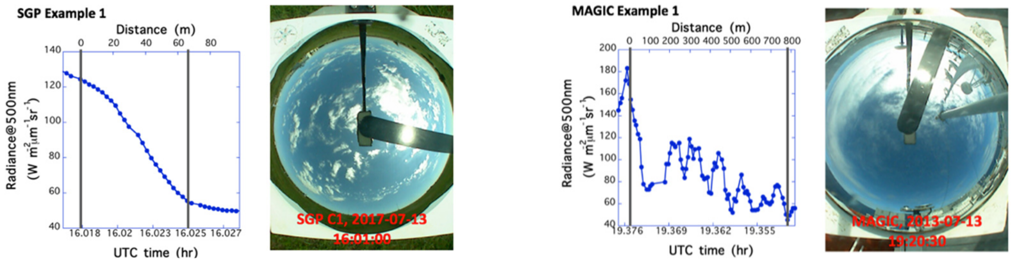

Figure 3. Left: an example of Shortwave Array Spectroradiometer-Zenith observed 500-nm zenith radiance variation for cloudy-to-clear transition cases at the SGP site with corresponding total sky imager images on 13 July 2017. Right: an example from MAGIC campaign on 13 July 2013 (from Yang et al., 2019).

Statistical models of broken cloud fields [4, 18]. We continued the series (started in the previous ASR proposal cycle) devoted to statistical parameterization and modeling of the cloud cover and structure characterized by sizes of clouds and gaps between them. The approach is based on cloud-mask statistics of 2D broken cloud fields derived from observations made along linear transects. Such observations consist of the lengths of cloudy and clear intervals in each transect. In distinction to, for example, area-based characterization, this approach works equally well for cumulus and stratocumulus cloud fields with a smooth transition between these types. Earlier were described the statistics of shallow, broken cloud fields generated using a realistic LES model. Now these results were interpreted in terms of the theory of the binary Markov processes.

Microphysical (model) simulations. During past 3.5 years the microphysical studies were performed in 3 main directions.

A) Improvement of our understanding of microphysical processes and development of the accurate approaches in cloud-resolving models (CRM) with detailed (bin) microphysics: ice formation and multiplication **[30, 37, 39, 47, 48]**. New methods with new parameterization schemes [**48]** have been developed. The mechanisms of hail formation have been investigated and the formation of huge hail stones was simulated. Effects of microphysics on radar signatures (especially dual polarimetric radar) were evaluated and the correlations between observations and numerical simulations were calculated. New bin microphysics scheme was successfully used for simulations of mesoscale convective systems and hurricanes **[41,42]**. The results of these and other studies were generalized and described in a new monograph [**49**].

B) Several simplified models of clouds have been developed [**34-36**], as well as mixing between clouds and their surrounding [**38, 43-45**]. Time-dependent changes in the size distribution functions near cloud edge were calculated. The rates of the development of the transition zone, appearance of humid shell, the velocity of the front of cloud interface were calculated and the parameters determined this evolution were found. It was found that at the stage of cloud development, there is a competition of adiabatic processes related to cloud updrafts and mixing that leads to deviation of cloud properties form adiabatic. At the decaying stage, clouds dissipate due to both air settling and lateral mixing.

C) A new set of investigations is related to utilization of large-eddy simulations (LES) [**50, 52**]. In these studies, non-precipitating Cu were simulated and the main microphysical parameters were calculated. In [**51, 52]** these simulations of cloud were performed with a very high spatial resolution (10 m). Such resolution allowed to simulate well cloud zones with high gradients close to cloud edges. Figure 4 shows horizontal cross-sections of a cloud at t=33 min at z=1500 m.

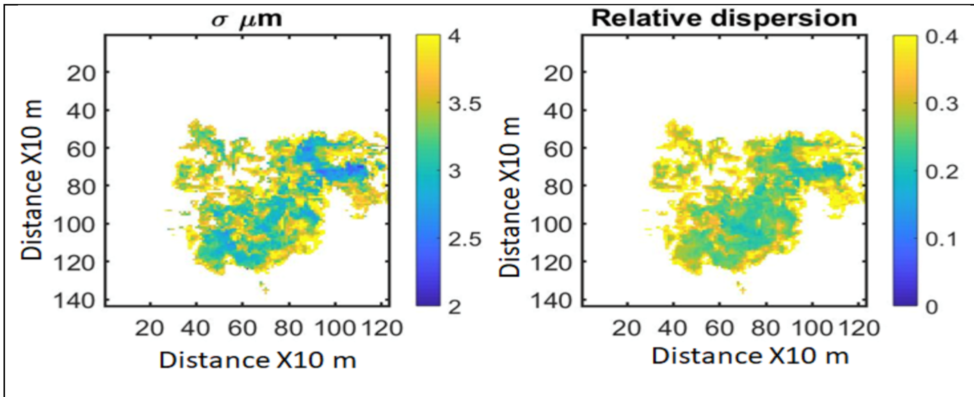

Figure 4: Fields of droplet spectra width and relative dispersion in simulation with System for Atmospheric Modelling (SAM) with bin-microphysics and resolution of 10 m.

One can see that droplet size distributions are wide at cloud edges and narrow in the cloud core. We see that the properties of the transition zone near cloud edges differ from those in the cloud center. It indicates the importance of the investigation of the processes in the transition zone. It was found that effective radius changes in the horizontal direction relatively slowly.

Figure 5 shows horizontally cross-sections in the fields of cloud water content (q_c), the droplet number concentration (N_d) and effective radius (r_e).

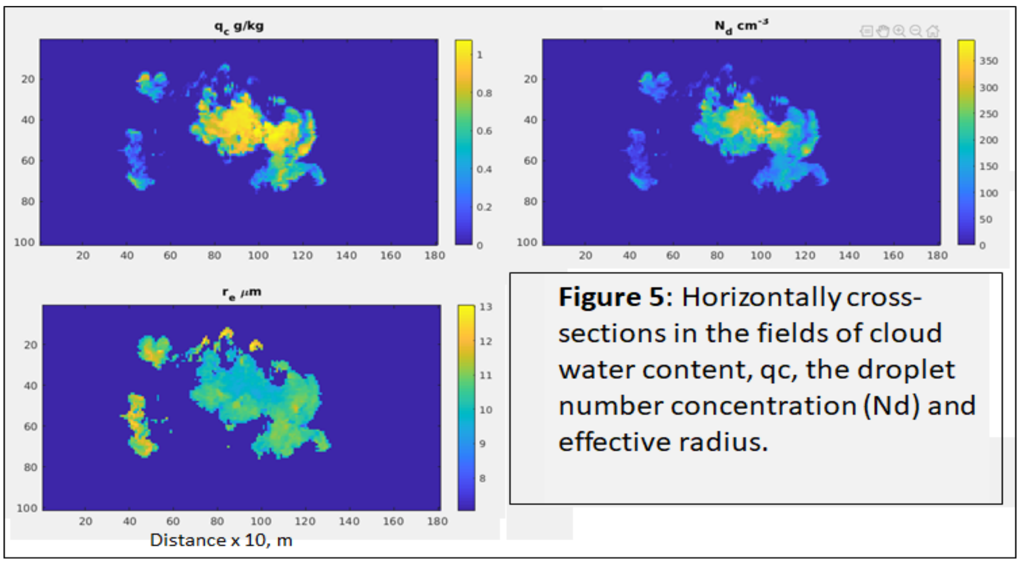

Figure 5: Horizontally cross-sections in the fields of cloud water content, qc, the droplet number concentration (Nd) and effective radius.

One can see that despite the high inhomogeneity of q_c and N_d, the effective radius, r_e, is nearly constant and varies between 11 μm and 12 μm. The low variability of effective radius was also found from radiative measurements.

Publications (2017 – 2020) (Members of our science team are in bold. Out of the total number of 52 papers, we listed below only those papers that are related to our DoE funded research)

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[52] **Pinsky** M.**,** E. Eytan, I. Koren, O. Altaratz and A. **Khain,** 2020: Convective and turbulent motions in non-precipitating Cu. Part 1: Method of separation of convective and turbulent motions, *J. Atmos. Sci.* (In revision).

Conference Papers and Presentations

A. **Marshak** and W. **Yang**, "Study of cloud-aerosol interactions and mixing processes in the clear-to-cloud transition zone using ARM Shortwave Spectrometers" March 20, 2018, Tysons, VA.
Marshak A., and W. **Yang**, "ARM shortwave spectrometers to study the clear-cloud transition zone and mixing processes" Feb. 25, 2018, Boulder, CO.
E. Gavze, E. Ilotoviz and A. **Khain**, 2019: A computationally efficient linear semi-Lagrangian scheme for the advection of microphysical variables in cloud-resolving models. Workshop on Eulerian vs. Lagrangian methods for cloud microphysics, Krakow, Poland, 2019.
E. Eytan, I. Koren, O. Altaratz, A. **Khain** and M. **Pinsky**, 2019: Clouds mixing: a continuous description from the core to the non-distributed environment. Workshop on Eulerian vs. Lagrangian methods for cloud microphysics, Krakow, Poland, 2019.