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"Use of ARM observations and numerical models to determine radiative and latent heating profiles of mesoscale convective systems for general circulation models"

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(Publications supported under the PI's DOE research are shown in italics when first mentioned in the discussion below. These publications are also listed following this discussion.)

In *Cetrone and Houze (2009)* we examined cloud radar data in monsoon climates, using cloud radars at Darwin in the Australian monsoon, on a ship in the Bay of Bengal in the South Asian monsoon, and at Niamey in the West African monsoon. The anvils spreading out from the precipitating cores of MCSs were subdivided into thick, medium and thin portions. The thick portions of anvils showed distinct differences from one climatological regime to another. In their upper portions, the thick anvils of West Africa MCSs were found to have a broad, flat histogram of reflectivity, and a maximum of reflectivity in their lower portions. The reflectivity histogram of the Bay of Bengal thick anvils has a sharply peaked distribution of reflectivity at all altitudes with modal values that increase monotonically downward. The reflectivity histogram of the Maritime Continent thick anvils is intermediate between that of the West Africa and Bay of Bengal anvils, consistent with the fact that this region comprises a mix of land and ocean influences. This study concluded that the difference between the statistics of the continental and oceanic anvils is related to some combination of two factors: (1) the West African anvils tend to be closely tied to the convective regions of MCSs while the oceanic anvils are more likely to be extending outward from large stratiform precipitation areas of MCSs, and (2) the West African MCSs result from greater buoyancy, so that the convective cells are more likely to produce graupel particles and detrain them into anvils.

In *Cetrone and Houze (2011)* we followed on with a more in-depth study of the continental MCSs over West Africa. Because the West African MCSs all had similar structures consisting of leading lines of intense convection followed by a trailing stratiform region, it was possible to distinguish two types of anvil structure. Anvil clouds leading a convective line were generally higher in altitude than the trailing anvil, likely because the hydrometeors in the leading anvil were directly connected to the convective updraft. Trailing anvils extended out of the lower-topped stratiform precipitation region. When the anvils were subdivided into thick, medium, and thin portions, the thick leading anvils were seen to have systematically higher reflectivity than the thick trailing anvil, suggesting that the leading anvil contains numerous larger ice particles owing to its direct connection to the convective region. As the leading anvil moves laterally away from the convective region, the largest particles quickly fall out, and the cloud becomes thinner while retaining its high top. The leading anvil appears to add hydrometeors at the highest altitudes, while the trailing anvil is able to moisten a deep layer of the atmosphere.

In *Powell et al. (2012)* we investigated whether the West African anvil clouds connected with squall line MCSs passing over the Niamey ARM site could be simulated in a numerical model by comparing the observed anvil clouds to anvil structures generated by the Weather Research and Forecasting (WRF) mesoscale model at high resolution using six different ice-phase microphysical schemes. The ARM radar data provide the statistical distribution of the radar reflectivity values as a function of height and anvil thickness. These statistics are compared to the statistics of the simulated reflectivity of modeled anvil clouds at all altitudes. Requiring the model to be statistically accurate at all altitudes is a stringent test of the model performance. All schemes reproduce the anvils to at least a rough approximation, though some schemes get much closer to the observations than others. The typical vertical profile of radiative heating in the anvil clouds is computed from the radar observations using the methodology similar to that of McFarlane et al. (2007). The variability of anvil structures from the different microphysical schemes provides an estimate of the inherent uncertainty in these anvil radiative heating profiles.

In *Zeng et al. (2012)* we carried out further simulations with a cloud-resolving model forced by sounding network budgets over the Niamey region and over the northern Australian region. The sounding data are from two field campaigns: the African Monsoon Multidisciplinary Analysis (AMMA) and the Tropical Warm Pool-International Cloud Experiment (TWP-ICE). The results indicate the different nature of anvil clouds produced in these two environments, which differ both dynamically and in terms of the aerosol environment. The results show that strong vertical wind shear in the upper troposphere brings about broad anvil clouds in TWP-ICE whereas high ice crystal concentrations are one of the key factors that contribute to large AMMA MCSs.

The modeling work in the Powell et al. (2012) study and the Zeng et al. (2012) paper were done in collaboration with NASA/GSFC scientists W.-K. Tao, X. Zeng, and A. Kumar, and we will continue to work with them in the proposed study.

To assess the global importance of the anvil clouds of MCSs observed by ARM radars, the point measurements at ground sites need to be upscaled. Satellite data have the global coverage needed to upscale the ground-based measurements. We have therefore devoted some of the effort of this project to examining how well satellite data can determine the global breadth of the anvil cloud measurements obtained at the ARM ground sites. To address this problem, we have employed A-Train satellite data, which include the CloudSat millimeter-wavelength cloud radar, which is similar to the ground-based cloud radars of ARM. Under this project, Cetrone and Houze (2009) verified the ARM ground-based cloud radar observations of anvil clouds at Niamey and Darwin against CloudSat radar observations of anvils. They found close agreement in the anvil cloud radar statistics despite the fact that the ARM radars were upward looking while the CloudSat radar looks downward through the anvil clouds. Establishing this consistency between the ground-based and spaceborne observations was an important step because it implies that the ARM ground-based radar data can be upscaled to determine the global effects of anvil clouds.

Having made this verification, we next considered whether satellite data could be objectively analyzed to so that their large global measurement sets can be systematically related to the ARM measurements. The analysis of Cetrone and Houze (2009), which determined the basic consistency of the CloudSat and ARM anvil cloud datasets, were based on a manual analysis of geosynchronous satellite data to determine which ARM cloud radar data samples were obtained in the anvil clouds of MCSs. This methodology was sufficient to make the initial ground-truth test of the CloudSat radar observations. However, to examine the global extent and effects of anvil clouds an objective method is needed to handle large multi-year global datasets. To begin this determination, *Yuan and Houze (2010)*, in a joint DOE-NASA study, examined A-Train data to objectively identify MCSs and their anvils by combining data from three satellite instruments: the Moderate Resolution Imaging Spectroradiometer (MODIS) for cloud-top size and coldness, Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) for rain area size and intensity, and CloudSat for horizontal and vertical dimensions of anvils.

In the satellite data, we distinguished three types of MCSs: small and large separated MCSs and connected MCSs. The latter are MCSs sharing a contiguous rain area. Mapping of the objectively identified MCSs showed patterns of MCSs that are generally consistent with previous studies of tropical convection, with separated MCSs dominating over Africa and the Amazon regions and connected MCSs favored over the warm pool of the Indian and west Pacific Oceans. By separating the nonprecipitating (or lightly precipitating) anvil cloud from the high cloud atop the more heavily raining portions of MCSs, this study led to quantitative global maps of anvil coverage. We were further able to establish different types of anvils, but that while they differ slightly from region to region and season to season, their characteristics do not vary widely, implying that the selected ARM ground site data are highly representative of the larger population of anvil clouds of MCSs. There were, however, notable differences between land and ocean MCS anvils. Most anvils everywhere covered areas 1.5-2 times the equivalent radii of the primary rain areas of the MCSs; however, over the warm pool, anvils tended to be larger, sometimes extending out to ~5 times the rain area radius. The modal thickness of MCS anvils was generally ~4-5 km, with the warm-ocean MCSs tending to have thicker non-raining and lightly raining anvils near the edges of their actively raining regions. Such thicker anvils were nearly absent over continental regions. The maps of the global coverage of MCS anvils of various thicknesses derived from satellite information lay the foundation for upscaling the ARM measurements to determine the global radiative effects of anvil clouds. They also show that while the anvils are largely similar everywhere in the tropics, the differences between land and ocean anvils indicated by satellite suggest that it is important to analyze ARM ground-site data from both land and ocean locations in the tropics. Since the Cetrone and Houze (2009) and Powell et al. (2012) studies concentrated mostly ARM site data on MCS anvil clouds over land, it is important now to focus on oceanic anvil clouds, as we will do with the ARM Madden-Julian Oscillation (MJO) Investigation Experiment (AMIE) dataset in our new proposed research.

Yuan et al. (2011) detailed further differences between the land and ocean MCS anvil clouds by examining the interior structure of the anvils with the satellite-detected the CloudSat Cloud Profiling Radar (CPR). Reflectivity histograms of MCS anvil clouds from the CPR were found to vary only slightly across the tropics, except that (i) in continental MCS anvils, broader distributions of reflectivity occurred at the uppermost levels in the portions closest to active raining areas; (ii) the frequency of occurrence of stronger reflectivity in the upper part of anvils decreased faster with increasing distance in continental MCSs; and (iii) narrower-peaked ridges are prominent in reflectivity histograms of thick anvil clouds close to the raining areas of MCS superclusters occurring over oceans. These results suggest, again, that since up to now we have emphasized continental tropical anvil clouds (at Niamey, Cetrone and Houze 2009, 2011; Powell et al. 2012), it is important to focus attention on oceanic anvil clouds, which are the subject of our follow-on study proposed here.

Yuan and Houze (2012) continued their satellite survey of anvil clouds in the Indo-Pacific region to determine the role of MCSs in producing the cloud pattern associated with the MJO. This study provided background climatology of MCS anvil clouds in preparation for AMIE. MCSs were found to occur in a pattern consistent with the formation and eastward propagation of the large-scale convective envelope of the MJO. Over the open ocean, the anvil-producing MCSs tended to be merged superclusters ("connected MCSs"), while over the maritime continent area they tended to be separated or discrete systems. Over all regions affected by the MJO, connected systems increase in frequency during the active phase of the MJO. Characteristics of each type of MCS (separate or connected) are not found to vary much over MJO-affected regions. However, separated and connected MCSs differ in structure from each other. Although the upper-level clouds of the connected superclusters are massive, and their anvils are thick, the nonprecipitating anvils of connected MCSs are spatially limited by the fact that they tend to be bridges between clustered precipitation convective systems. The maximum height of MCS precipitating cores was found to vary only slightly from one phase of the MJO to the next, and the variation was related to sea surface temperature. Enhanced large-scale convection, greater frequency of occurrence of connected MCSs, and increased mid-troposphere moisture coincide, regardless of the region, season or large-scale conditions (such as the concurrent phase of the MJO), suggesting that the coexistence of these phenomena is likely the nature of deep convection in the MJO, and perhaps the oceanic tropics in general. The increase of mid-troposphere moisture in locally subsiding regimes during large-scale convectively active phases suggests that the source of mid-troposphere moisture is not local or instantaneous and that the accumulation of mid-troposphere moisture over MJO-affected regions needs to be better understood. These preliminary results on the nature of MCS anvil clouds in the MJO lay the groundwork for our proposed research focused on the anvil clouds of MCSs in the MJO.

As noted above, the examination of MCSs and their anvil clouds across the tropics is important preparation for the next phase research on MCS anvil clouds, which will examine oceanic MCSs, and will do so in the context of the MJO. The MJO is arguably the most significant variable phenomenon of the tropical general circulation, and its large-scale dynamics are linked to the oceanic cloud population. The MJO is indeed the ideal natural laboratory for studying anvil clouds in the oceanic tropics since it consists of well defined phases in which the synoptic environment varies. Focusing on the MJO will allow us not only to reveal aspects of the coupling of the cloud population with the large-scale dynamics of the MJO, it will show how MCS anvil clouds vary from one synoptic environment to the next. The nature of the cloud population of the MJO is the focus of AMIE and is the logical direction for a new study examining MCSs and their anvil clouds in the context of the MJO. This direction is the primary focus of AMIE and is the focus of the new study proposed here, which is aimed at using the special observations of AMIE to understand the nonprecipitating MCS anvil clouds of the MJO.

In addition to the above-described refereed publications, we have various aspects of the results in a wide variety of venues (see list of presentations below). These presentations have shown details of the observed characteristics of the MJO convective cloud population, both how the population of clouds varies within the MJO and how the MJO convection relates to convection in the tropics as a whole.

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Presentations under this grant

"The tropical convective cloud population," Seminar, National Taiwan University, Taipei, 15 April 2011. (Houze)

"The tropical convective cloud population," Seminar, Peking University, Beijing, 4 July 2011. (Houze)

"Severe Convection and MCSs," Lecture, Summer School on Severe and Convective Weather, Nanjing, 11 July 2011. (Houze)

"The Tropical Convective Cloud Population," Lecture, Summer School on Severe and Convective Weather, Nanjing, 11 July 2011. (Houze)

"Convective Feedbacks to Large Scales: Physical Mechanisms," Lecture, Summer School on Severe and Convective Weather, Nanjing, 11-15 July 2011. (Houze)

"Diurnal Variability of Deep Tropical Convection," Lecture, Summer School on Severe and Convective Weather, Nanjing, 11-15 July 2011. (Houze)

"The Convective Cloud Population during the Buildup of the Madden-Julian Oscillation," AGU Fall Meeting, San Francisco, 7 December 2011. (Houze)

"The Convective Cloud Population of the Madden-Julian Oscillation: Observations from DYNAMO," Krishnamurti Symposium, AMS Annual Meeting, New Orleans, 26 January 2012. (Houze)

"The Convective Cloud Population of the Madden-Julian Oscillation: Early Results from DYNAMO," Int. Conf. on Opportunities and Challenges in Monsoon Prediction in a Changing Climate, Golden Jubilee of the Indian Institute of Tropical Meteorology, Pune, India, 23 February, 2012. (Houze)

"Nonprecipitating Phenomena Seen by the S-PolKa Radar In AMIE," ARM Science Team Meeting, Washington DC, 14 March 2012. (Houze)

"The Cloud Population of the Madden-Julian Oscillation." Atmos. Sci. Colloquium, Seattle, 6 April 2012. (Houze)

"The MJO Cloud Population over the Indian Ocean," 30th Conference on Hurricanes and Tropical Meteorology, 19 April 2012, Ponte Vedra Beach, Florida. (Barnes)

"Indian Ocean Convection Seen by the S-PolKa Radar in DYNAMO," 30th AMS Conf. on Hurricanes and Tropical Meteorology, Ponte Vedra, Florida, 19 April 2012. (Houze)

"Tropospheric Humidification by Anvil Clouds over the Indian Ocean," 30th AMS Conf. on Hurricanes and Tropical Meteorology, Ponte Vedra, Florida, 19 April 2012. (Powell).