Final Report of ASR Project "**Advancing Clouds Lifecycle Representation in Numerical Models Using Innovative Analysis Methods that Bridge ARM Observations and Models Over a Breadth of Scales**" (ER65292) for 2011 – 2014

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Overview

This is the final report. Our group conducted several different research projects with funding support from DOE. The research efforts were focused on two of the three research themes of our funded proposal: Cloud turbulence and dynamics (subsections 1 and 2) and their role in cloud lifetime and analysis of the Azores field deployment dataset (subsections 3, 4 and 5) with emphasis on cloud climatology and drizzle retrievals. Three papers were published, one manuscript was submitted and two more are in preparation. A description of the research efforts is given below:

1. Long-term Observations of Fair-Weather Cumuli at the ARM Southern Great Plains Facility

A long record (14-year) of ground-based observations at the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site is used to document the properties of fair-weather cumuli clouds. First, a fuzzy-logic based algorithm is developed to eliminate insect radar echoes in the boundary layer that hinder our ability to develop cloud statistics. The refined dataset is used to document the daytime evolution of fair-weather cumuli clouds. Doppler velocities are processed for lower reflectivity thresholds that contain small cloud droplets having insignificant terminal velocities; thus Doppler velocities used as tracers of air motion. The algorithm is implemented to process entire 14 yr dataset of cloud radar vertical velocity data. There is a noticeable variability in the inter-annual occurrence of summer-time FWC (2-4 % minimum to 12-17 % maximum) with maximum occurrence observed every four years. It is clear that the summer time shallow FWC contain small amounts of liquid water content with liquid water path peaks at 30-60 gm^{-2} and the cloud radar sensitivity fails to detect the significant fraction of thin clouds whose LWP<50 gm^{-2}. Composite diurnal variation of the cloud vertical velocity statistics, surface parameters and profiles of updraft fraction and updraft mass flux are calculated. Statistics on the cloud geometrical properties such as, cloud thickness, cloud chord length, cloud spacing and aspect ratios are calculated on cloud scale. It is observed that the typical occurrence of cloud thickness values are 300-600 m and cloud chord length is ~ 200 m. The maximum occurrence of aspect ratio is at 0.5, indicating the dominance of tower like clouds with vertical extent higher than their horizontal dimensions. The present dataset provides a unique insight to understand the daytime evolution and statistical description of the turbulent structure inside fair-weather cumuli over land. A manuscript describing the analysis results was submitted to the J. of Climate. Currently, we are working on the analysis of the fair weather cumulus dataset collected at the ARM SGP site during the MC3E field experiment and the analysis of the Doppler lidar observations for the determination of the subcloud and cloud base turbulence.

2. Turbulence and gravity waves in cirrus clouds

Ice cloud properties are influenced by cloud-scale vertical air motion. Dynamical properties of ice clouds can be determined via Doppler measurements from ground-based, profiling cloud radars. Here, the decomposition of the Doppler velocities into reflectivity-weighted particle velocity V_t and vertical air motion w is described. The methodology is applied to high clouds observations from 35-GHz profiling millimeter wavelength radars at the Atmospheric Radiation Measurement Program (ARM) Southern Great Plains (SGP) climate research facility in Oklahoma (January 1997–December 2010) and the ARM Tropical Western Pacific (TWP) site in Manus (July 1999–December 2010). The Doppler velocity measurements are used to detect gravity waves (GW), whose correlation with high cloud macrophysical properties is investigated. Cloud turbulence is studied in the absence and presence of GW. High clouds are less turbulent when GW are observed. Probability density functions of V_t, w, and high cloud macrophysical properties for the two cloud subsets (with and without GW) are presented. Air-density-corrected V_t for high clouds for which GW (no GW) were detected amounted to hourly means and standard deviations of 0.89 ± 0.52 ms^{-1} (0.86 ± 0.48 ms^{-1}) and 1.03 ± 0.41 ms^{-1} (0.86 ± 0.49 ms^{-1}) at SGP and Manus, respectively. The error of w at one standard deviation was estimated as 0.15 ms^{-1}. Hourly means of w averaged around 0 ms^{-1} with standard deviations of ±0.27 (SGP) and ±0.29 ms^{-1} (Manus) for high clouds without GW and ±0.22 ms^{-1} (both sites) for high clouds with GW. The midlatitude site showed stronger seasonality in detected high cloud properties. Published in the Journal of Climate 2013 doi: http://dx.doi.org/10.1175/JCLI-D-12-00695.1

3.Verification of radar-based vertical air motion retrievals using airborne observations

We performed a statistical comparison of vertical velocity observations within cirrus from aircraft and ground-based Doppler cloud radar. Two cases of midlatitude anvil cirrus forming under very similar environmental conditions are examined. The case studies benefit from simultaneous observations of vertical velocities in cirrus collected at and around the Atmospheric Radiation Measurement Southern Great Plains site during the U.S. Department of Energy Small Particles in Cirrus field campaign. Observations from both platforms suggest that the majority of vertical velocities in the examined midlatitude anvil cirrus cases are roughly within ±1 ms^{-1} although higher vertical velocities are occasionally observed. The quality of the vertical velocity comparison between in situ aircraft measurements and ground-based Doppler radar retrievals depends on the case. For the first case on 23 April 2010, the comparison suggests that the radar retrieval may underestimate vertical velocities in the range between roughly 50 cms^{-1} and 1 ms^{-1}. For the second case on 14 June 2010, the agreement between radar and aircraft is excellent, and the differences are largely within the observed variability of vertical velocities within cirrus. Differences in the spatial scales of vertical velocities and turbulence sampled by the aircraft and Doppler radar, which arise due to differences in the temporal resolution of the observational platforms are not found to explain the observed discrepancies. Estimates for the dissipation rate of turbulent kinetic energy agree to within 1 order of magnitude between the two observational platforms. Published in the Geophysical Research Letters 2014 doi: http://dx.doi.org/10.1002/2014GL062279

4. Identification of microphysical processes in ice clouds using Doppler radar measurements

In this novel study, we used ground-based 35 GHz profiling Doppler cloud radar observations of ice clouds to derive the power law relation between Doppler velocity V_d and radar reflectivity Z ($V_d = aZ^b$). By removing the vertical air motion from V_d, the power law can be rewritten as $V_t = aZ^b$ with V_t being the reflectivity-weighted particle terminal fall velocity. Profiles of this relation are variable with height. An attempt was made to relate this variability to the dominant microphysical processes in different layers of the cloud. Based on that, the possibility of using profiles of the parameters a and b to distinguish different microphysical regimes was explored. The methodology was applied to long-term measurements (January 1997 to December 2010) at the Atmospheric Radiation Measurement site in the Southern Great Plains. Principal component analysis was used to determine the modes of the profiles that explain most of the observed variance in the observations. Profile-averaged means and standard deviations of parameters a and b amounted to 0.65 ± 0.42 and 0.03 ± 0.19, respectively. Furthermore, three commonly used microphysical relations related to bulk quantities were used to determine values of a and b. These results were found to compare reasonably well with the values obtained from the radar observations. Finally, microphysical considerations showed that radar-derived values of parameter b can be explained in terms of particle size distribution moment changes. Published in the Journal of Geophysical Research – Atmospheres 2013 doi: http://dx.doi.org/10.1002/2013JD020386

5. Marine Boundary Layer Cloud Observations in the Azores

The recent deployment of the ARM Mobile Facility at the Graciosa Island, Azores, in the context of the Clouds, Aerosol and Precipitation in the Marine Boundary Layer (CAP-MBL) field campaign added the most extensive (19 months) and comprehensive dataset of MBL clouds to date. Cloud occurrence is high (60-80%) with a summertime minimum. Liquid precipitation is frequently present (30-40%), mainly in the form of virga. Boundary layer clouds are the most frequently observed cloud type (40-50%) with a maximum of occurrence during the summer and fall months under the presence of anticyclonic conditions. Cumulus clouds are the most frequently occurring MBL cloud type (20%), with cumulus under stratocumulus layers (10-30%) and single-layer stratocumulus (0-10%) following in frequency of occurrence. A stable transition layer in the subcloud layer is commonly observed (92% of the soundings). Cumulus cloud bases and stratocumulus cloud tops correlate very well with the top of the transition layer and the inversion base respectively. Drizzling stratocumulus layers are thicker (350-400 m) and have higher liquid water path (75-150 g m^{-2}) than their non-drizzling counterparts (100-250 m and 30-75 g m^{-2}respectively). The variance of the vertical air motion is maximum near the cloud base and is higher at night. The updraft mass flux is around 0.17 kg m^{-2} s^{-1}, with 40-60% explained by coherent updraft structures. Despite a high frequency of stratocumulus clouds in the Azores, the MBL is almost never well mixed and is often cumulus-coupled. Published in the Journal of Climate 2012 doi: http://dx.doi.org/10.1175/JCLI-D-11-00610.1

6. Cloud radar Doppler spectra in drizzling stratiform clouds: 1. Forward modeling and remote sensing applications

Several aspects of spectral broadening and drizzle growth in shallow liquid clouds remain not well understood. Detailed, cloud-scale observations of microphysics and dynamics are essential to guide and evaluate corresponding modeling efforts. Profiling, millimeter-wavelength (cloud) radars can provide such observations. In particular, the first three moments of the recorded cloud radar Doppler spectra, the radar reflectivity, mean Doppler velocity, and spectrum width, are often used to retrieve cloud microphysical and dynamical properties. Such retrievals are subject to errors introduced by the assumptions made in the inversion process. Here, we introduce two additional morphological parameters of the radar Doppler spectrum, the skewness and kurtosis, in an effort to reduce the retrieval uncertainties. A forward model that emulates observed radar Doppler spectra is constructed and used to investigate these relationships. General, analytical relationships that relate the five radar observables to cloud and drizzle microphysical parameters and cloud turbulence are presented. The relationships are valid for cloud-only, cloud mixed with drizzle, and drizzle-only particles in the radar sampling volume and provide a seamless link between observations and cloud microphysics and dynamics. The sensitivity of the five observed parameters to the radar operational parameters such as signal-to-noise ratio and Doppler spectra velocity resolution are presented. The predicted values of the five observed radar parameters agree well with the output of the forward model. The novel use of the skewness of the radar Doppler spectrum as an early qualitative predictor of drizzle onset in clouds is introduced. It is found that skewness is a parameter very sensitive to early drizzle generation. In addition, the significance of the five parameters of the cloud radar Doppler spectrum for constraining drizzle microphysical retrievals is discussed. A paper was published in 2011: Kollias, P., J. Rémillard, E. Luke, and W. Szyrmer (2011), Cloud radar Doppler spectra in drizzling stratiform clouds: 1. Forward modeling and remote sensing applications, *J. Geophys. Res.*, *116*, D13201, doi:10.1029/2010JD015237.

7. Cloud radar Doppler spectra in drizzling stratiform clouds: 2. Observations and microphysical modeling of drizzle evolution

In part I, the influence of cloud microphysics and dynamics on the shape of cloud radar Doppler spectra in warm stratiform clouds was discussed. The traditional analysis of radar Doppler moments was extended to include skewness and kurtosis as additional descriptors of the Doppler spectrum. Here, a short climatology of observed Doppler spectra moments as a function of the radar reflectivity at continental and maritime ARM sites is presented. The evolution of the Doppler spectra moments is consistent with the onset and growth of drizzle particles and can be used to assist modeling studies of drizzle onset and growth. Time-height radar observations are used to exhibit the coherency of the Doppler spectra shape parameters and demonstrate their potential to improve the interpretation and use of radar observations. In addition, a simplified microphysical approach to modeling the vertical evolution of the drizzle particle size distribution in warm stratiform clouds is described and used to analyze the observations. The formation rate of embryonic drizzle droplets due to the autoconversion process is not calculated explicitly; however, accretion and evaporation processes are explicitly modeled. The microphysical model is used as input to a radar Doppler spectrum forward model, and synthetic radar Doppler spectra moments are generated. Three areas of interest are studied in detail: early drizzle growth near the cloud top, growth by accretion of the well-developed drizzle, and drizzle depletion below the cloud base due to evaporation. The modeling results are in good agreement with the continental and maritime observations. This demonstrates that steady state one-dimensional explicit microphysical models coupled with a forward model and comprehensive radar Doppler spectra observations offer a powerful method to explore the vertical evolution of the drizzle particle size distribution. A paper was published in 2011: Kollias, P., W. Szyrmer, J. Rémillard, and E. Luke (2011), Cloud radar Doppler spectra in drizzling stratiform clouds: 2. Observations and microphysical modeling of drizzle evolution, *J. Geophys. Res.*, *116*, D13203, doi:10.1029/2010JD015238

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9. Clouds, Precipitation and Marine Boundary Layer Structure during the MAGIC field campaign

The recent ship-based Marine ARM GCSS Pacific Cross-Section Intercomparison (GPCI) Investigation of Clouds (MAGIC) field campaign with the marine-capable Second ARM Mobile Facility (AMF2) deployed on the Horizon Lines cargo container M/V *Spirit* provided nearly 200 days of intraseasonal high-resolution observations of clouds, precipitation, and marine boundary layer (MBL) structure on multiple legs between Los Angeles, California, and Honolulu, Hawaii. During the deployment, MBL clouds exhibited a much higher frequency of occurrence than other cloud types and occurred more often in the warm season than in the cold season. MBL clouds demonstrated a propensity to produce precipitation, which often evaporated before reaching the ocean surface. The formation of stratocumulus is strongly correlated to a shallow MBL with a strong inversion and a weak transition, while cumulus formation is associated with a much weaker inversion and stronger transition. The estimated inversion strength is shown to depend seasonally on the potential temperature at 700 hPa. The location of the commencement of systematic MBL decoupling always occurred eastward of the locations of cloud breakup, and the systematic decoupling showed a strong moisture stratification. The entrainment of the dry warm air above the inversion appears to be the dominant factor triggering the systematic decoupling, while surface latent heat flux, precipitation, and diurnal circulation did not play major roles. MBL clouds broke up over a short spatial region due to the changes in the synoptic conditions, implying that in real atmospheric conditions the MBL clouds do not have enough time to evolve as in the idealized models. Published in the Journal of Climate doi: *http://dx.doi.org/10.1175/JCLI-D-14-00320.1*