Cloud and Dynamical Processes of Precipitating Warm Cumuli During RICO

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This proposal is linked to the Rain in Cumulus over the Ocean (RICO) project, described in the RICO Scientific Overview Document. The project's aim is to study shallow, precipitating cumulus over a tropical ocean. A field campaign is planned for the winter 2004-05 in the area of the Lesser Antilles. The proposed work is for the study the onset of precipitation, and its effect on cumulus organization and evolution, by means of data collected in RICO by the Wyoming King Air (WKA) and the Wyoming Cloud Radar (WCR).

The WKA will carry an array of cloud, atmospheric state, wind, radiation, and flux probes, in addition to the WCR. The WCR is a 95 GHz Doppler radar, providing high-resolution reflectivity and velocity data in vertical and horizontal sections along the flight track. The ability to place airborne in situ observations in the context of radar-derived echo and vertical velocity information at ~30 m resolution constitutes a powerful tool for cloud and precipitation studies. The PIs have extensive experience in using this combination of observing systems.

The proposed work will explore the linkages between the kinematic evolution of warm marine cumulus and precipitation development, as well as between the cloud microphysical and the dynamical processes that sustain precipitating cumulus clusters. The objectives are twofold, but interconnected.

The first objective is to use the WCR transects, together with the in situ thermodynamic and cloud data, and situational data from S-POL, to diagnose features of the cloud structure that bear most importantly on the initial formation of precipitation. Substantial evidence exists that the development of precipitation in warm cumulus is strongly influenced by processes of scales smaller than that of the cumulus or even its updraft, making the high-resolution radar and in situ data we plan to gather specially appropriate for this objective.

The second objective relates to the mesoscale dynamics of precipitating warm cumuli. What processes control cell regeneration in cumulus clusters, whose lifetime far exceeds that of the cells? How do evaporative cooling and entrainment contribute to the formation of a cold pool, and how does that cold pool interact with ambient shear? Or is the primary mechanism by which cold pools organize tropical convection primarily thermo-dynamic, driven by convectively-induced surface fluxes? The dynamical interpretation will be based on multi-scale observations: the temporal and mainly horizontal S-POL perspective, plus ambient soundings, set a context for the WCR-based description of the fine-scale vertical cloud and kinematic structure of cumulus clusters, and WCR data in turn are a context for the WKA-measured variations in the thermodynamic, kinematic and water fields.

The objectives of this proposal are fully consistent with overall RICO goals. The flight plans proposed have been incorporated into those presented in the Facility Request for the WKA. Those flight plans have been devised to make efficient use of flight hours for our objectives and for those of collaborators.

The broader impacts of the proposed work include the further development of methods of cloud studies with instrumented aircraft and aircraft-mounted cloud radar and the collection of millimeter radar data in preparation for NASA's launching of a similar radar (CloudSat). Shallow, precipitating cumuli are ubiquitous over tropical oceans, yet models of the global atmospheric circulation (GCMs), which are used for climate prediction, generally assume that these clouds do not precipitate. A better understanding of the microphysical to mesoscale processes governing these clouds will yield a more accurate parameterization of their effects in GCMs and in numerical weather prediction models. The research will also advance understanding of fundamental cloud physics, aerosol/cloud interaction and precipitation measurement issues. The proposed research will also support the training of graduate students in the special techniques of these studies, and will engender collaboration among a wide range of scientists.

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[1] This proposal is written as a joint effort between the University of Wyoming and NOAA ARL. The NOAA ARL budget will be covered under a proposal submitted to NOAA's Office of Global Programs under the NOAA Climate and Global Change Program. The two proposals are identical and their objectives represent a close synergy between the two groups.

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1. Cloud radar studies: objectives and significance

1.1 RICO

This proposal is linked to the Rain in Cumulus over the Ocean (RICO) campaign. The campaign, to be conducted in the winter of 2004-'05 in the Lesser Antilles, intends to characterize and interpret warm maritime cumuli at multiple scales, with an emphasis on precipitation formation and its effect on cumulus evolution. Questions on the microscale surround the rapid onset of precipitation and the transition from non-precipitating clouds to mature rainshafts. On the mesoscale, the key questions regard why tradewind cumuli are organized in clusters, why these clusters are often long-lived, and specifically, how cells are regenerated around precipitation-induced cold pools. On the largest scale, RICO hopes to provide an insight in the energy exchange between tropical oceans and the atmospheric boundary layer (BL) containing trade wind cumuli.

RICO hopes to field several research aircraft, including the NCAR C-130 and the Wyoming King Air (WKA), and the NOAA Ron Brown vessel. Most flights will be conducted within coverage of the S-POL radar, which will be complemented by a coincident Ka-band radar scanning synchronously. For more details, the reader is referred to the RICO Scientific Overview Document (RICO SOD), available at http://rico.atmos.uiuc.edu/.

Of particular importance to this proposal is the WKA. It will carry the Wyoming cloud radar (WCR) in addition to an array of cloud, atmospheric state, wind, radiation, and flux probes. The WCR is a 95 GHz Doppler radar, providing high-resolution reflectivity and velocity data in vertical and horizontal sections along the flight track. The ability to place airborne in situ observations in the context of radar-derived echo and vertical velocity information at ~30 m resolution, mainly above and below the aircraft, constitutes a powerful synergy for cloud and precipitation studies. Pencil-line in situ data can be placed in the context of the cloud vertical structure, and radar reflectivities can be interpreted by means of airborne drop size distribution measurements.

1.2 Significance

Warm, precipitating cumuli, topping at altitudes between 1.5-4.5 km, are prevalent over the oceans, globally between the subtropical highs and the intertropical convergence zone (ITCZ). Such cumuli are common even within the ITCZ and the western equatorial Pacific warm pool (Rickenbach and Rutledge 1998).

These 'trade wind' cumuli have a large potential impact on climate, not only for their effect on the Earth's radiation balance, but also for the role they play in the heat balance of the tropical lower troposphere. Regarding the latter, radiative cooling tends to balance latent heating from deep precipitating systems in the upper tropical troposphere, but in the lower troposphere a net cooling occurs (Mapes 2000), which can only be explained by an underestimation of the precipitation from warm cumuli. Spaceborne radar data suggest that warm rain is surprisingly common over the tropical oceans (Short and Nakamura 2000), yet its true significance remains unknown, since the combination of limited sensitivity (18 dBZ) and resolution (5 km) causes much of the rainfall from trade wind cumuli to be invisible for this spaceborne radar. Other spaceborne probes also fail to quantify warm rain over the oceans, because they have no marked IR brightness deficit and no passive microwave (85 GHz) ice scattering signature. Moreover, state-of-the-art general circulation models (GCMs) generally assume that trade wind cumuli do not precipitate. This assumption must imply errors in the lower tropospheric latent heating, and hence possibly in the parameterization of surface fluxes, the water vapor profile, and the radiative flux divergence.

To make progress with these large-scale questions, a better understanding of the microscale and mesoscale processes that control trade wind cumuli is needed. Broad questions that this proposal is aimed at are as follows.

(a) How do cloud and aerosol processes produce and sustain rain in trade wind cumuli? and

(b) How is the mesoscale organization of trade wind cumuli affected by the rain it generates?

Ultimately a better understanding of the microphysical to mesoscale processes governing trade wind cumuli will yield a more accurate parameterization of these cumuli in GCMs and in numerical weather prediction models.

1.3 Characteristics of Caribbean trade wind cumuli

The literature is sparse on the sizes, lifetimes, composition, etc. of the small but precipitating trade wind cumuli. Lopez (1976) and Warner and Austin (1978) use GATE C-band radar data to demonstrate that cumulus heights are lognormally distributed from ~1 km to the tropopause. GATE was conducted in the Atlantic ITCZ (5-11°N) during July-September. Johnson et al. (1999), examining the population of cumuli in the western equatorial Pacific, distinguish between shallow cumuli, with radar echo tops near 2 km, and congesti, with echo tops near the freezing level. It remains to be seen whether two spectral peaks can be found in the RICO cumulus population. In the Lesser Antilles in winter (DJF), cumulonimbi with or without anvil are observed about 15% of the daytime, 'moderate to large cumuli' just over 35%, and 'small cumuli' 25-30% (Norris 1998a). These statistics are based on human observations, and the cloud classification is according to the WMO synoptic code (WMO 1975).

Our interest is in the entire spectrum of precipitating warm cumuli. To gain an impression of the cloud patterns to be expected during RICO, we examined the San Juan WSR-88D, GOES visible, and radiosonde data for December 2001. The following summarizes our findings. In addition, we consulted with Dr. Knight, who observed clouds from the shores of Puerto Rico (PR). His photos can be viewed at http://rico.atmos.uiuc.edu/photos.htm.

A deep, moist mixed-layer with a cap below the freezing level and little low-level shear is expected to be favorable for the development of precipitating cumuli. Twice-daily sounding data indicate that such condition, with a cap between 2-4.5 km, prevailed 22% of the time in December 01 over PR and 37% of the time at Guadeloupe in Dec 02 and Jan 03. Additionally, some 24% of the PR soundings featured a deep layer of CAPE (convective available potential energy), but stable layer near the freezing level (650-450 mb). Such profile is conducive to congesti, but it may also allow deep convection. All of these days, about 50% in total, are considered suitable for our objectives.

On these days, precipitating cumuli are present, and the satellite-inferred cloud coverage appears to be not much larger than the radar echo field. Two types of echoes occur in a continuum of sizes. Most numerous are the smaller patches, ~ 5 km in diameter, apparently randomly scattered, without any evident linear organization. Sometimes an alignment can be detected, in various orientations, with various relations to the low-level wind or wind shear. These small echoes have a short lifespan (usually <1 hr), and a peak reflectivity of 30-35 dBZ. *Clusters* of mesoscale dimensions also occur, with a long axis around 20 km. Sometimes they are amorphous, but more commonly they are linear. When multiple cumulus bands are present, their spacing varies. The mesoscale echoes have a lifespan of more than 1 hr, sometimes this assessment is contrained by the size of the radar domain. Their maximum reflectivity is about 30-35 dBZ as well. The flight plans we propose (Section 6) are designed with these observations in mind: the smaller patches are preferred for microphysical studies, while the clusters are preferred for cumulus interaction studies.

Eight days in Dec 01 experienced a marine BL capped at 820-860 mb by warm, dry air. On these 'suppressed' days, cloudiness was mostly widespread while precipitation echoes were shallow, tiny (< 5 km), and weak (max 20 dBZ), yet not absent. Presumably these are drizzle patches within stratocumulus. The brightness of the cloud field varied considerably, with well-defined, brighter convergence lines, some persisting for over two hours. The echo patches were clearly coincident with these lines, yet they did not reveal the linear nature. LeMone and Pennell (1976) examine the distribution of non-precipitating trade wind cumuli on two such suppressed days. Finally, the remaining seven days in Dec 01 exhibited deep convection, with low cloud bases, little convection inhibition (CIN) and CAPE values between 1300-2200 J/kg. On such days large anvils form, core reflectivity values may exceed 50 dBZ, a convective/stratiform separation is seen, and precipitation systems may exceed 20 km in diameter. But even on such days, there are more shallow lines or clusters whose peak reflectivity never exceeds 40 dBZ during a lifespan of several hours. Neither the suppressed nor the deep-convection conditions are our primary target in RICO.

1.4 Objectives

Broadly speaking, we aim to explore the linkages between the kinematic evolution of warm marine cumulus and early precipitation development, as well as between the cloud microphysical and the dynamical processes that are responsible for the maintenance of precipitating cumulus clusters. The objectives are twofold, but interconnected. In terms of PI involvement, objective 1 will be the focus for Drs. French and Vali, while objective 2 will be Dr. Geerts'.

Objective 1 (Section 3): Our first objective is to advance understanding of the initial development of precipitation. Substantial evidence exists that the development of precipitation in warm cumulus is strongly influenced by processes of scales smaller than the cloud dimension or even the major updraft region. The WCR, together with the in situ thermodynamic and cloud data, and situational data from S-POL, will be used to diagnose the development of precipitation. These factors, in the context of diagnosed motion fields, will help to frame descriptive and numerical models of the relevant cloud processes.

Objective 2 (Section 4): Our second objective relates to the mesoscale dynamics of precipitating cumulus cloud clusters. Why are cumuli organized in clusters whose lifetime far exceeds that of the component cells? What process controls the regeneration of cells? Again the temporal and mainly horizontal S-POL perspective, plus ambient soundings, set a context for the fine-scale description, by the WCR, of the vertical cloud and kinematic structure, and WCR data in turn are a context for the WKA-measured variations in the thermodynamic, kinematic and water fields.

1.5 Relevance of other RICO instruments to this proposal

Our exploration of the linkages between cloud kinematics and early precipitation development, and between latent heating, ambient shear, and cumulus regeneration, will focus on the WKA probes, in particular the WCR. But other instruments are relevant. Most important is the S-POL-Ka radar system, which provides a continuous mainly horizontal context of the cumulus clusters at a resolution about one order of magnitude larger than the WCR. The operation of the WKA within S-POL-Ka coverage is essential not only to initially guide the WKA, but also, after the field phase, to examine precipitation onset and mesoscale dynamics of cumulus clusters. The C- and W-band radars aboard the Ron Brown may act in a similar surveying capacity as S-POL.

Ambient soundings are essential. These can be dropsondes from an aircraft in the vicinity, upsondes from the Ron Brown or Barbuda, or WKA soundings from near sea level to above the highest cumulus towers in the cluster. The C-130 will provide an additional source of data for the cloud process studies, in particular on days when the C-130 flies 60 km diameter circles around the WKA cumulus target. The C-130, and other RICO aircraft, may also penetrate the same cluster, simultaneously, at different levels. Our cumulus interaction hypothesis (Section 4.2) will benefit from ground-based flux measurements, during the passage of a cumulus cluster. Finally, the C-130 and WKA flux and cloud measurements will need to be intercompared along proximity flight legs.

1.6 Contribution of the Wyoming King Air and Cloud Radar to RICO objectives

The WKA and WCR will contribute to RICO's objectives, as detailed in the RICO SOD, both at the cloud microphysics and at the cloud interaction scales. Several scientists have indicated an interest in the use of WKA and WCR data, including Drs. Jeff Snider, Bjorn Stevens and David Kristovich. Through a separate RICO proposal, Dr. Snider plans to use WKA-based CCN measurements to complement a ship-based CCN/aerosol intercomparison. Invariably his interest, and that of others, will lead to some degree of collaboration. We expect this collaboration to define itself at the preparatory RICO workshops, and mainly in the field.

The key measurements at the cloud scale are the drop size distribution, determined from the cloud particle probes, and the vertical air motion, obtained from the gust probe. The WCR reflectivity is a robust indicator of drizzle presence, at least in marine stratocumulus, therefore it may complement in situ measurements of spectral broadening in the pre-precipitation stage. The WCR will also be useful in understanding the complex fine-scale structure of cumuli. The WCR-derived vertical structure of up- and downdrafts is important to test entrainment/ buoyancy theories. The depiction of the vertical cloud structure will shed light on the often contradictory interpretations of cloud probe data.

At the cloud-interaction scale, the WCR data will provide the vertical context for in situ cloud, thermodynamic, and humidity measurements. A key variable is buoyancy, which requires an accurate determination of humidity, temperature, water loading, and aircraft altitude, both within and outside clouds. Both WCR and in situ data are required to depict the strength and horizontal/vertical extent of cold pools, from their development until the regeneration of convection around their peripheries. The lowest flight levels are used also to estimate changes in surface fluxes.

2. Summary of prior relevant research

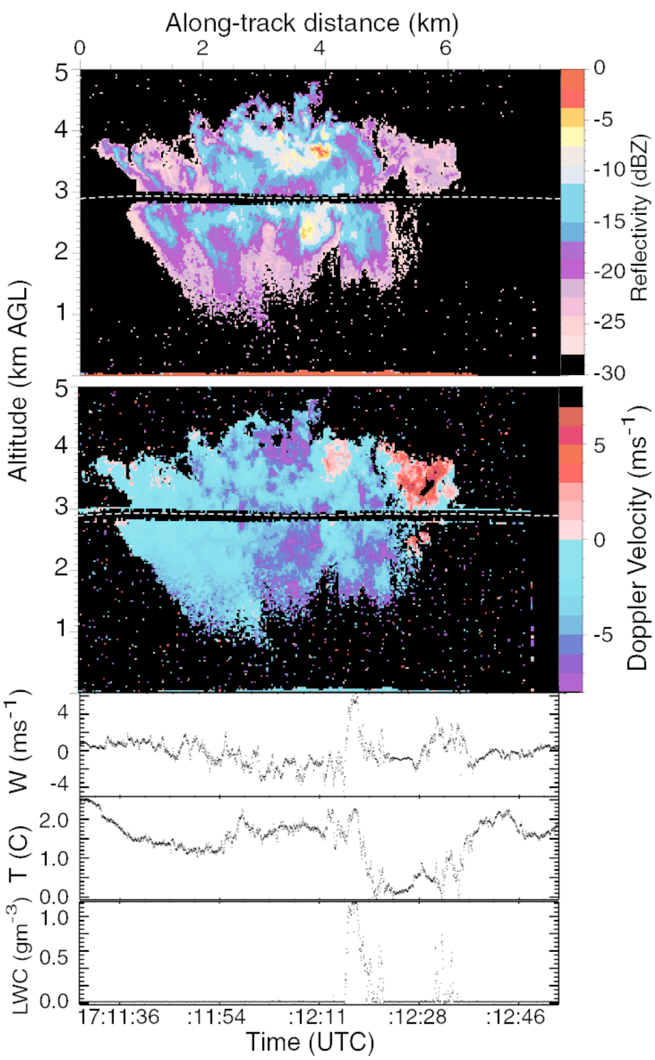
The centerpiece of this proposal is the Wyoming Cloud Radar (WCR) aboard the WKA. The in situ cloud and thermodynamic measurements, combined with high resolution cloud radar reflectivity and velocity profiles in vertical and horizontal transects around the aircraft, yield a rich dataset for the study of cloud microphysical and dynamical aspects of precipitating shallow cumuli.

The WCR was developed in the early 1990's (Pazmany et al. 1994) and has participated in 12 field experiments since then (cf. <http://www-das.uwyo.edu/wcr/>). An array of possible research applications for this linear polarization Doppler 95 GHz radar is discussed in Kropfli and Kelly (1996). Of most direct relevance to this proposal is the WCR deployment in the Small Cumulus Microphysics Study (SCMS) in the summer of 1995 in east-central Florida. One

WCR antenna was available in that project, looking either up or sideways from the WKA. Results from that project are in French et al. 1999 and 2000, and points relevant to RICO are also summarized in Section 3.

In the TRAC98 (Turbulence et Circulations Coherentes dans la couche limite Atmospherique) campaign in France the WCR was installed on a Fokker-27 airplane, and the vertical-plane dual-Doppler (VPDD) antenna configuration was employed for the first time (Leon et al. 1999). This campaign focused on the microphysics and dynamics of BL cumuli. It was the TRAC98 data that inadvertently lend support to the use of the WCR in the study of the optically-clear convective BL, opening the door to the study of BL processes leading to convective initiation. This led to participation in IHOP (International Water Vapor Project, Weckwerth et al. 2003), where VPDD and profile data were collected for the first time aboard the WKA, thanks to a new nadir port. At this time the finescale structure of several clear-air convergence lines is being analyzed, including a cold front (Geerts and Leon 2003) and an undular bore (Koch et al. 2003). The echo strength turned out to be sufficient to describe thermals in the undisturbed convective BL (Geerts and Miao 2003a, 2003b) (cf http://www-das.uwyo.edu/wcr/projects/ihop02/).

The Office of Naval Research sponsored three studies of marine stratus, two off the Oregon coast with the WCR aboard the WKA, in the summers of 1995 and 1999. Vali et al. (1998) found that both the reflectivity and velocity fields of coastal stratus display pronounced fine-scale variation that is not apparent in its optically smooth appearance. The results also showed that vertical velocity[1] and drizzle are positively correlated in the upper parts of stratocumulus. During DYCOMS-II (Dynamics and Chemistry of Marine Stratocumulus), conducted in July 2001 a few hundred km southwest of San Diego, the WCR operated on the NSF/NCAR C-130 aircraft, again in VPDD mode.



The DYCOMS field study and initial findings from it are summarized in Stevens et al. (2003). Additional studies are reported on www-das.uwyo.edu/~vali/dycoms/ dy_rept.html. Suggestions from these studies, whose manifestations in RICO we will be examining carefully, are **a)** that drizzle in quite prevalent in stratocumulus, **b)** that small (sub-kilometer) regions of updrafts and heavier drizzle are co-located, and, **c)** that drizzle and no-drizzle regions of tens of kilometers in extent occur side by side. Some of the latter variability appears to be related to changes in CCN populations but that conclusion is quite tentative at this point and the exploration of other possible explanations continues.

The High-Plains Cumulus (HiCu) campaign, conducted with the WCR and the WKA near Flagstaff AZ (summer '02) and Laramie WY (summer '03) has similar objectives to RICO and thus constitutes an important learning experience ahead of RICO. One sample from HiCu02 is shown in **Fig. 2.1.**

Fig 2.1. *Example of WKA and WCR profiling data from a partially growing and partially decaying cumulus near Flagstaff, on 20 July 2002. The WCR provided simultaneous upward and downward views. The flight level is indicated by the dashed lines though the echoes. The altitude is above ground level. In situ observations of liquid water content (LWC), air temperature (T), and vertical air motion (w) can be interpreted in terms of the cloud vertical structure shown in the color panels, and WCR reflectivity/ velocity data can be interpreted in terms of the more direct in situ cloud and kinematic information. (image courtesy of Dave Leon).*

[1] Vertical velocities include the fallspeed of drizzle, i.e. they represent the drizzle settling speed. More on this topic in Section 5.3.

There were only a handful of flights in summer '02 and only a couple of those have radar data, so that only 'sample' analyses are available at this time. Another opportunity to test the combination of radar profiles with in situ measurements in cumuli is the HiCu03 campaign, which has just commenced. A very recent example is shown in **Fig 2.2** illustrating both the complexities that may present themselves in precipitating cumulus and the opportunities for interpretations of cloud structure. We believe this to be one of the most powerful ways in existence to depict and study cumulus structure. Several flight strategies proposed for RICO (Section 6) will be tested this summer in similar cumuli.

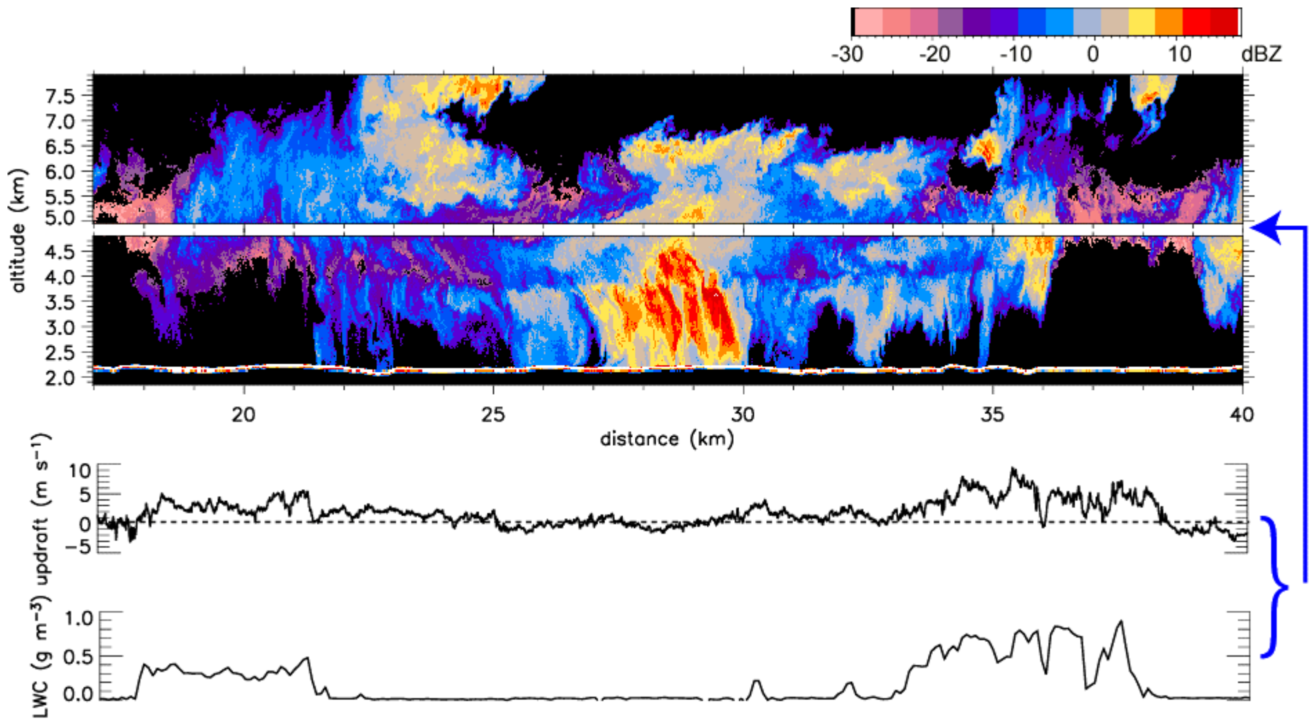


Fig 2.2. *WCR up/down profile data and WKA traces for a congestus observed near Laramie, WY, on June 20, 2003. The large arrow points to the flight level. Temperature at flight level was near -5 °C. The altitude is expressed above sea level, and the white line near 2.2 km is the ground echo. The aspect ratio of the reflectivity images is 1:1.*

3. Linkage between cloud kinematics and the onset of precipitation

The task of connecting cloud dynamics and the evolution of hydrometeors is especially daunting in cumulus, whether one considers ice initiation or the early stages of precipitation formation through warm processes. The difficulty is vividly illustrated by how soft the definitions are for turrets, cells, clusters etc, elements thought of as cumulus building blocks. Results from SCMS underscored these difficulties and RICO is not likely to fully resolve the problems. But at least our observational plans recognize these difficulties and address them as well as possible.

The main tools currently used to observe the behavior of cumulus —aircraft and ground-based radar—fail in one important regard. Neither can provide good depictions of the vertical motion fields within cumulus, either at an instant or as a function of time. It is in this regard that the importance of the WCR was clearly demonstrated in SCMS and other projects. While the WCR is not capable of producing observations of vertical motions throughout the cloud volume, it can yield the vertical air motion in a vertical plane above and below the aircraft, and two components of the air motion below the aircraft. These are very revealing measurements, especially when coupled with the in situ data along the flight path. *Thus, our goal with this part of the effort is to explore in the best possible way the connections between measured air motions and the early development of precipitation.*

3.1 Connections to earlier studies

Studies that bear the most relevance to this proposed work are SCMS and HiCu. In those studies much has been learned in regards to sampling strategy and how best to utilize the WKA/WCR combination in probing rapidly evolving cumuli. Important additional ideas come from the DYCOMS studies.

The cumuli targeted in SCMS were rather small and evolved rapidly, changing character dramatically in periods as short as 3 to 5 minutes. **Fig 3.1** shows the evolution of a cloud, illustrating the detail in the structure that the WCR data provides. Although the spatial resolution provided by the WCR is very good, the temporal resolution was limited by the repeat cycle of aircraft penetrations. In general terms, these clouds evolved through a life cycle best represented by pulses of growth followed by decay. Individual pulses were spaced roughly 10 to 15 minutes apart, with a cloud experiencing two to four pulses during its lifetime (French et al. 1999). The SCMS data suggest that later pulses may produce more drizzle at a given level than earlier pulses.

In general, drizzle drops were clustered in and around regions of high cloud liquid water content. However, a number of drizzle drops were found near cloud edges or even completely outside of cloud. Such regions were devoid of cloud water and were normally associated with weak downward motion. Figures 11, 12 and 13 in French et al. (2000) illustrate this point; the few drizzle drops detected by the in situ probes frequently were located at unexpected places in or near the cumulus. These observations do not readily lend themselves to an interpretation of the origin of the drizzle.

The correlation found in DYCOMS between higher drizzle rates and vertical velocities (as mentioned in Section 2) contrasts with the SCMS findings discussed in the preceding paragraph. Lower vertical velocities in Sc than in Cu may be part of the reason, but also there is a slightly different focus between the presence of sparse drizzle drops in Cu and more intense drizzle in Sc; this latter recognition leads us to focus in this proposal on regions of 'early but substantial' precipitation in RICO. Depending on the cloud types on given days, this may still mean drizzle (roughly <1 mm h^{-1} intensity and < 300 μm diameter) or moderate rain (factors of 10 above drizzle).

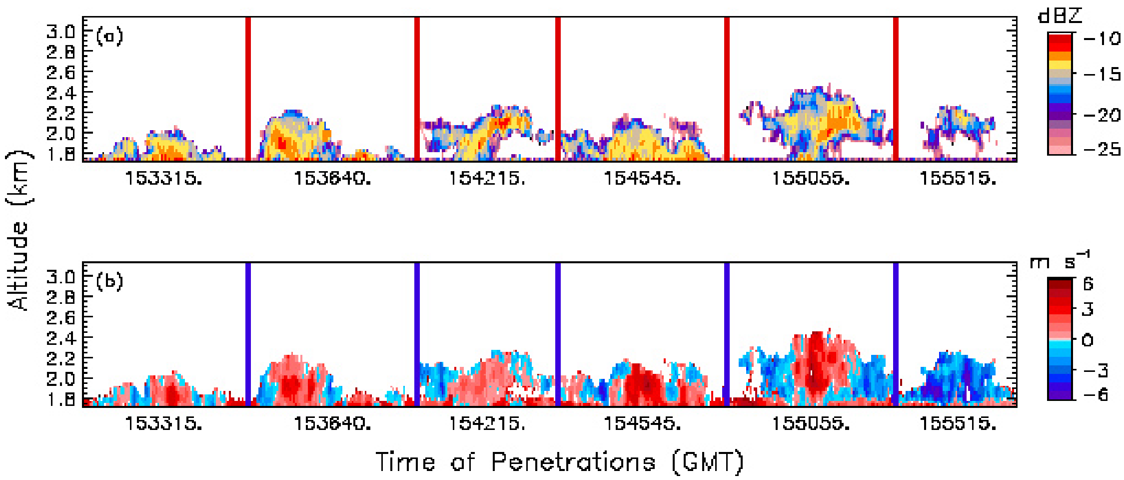


Fig 3.1. *Example of the evolution of two growth pulses from a single cloud during SCMS. The data were collected using the WCR in up-looking mode. The top illustration shows the reflectivity field, the bottom shows the velocity field (positive is upwards). The times indicate the time of penetration in GMT. The aspect ratio for each panel is 1:1.*

The WCR data from SCMS was limited to profiling above the flight path of the WKA. This limitation leads to preferential sampling near cloud base. Full profiling above and below the WKA is now possible (Section 5, Figs 2.1 and 2.2). We will be emphasizing the use of this observational scheme in RICO.

3.2 Research Questions

For the cloud process studies in RICO, we propose to explore linkages between the kinematic and microphysical character of the clouds and early precipitation development. We will investigate how the initial development of precipitation is related to the evolution of individual pulses. We will attempt to determine the significance (if any) of the re-circulation of precipitation. We will look for entrainment signatures and investigate the importance of entrainment as it relates to the evolution of cloud droplet spectra and to precipitation development. The specific research questions we will address as part of the RICO cloud process studies are:

1. What is the life cycle of individual cloud elements? What description best combines the view of the cloud as individual pulses or bubbles mixing with the surrounding air or cloud, or as plumes with a distinct in-flow/out-

flow? The relative locations of pulses, their temporal spacing, and the circulations associated with both growth and decay are important for questions related to thermodynamic pre-conditioning and possible precipitation re-circulation. These factors are relevant to what might be appropriate modeling frameworks for the clouds.

2. How are the reflectivity and velocity fields related in vertical and horizontal sections across the clouds? The evolution of precipitation is constrained by the velocity fields, and the reflectivity fields indicate where precipitation is located. These fields, as functions of early growth-to-decay cloud phases, are the most relevant data sources for our objectives, and those of several other RICO participants. While the inherent size/concentration ambiguity of radar reflectivity is a hindrance here, that problem is at least partially softened by having simultaneous in situ size distribution data. As the example in **Fig . 3.1** shows, the simultaneous velocity and reflectivity data offer ample opportunities for analyses of spatial correlations, height-dependent patch size distributions, construction of vertical profiles, etc. We have good experience with these types of analyses from SCMS, DYCOMS and other studies. To some extent, these observations and analyses will frame the other issues we plan to examine: Is there a preferred location for the earliest observed precipitation in growing pulses? Is there evidence for the re-circulation of precipitation?

3.. What governs droplet spectra near cloud base? This question is the starting point of discussions about CCN, ultra-giant nuclei (UGN), and the activation process in general, and of considerations of the subsequent evolution of cloud hydrometeors. UGN provide a possible solution to explaining the formation of precipitation-sized hydrometeors from shallow, warm cumulus in short time periods (ie Woodcock 1953, Johnson 1982, Lasher-Trapp et al. 2001). However, for UGN to be significant in the precipitation process they must be present in concentrations large enough to account for most (or all) of the precipitation and/or grow fast enough to large sizes so that breakup occurs in a 'quasi-embryonic multiplication' process. The WCR vertical velocities profiles and in situ data collected close to cloud base should provide a good basis for reducing uncertainties regarding this issue. The radar-observed velocities below and above the aircraft will support interpretations of continuity or the lack of it in transport from cloud base to the observations level, and the in situ droplet measurements will be correlated with both the radar velocities and the in situ air motion measurement. The radar reflectivity and its gradient across the flight level will constrain speculations about small numbers of large drops being missed by the in situ probes.

4. What evidence exists for entrainment within growing pulses? Where within the pulse does entrainment occur? How do entrainment signatures change as the pulse reaches maturity and begins to decay? How is the evolution of the droplet spectra at different levels affected by entrainment? The SCMS dataset allowed us to conclude that the principal effect of mixing events on the cloud droplet spectrum was to reduce the concentration of large-mode droplets while leaving their size unchanged (Austin et al. 1985, Hill and Choularton 1985, Paluch 1986, French et al. 2000), observations consistent with models of inhomogeneous mixing (Baker and Latham 1979). The data we seek to collect will provide clues to entrainment processes in RICO clouds. The RICO SOD outlines a number of ideas to be explored related to entrainment. We will collaborate with other RICO scientists interested in entrainment; our focus is on the microphysical and dynamical effects of entrainment.

5. How is the initial development of precipitation within an individual cloud element affected by environmental pre-conditioning from earlier elements within the same cluster? What effect does the latent heat released by decaying pulses have on development of subsequent cloud pulses, in terms of their vigor, diameter, and depth? A stronger updraft and greater depth improves the chances for cloud droplets to grow through condensation and coalescence. While later pulses were more likely to contain drizzle in SCMS, no simple relationship between cloud depth and the presence of drizzle or raindrops was noted. We want to re-examine this question for RICO clouds, shifting our focus somewhat from low concentrations of drops to appreciable precipitation rates.

3.3 Strategy

The basis of our effort will be the synthesis of observations from the dual-frequency, scanning ground-based radar, the airborne cloud radar and the in situ data from all aircraft. Additionally, we'll consider the ground-based aerosol measurements, satellite data, soundings, etc. We'll be aided in this effort by the expanded capabilities of the WCR (Section 5), and the planned improvements in the airborne sampling strategy (Section 6). In the data syntheses, we'll be seeking overlaps with model formulations and model results by means of collaborations.

There will be two levels of analyses: case studies and statistical summaries. Case studies will be formed from the most comprehensive data sets, in other words, where there is the best match between the flight strategy employed and the actual cloud development, with additional consideration of other data sources. Statistical summaries will be aimed at capturing the essential characteristics of the reflectivity, velocity and hydrometeor observations for purposes of examining the ranges of variables, searching for correlations and providing constraints for modeling. Similar work with the SCMS and DYCOMS data sets the precedents and forms the point of departure for the proposed RICO work.

4. The structure and evolution of precipitating trade-wind cumulus clusters

4.1 Significance

The trade wind environment has 'suppressed' days, with a BL cap at 1-2 km (Section 1.3). On such days drizzle may be generated in shallow cumuli. In studying the structure and longevity of cumulus clusters, our interest is focused on deeper mixed layers, with a stable layer between 2-4.5 km. The deeper trade wind cumuli are more likely to produce rain (e.g. Chen and Feng 1995). They are ubiquitous over the low-latitude oceans (Lopez 1977, Johnson et al. 1999), yet our understanding of their dynamics is does not compare to that of deep and/or strongly-forced convection. Even over the tropical oceans most attention has gone to deep convection and its mesoscale organization, yet Rickenbach and Rutledge (1998) showed that the most common precipitating cloud systems in the western Tropical Pacific were shallow. If this is true in the equatorial west-Pacific 'warm pool' region, then it should a fortiori apply to the trade wind environment just poleward of the ITCZ.

Environmental characteristics for shallow, precipitating trade-wind cumuli are low-level easterly winds, a moist yet ill-defined BL, little CIN and CAPE, and a stable layer near or below the freezing level (Section 1.3). The lower-tropospheric shear (within the cumulus layer) is generally weak, and can be easterly or westerly, while the mid-tropospheric shear (at and just above the stable layer) is generally westerly. This environment offers less upward, as well as less downward convective forcing than typical land-based convection. Theories of cold-pool/shear interactions (Weisman et al. 1988, Rotunno et al. 1988, Fovell and Tan 1998), developed for deep convection, i.e. for storms that are 3-6 times deeper and that have an ice phase, may not be applicable to shallow, precipitating trade-wind cumuli. The question is not just one of scale. Both the shear and the negative buoyancy defining the cold pool are believed to be significantly weaker. The entrained low-θ_e[2] air may only have slightly less moist static energy, and evaporative cooling is limited by the high relative humidity in the sub-cloud layer. In fact the buoyancy forcing may be so weak that transient changes in fluxes at the sea surface may impact the regeneration of cumulus cells and as such contribute to the maintenance of clusters (Tompkins 2001).

4.2 Dynamic or thermodynamic control?

Limited observations suggest that trade-wind cumuli often appear in clusters whose size is on the order of 10 km, as compared to cumulus cells whose updraft has a diameter on the order of 1 km (e.g. Wielicki and Welch 1986, Houze and Cheng 1977; Section 1.3, Fig 3.1). While the distinction between a 'cluster' and a 'cell' may be artificial, we expect that trade-wind cumulus cloud fields generally are composed of multiple updraft/downdraft cores. A second observation is that trade-wind cumuli are often organized in rather long-lived lines (Malkus and Riehl 1964, Section 1.3). Houze and Cheng (1977) find that 83% of the GATE echoes in the size range 10^2-10^3 km^2 are elongated, with an orientation that is weakly correlated with the lower-tropospheric easterlies. However these GATE echoes include cases of deep convection. LeMone and Meitin (1984) report that under 'fair-weather' conditions during GATE, cumulus structures "were most often linear, with alternating 7-15 km bands of small cumulus and clear air". The three lines they examine are aligned with the low-level shear, however they all occur under suppressed conditions, with a very shallow BL. Even when warm congesti do not appear linearly-organized, radar reflectivity animations and proximity hodographs (Section 1.3) suggest that they have a fore and a rear side, usually on the western and eastern ends, respectively, and that they have an upshear and downshear side, again usually to the west or the east.

The trade wind environment is characterized by fairly strong low-level easterlies, ~10 ms^{-1} at the top of the Ekman layer, and either westerly or easterly shear. The shear refers to that found over the depth of the warm congesti. Convectively-induced downdrafts, resulting from precipitation loading, evaporative cooling, and/or entrainment of low-θ_e air from the cumulus layer above the BL, will carry momentum towards the surface. On the downshear side of the cumulus line, enhanced convergence occurs, and the baroclinically-induced shear near the outflow boundary will oppose the ambient shear. Assuming that the horizontal vorticity induced by the weak cold pool balances the equally weak ambient vorticity (an application of the Rotunno et al. [1988] theory), this would argue for *cell regeneration on the downshear side of an existing line*. This implies a westward progression of the cumulus line at a speed slower

[2] θ_e stands for equivalent potential temperature, θ for potential temperature.

(faster) than the ambient low-level winds, in case of westerly (easterly) shear, as shown in **Fig 4.1a** (**Fig 4.1b**). This dynamic theory for cell regeneration and the maintenance of a cluster or line of warm congesti can be viewed as a mesoscale, shallow version of CISK (convective instability of the second kind), i.e. an unstable interaction between shallow convective heating and low-level moisture convergence. This type of small-scale CISK however is not substantially different from regular static instability (conditional instability of the first kind), because CISK has its maximum growth rate on the scale of an individual cumulus cloud, as Ooyama (1982) noted.

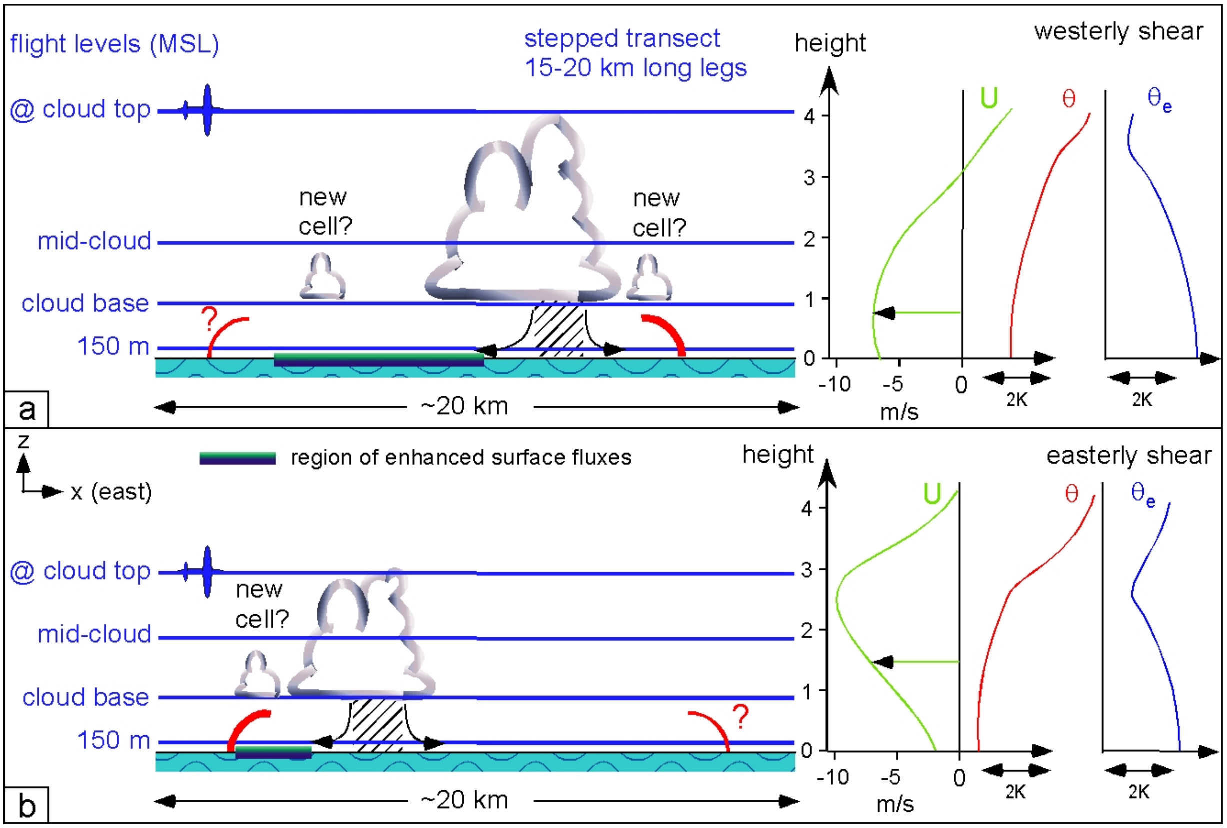


Fig 4.1. *Schematic of cell regeneration mechanisms near a cluster of shallow, precipitating cumuli. The mature cluster (elongated normal to this transect), the gust front(s), regions of enhanced surface fluxes, and possible cell regeneration loci are shown on the left, together with suggested flight levels. Typical profiles of wind, θ and θ_e are shown on the right, for the case of (a) westerly shear, and (b) easterly shear. The profiles of θ and θ_e are loosely based on observed soundings (Section 1.3) and on Norris (1998b, Fig 5, for 'moderate and large cumulus').*

It should be noted that the validation of this dynamic theory of cell regeneration depends critically on the location of new cells (the downshear side), not on the precise balancing between ambient shear and cold pool-induced shear. Several recent studies of long-lived squall lines have shown that the ambient low-level shear is often weaker (Coniglio and Stensrud 2001, Evans and Doswell 2001, Gale et al. 2002), and further modeling work by Weisman and Rotunno (2001) shows that optimal conditions for cell regeneration may include slightly stronger cold pool-induced shear than ambient shear. Equally important is the fact that the theory has been developed and tested only for deep, strongly-forced convective systems. The key factor that distinguishes dynamical control in the maintenance of any type of convection, deep or shallow, is that *cell regeneration should occur on the downshear side.*

On the downshear side of the line, the convergence associated with the gust front is well-defined, but the gust front does not propagate away from the cluster, not only because of the shear profile, but also because the cold pool is relatively weak (Section 4.1). On the upshear side, a convergence zone separating ambient from convectively-modified air is non-existent or weak, and this zone rapidly distances from the cluster.

The possibility exists that the relatively weak cold pool erodes by enhanced fluxes from the warm ocean surface (Tompkins 2001). Surface flux enhancement is expected in areas where ambient trade winds are aided by divergent cold pool winds (Fig 4.1). This enhancement of the moisture and heat flux from the ocean surface is transient, because the core of the cold pool may quickly warm due to downward entrainment of air from above the BL in the wake of the expiring downdraft, and therefore the acceleration due to density current dynamics quickly vanishes. Even so, it may be sufficiently long and strong to enhance CAPE and to trigger new convection *within* the remnants of the cold pool. In fact Tompkins' (2001) simulations, for deep convection and without the low-level shear typifying a trade-wind environment, suggest that convection is regenerated *inside* the boundary of the spreading cold pool, because of increased surface heat and moisture fluxes. The basis of this theory is that cumulus convection is sustained by the surface fluxes it generates over the tropical ocean. This basis is the same as that of the air-sea interaction theory for the maintenance of hurricanes (Emanuel 1986).

In the presence of easterly shear, surface flux enhancement is limited to a small region on the downshear side of the cluster (Fig 4.1b). The enhancement may weaken the cold pool, which may reduce or strengthen the changes for cell regeneration, depending on the strength of the ambient shear. Either way, it may be too short-lived and insignificant compared to the dynamic forcing there. On the upshear side, i.e. in the lee of the cluster, ambient and convectively-induced winds oppose, so surface fluxes are suppressed, making cell regeneration even less likely there. In the presence of weak westerly shear, surface fluxes are enhanced over the larger outflow region upshear of the cluster (Fig 4.1a). It is in this region that Tompkins' theory of cell regeneration within the cold pool appears plausible.

In short, *a dynamic mechanism, similar to that proposed by Rotunno et al. (1988) for squall lines, would dominate if cells mainly regenerate on the downshear side of a line of cumuli, whereas a thermodynamic mechanism, based on air-sea interaction (Tompkins 2001), would dominate if they mainly regenerate on the upshear side or within the periphery of the cold pool.*

4.3 Analysis of airborne measurements

The above theory (Section 4.2) will be tested by means of observations at the mesoscale (S-POL, soundings) and cumulus scale (WKA/WCR). Whether the maintenance of cumulus clusters is controlled dynamically or thermodynamically, the relatively rapid generation of precipitation in cumulus cells is believed to be instrumental to cell regeneration and the longevity of the cumulus cluster. As is the case for deep convection, downdrafts prevail in decaying shallow cells, and through evaporative cooling and the entrainment of low-θ_e air from above the BL, a cold pool should develop below the cells. New convection may be triggered along spreading outflow boundaries, or through BL modification in the wake of these boundaries. Small triggers as well as small thermodynamic changes may suffice, because of a lack of ambient CIN.

In order to characterize the vertical structure and evolution of cold pools, we need to measure the vertical structure of echo and vertical motion, as well as in situ estimates of buoyancy, relative humidity, and convergence. The measurement of these in situ variables is not trivial in the case of trade-wind cumuli. Variations in mixing ratio, θ, and wind anomalies around trade-wind cumuli are on the order of 1 g kg^{-1}, 1 K, and 2 ms^{-1} (LeMone and Meitin 1984). These magnitudes are not much larger than the absolute instrument accuracy. For instance, mean gust-probe derived horizontal winds are good to ~ 1 ms^{-1}, although departures from the leg-mean are good to ~0.1 ms^{-1} (LeMone and Pennell 1980; Rodi, pers. comm.). Signals of convective activity are relatively weak, and this represents a first major experimental challenge[3].

A second challenge regards the rapid evolution of cells within a cluster. Therefore a stepped transect of in situ data cannot yield a snapshot vertical cross-section. Here the WCR is an essential complement. The echo and vertical velocity profiles will locate and characterize cumulus cells, and even capture fine-scale entrainment and water loading events leading to convective downdrafts. These will be used to determine the cumulus growth phase and to interpret in situ observations in the context of the surrounding cloud structure (Figs 2.1 and 2.2). Where precipitation reaches the surface, the WCR VPDD data will yield the 2D flow field along the flight track to within 50 m of the sea surface, allowing an indirect estimate of surface flux enhancement. The WCR echo and velocity data may also capture downdraft divergence and the formation of a cold pool.

Latent heating can be estimated from the in situ vertical velocity and mixing ratio measurements. Latent cooling below cloud base can be estimated in the same way, but a profile of cooling rate can be inferred from the WCR reflectivity profile, assuming a Z-M (reflectivity – water mixing ratio) relationship derived locally from the in situ cloud probe data and nearest gate reflectivity values (Qing 2002).

In short, the analysis of cold pool / shear / surface flux interactions relies on kinematic, thermodynamic and cloud measurements aboard the WKA, but given the relative weak convective signal, and the rapid evolution of

[3] Estimating variations in surface fluxes, due to convective winds and temperature/humidity variations is particularly difficult, given the relatively small extent of cold pools (~10 km, Tompkins 2001). A flight strategy for flux measurements near cumulus lines is suggested in Section 6.2; else this part may have to be left to ground-based instruments, e.g. aboard the Ron Brown.

cumulus cells, WCR echo and velocity profiles are equally essential.

4.4 Numerical simulations

The theory proposed in Section 4.2 will be tested also by means of some numerical simulation experiments, if a separate funding request is successful. In preparation for this proposal, Shu-Hua Chen (UC Davis) ran the WRF model in 2D, at a resolution of 200 m, for two soundings in the Caribbean region: the San Juan PR sounding on 2001/12/08 at 12 UTC, with westerly shear, and the Guadeloupe sounding on 1998/01/27 at 12 UTC, with easterly shear. Convection is triggered by a bubble 4 km wide and 2 km deep. In both cases, new convective cells are triggered at the downshear side of the initial bubble within 30 minutes of simulation (not shown). The secondary cells reach their maximum strength within 45 minutes of simulation, and a new updraft forms on the downshear side. Much effort is needed to make these simulations more realistic and to validate the hypothesis in Section 4.2, in particular regarding parameterizations of surface fluxes and the BL. This work will be the focus of a separate, future proposal.

5. Wyoming Cloud Radar measurements in RICO

5.1 Antennas

The WCR is a 95 GHz, multiple-beam Doppler radar. There are four fixed WCR antennas on the WKA:

- one oriented towards nadir,
- one looking about 30º forward of nadir in the vertical plane,
- one looking sideways <u>or</u> upward [depending on the position of a mirror in a faring on the aircraft frame], and
- one looking 30º forward from the lateral beam in the horizontal plane.

The first (last) two antennas allow dual-Doppler synthesis of the air motion in the vertical (horizontal) plane, a configuration referred to as vertical (horizontal) plane dual-Doppler, or VPDD (HPDD). Along straight & level flight tracks, the two beams will view approximately the same sample volume from different directions, with time differences of the order of seconds, allowing dual-Doppler synthesis of the radial velocities in a plane below or to the right of the aircraft (Leon et al. 1999).

The WCR usually operates at a pulse width of 225 ns, for which the range resolution is about 30 m. This is also the across-beam resolution at a range of ~2.6 km, given an average beamwidth of 0.7º. A pulse width of 500 ns may be used as well, especially in the horizontal plane. This doubles the maximum range to about 6 km, albeit at the expense of a lower range resolution. The first useful gate is 120 meters below and 90 m above and to the side of the aircraft. The minimum detectible signal is about -28 dBZ at a range of 1 km and -19 dBZ at 3 km, varying somewhat from antenna to antenna. More detailed radar specs can be found at http://www-das.uwyo.edu/wcr/.

Since the WCR has two channels, two antennas can be operated in an interleaved fashion, resulting in two seamless data streams. Several antenna pairs can be operated, the key pairs are: VPDD (down/foreward down); HPDD (side/foreward side); and profiling (up/down). The VPDD mode is more sensitive than the HPDD mode, mainly because the nadir port antennas are larger. We also have more confidence in the feasibility of the VPDD mode, through several tests in the field, notably during IHOP, DYCOMS, and HiCu (Section 2). Other possible antenna pairs are up/down and side/down, providing reflectivity and Doppler velocity data.

Currently, switching between antenna pairs requires manual switching of the waveguides, plus a system reboot. This takes 2-4 minutes and will be done, whenever possible, while out of cloud. Nonetheless, we would like to move to an electronic fast switching capability, whereby pulses are transmitted in rapid sequence to the any selection of the four WCR antennas mentioned above. The fast switching capability will require about $80k, which we are seeking to obtain through another proposal, but still in time for RICO. This would be beneficial, but certainly not crucial for carrying out the plan described in this proposal. Slow (manual) switching allows for all the above-mentioned antenna pairs, and subsequent passes can use different pairs.

5.2 Reflectivity

The use of radar reflectivity to diagnose precipitation, separate from cloud water, is not rigorously possible and is especially troublesome in cumulus where (unlike in Sc) no relatively simple LWC profile pertains. In Sc, reflectivity dominated by cloud droplets only near the cloud top (Vali et al. 1998) and methods can be devised for differentiating between cloud and drizzle (Wang and Geerts 2003). In Cu, the LWC field is more complex, making reflectivity assignments more difficult. With maritime CCN and broad droplet spectra, the distinction is hindered even more. There is no complete solution to this problem, though. Some relief will be available for the immediate vicinity of the aircraft, where reflectivities can be compared to in situ hydrometeor observations. Further away from the aircraft, Doppler velocity can give selective information by limiting the reflectivity-weighted fall velocities that are plausible for given reflectivities. In all, how far the combined use of the different sources of information will go in constraining analyses is hard to predict. Further possibilities exist in the use of measurements at two wavelengths (WCR and S-POL), however, the reduced flexibility needed to coordinate the two radars is considered a greater loss than the potential gain in interpretation of reflectivities.

The two-way attenuation coefficient at 95 GHz is 4.6 dB/Km per g/m^3 (any size liquid water), plus about 0.3-0.6 dB/km due to water vapor (Lhermitte 1990, Vali and Haimov 2000). Attenuation will be evident in some of the reflectivity profiles, especially those aimed at documenting cold pool development. If deemed useful, the dual-beam tomography method of Guyot and Testud (1999) and Lopez (2000) can be applied to retrieve un-attenuated reflectivity.

One benefit of the WCR is that Bragg scattering is insignificant at 95 GHz, hence the visual cloud edge of a congestus should be close to the WCR observed one. Bragg scattering, due to refractive index turbulence at a scale of about 1.6 mm (half the WCR wavelength), yields a return that is 37 dB (55 dB) smaller for the WCR than for an X-band (S-band) radar (Knight and Miller 1993).

5.3 Velocity

WCR Doppler velocities, after removal of aircraft motion (Leon and Vali 1998, Leon 2003), correspond rather well with the motion of scatterers. A relatively high pulse repetition frequency (PRF) of 20 KHz will be used. This corresponds to a maximum unambiguous velocity width of 31.6 m/s. Vertical and horizontal dual-Doppler velocities along straight and level legs will be synthesized according to the algorithm provided by Leon (2003). The progression of the aircraft along a straight and level track causes the aircraft-normal beam to sample the same region as the fore-beam with a lag of <20 seconds for most ranges of interest. This time lag is much less than that used in ground-based dual-Doppler synthesis, making the airborne technique more attractive for rapidly evolving features, such as Cu. Still, there are many sources of error, but Leon (2003) demonstrates that the synthesized winds have an accuracy to better than 1 m s^{-1} with even greater relative precision, at least outside of strong shear zones. An example of the fine-scale (30x30 m) circulation in an atmospheric density current is shown in Geerts and Leon (2003).

The main uncertainty in deriving vertical air motion from WCR radial velocities is the hydrometeor fallspeed. Two echo types will be distinguished, those with drizzle or rain, and those without it. Cloud droplets of course have a negligible fall speed. The separation between the two regimes will be based mainly on WCR reflectivity, and secondarily on the difference between ambient WCR vertical motions and gust-probe-measured vertical air velocity. Investigating the contribution to the reflectivity from cloud droplets and drizzle/precipitation drops using the WKA cloud physics probes can lead to further inferences.

In precipitation, the droplet fallspeed V_t can be estimated from reflectivity Z, however the Z-V_t relationships in the literature (e.g. Doviak and Zrnic 1992, p. 216) are based on idealized drop size distributions. The WCR profiling mode (Section 5.1) will allow us to build an empirical Z-V_t relationship for trade wind cumuli, and to examine its variation with altitude in cloud, cloud age, etc. The method uses the nearest gates of up and down WCR reflectivities and velocities. These measurements are centered on the aircraft, which measures vertical air motion (Geerts and Miao 2003a). The accuracy of the resulting vertical air velocity profiles remains uncertain, but certainly we will be in the best position to assess that.

6. WKA/WCR operations in RICO

Separate flight patterns are developed for the cumulus microphysics/kinematics objectives for this proposal, and its cumulus interaction objectives. However an overlap exists between the 'micro' and 'meso'scale objectives of this proposal, and cumulus sizes vary continuously from the smaller patches, favored for the 'micro' component, to larger clusters, favored for the 'meso' component. Most 'micro' flights should yield good data for 'meso' studies, and vice versa. And data from all flights should be useful for RICO's large-scale objectives (see RICO SOD).

The WKA will fly most of its hours within 70 km range of S-POL-Ka, not only to guide the WKA to the suitable target, but mainly to provide a horizontal and temporal context of the cumulus cluster examined. During the short ferry flight to target, the WKA will conduct a sounding through the entire depth of the BL to a level 1-2 km above the inversion. During this ferry, the flight scientist will coordinate with the scientist at S-POL to determine the targets/locations for the flight. Generally, the choice of cumulus cluster to be targeted will involve ground coordination, but the detailed flight path within a select cluster is decided by the WKA scientist.

Specific flight strategies are listed below. These plans are not rigid, they may be altered depending on the desires of other RICO participants, and as experience in the field dictates.

6.1 WKA cumulus microphysics flights

Two principles are explored for the development of flight patterns dedicated to the study of cloud microphysics. The first is to focus on individual cells. This is the 'traditional' method probing cumulus clouds. However, experience testifies that the rapid evolution of small cumulus present difficulties in interpreting data from subsequent penetrations and significantly reduces the amount of data collected due to the time spent out of cloud. Further, some bias exists in picking the 'correct' cell. For this reason flight patterns are proposed along which cumuli, and their microscale characteristics, are sampled statistically. This approach will alleviate some of the aforementioned problems, but will introduce others such as coherency between penetrations and understanding the context in which the in situ measurements are obtained.

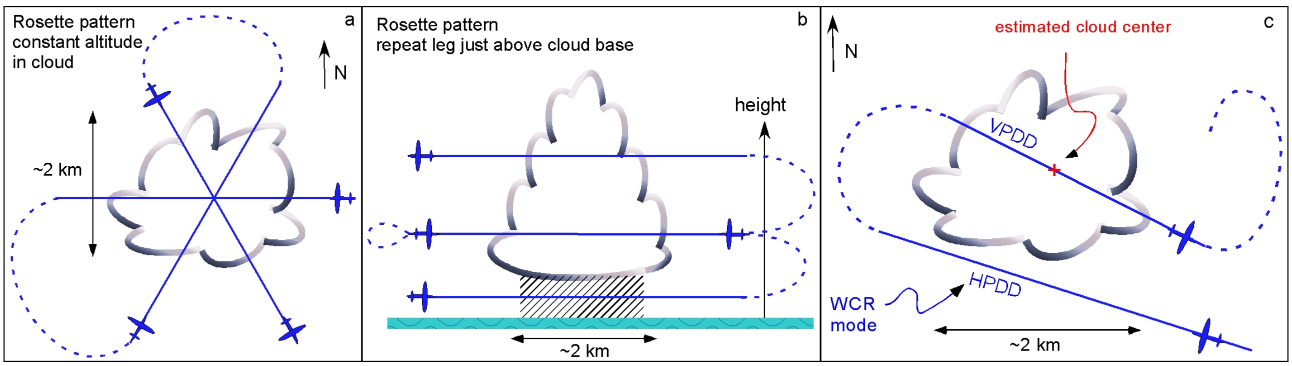


Fig 6.1. *Flight patterns for individual turrets. (a) Constant altitude Rosette. (b) Variable altitude Rosette. (c) Side-swipe pattern for an individual cumulus cell. The WKA grazes along the cumulus along a level track, and then aims for the previously-estimated cloud center.*

For the individual cell approach, initial targets will be young, growing cumulus cells that are not precipitating yet. It is important to document evolution of the droplet spectrum and precipitation development through the entire life cycle of the cell. The flight patterns will advect with cell motion. To minimize the out-of-cloud turn-around time, repeated penetrations through the same cloud will utilize a rosette pattern (**Fig 6.1a**). The WCR will operate primarily in profiling mode, occasionally in VPDD mode, or both if electronic fast switching is available. Typically penetrations will be made at constant altitude. However, altitude changes between penetrations may occur, particularly when the WKA is operating solo (**Fig. 6.1b**). Individual cells may also be examined using the WCR's side antennas. The sideswipe (**Fig. 6.1c**) pattern is one example. It uses the WCR to look into the cloud horizontally during one pass outside, followed by a second pass that penetrates through the cell with the WCR looking vertically. Either of these two patterns can be used in combination with the standard rosette.

For the statistical approach, targets will focus on cumulus clusters. Constant altitude flight paths will be aligned along (or across) clusters, up to 20-30 km. The WKA will intersect growing and decaying turrets during through transect (**Fig 6.2**). One approach assumes a straight, unbiased path (**Fig. 6.2a**). Another allows the pilot to make small corrections to penetrate the visible center of the turret (**Fig. 6.2b**). Following a transect, the WKA will reverse heading to complete the pattern again. It is not the purpose to make multiple penetrations in the same turret.

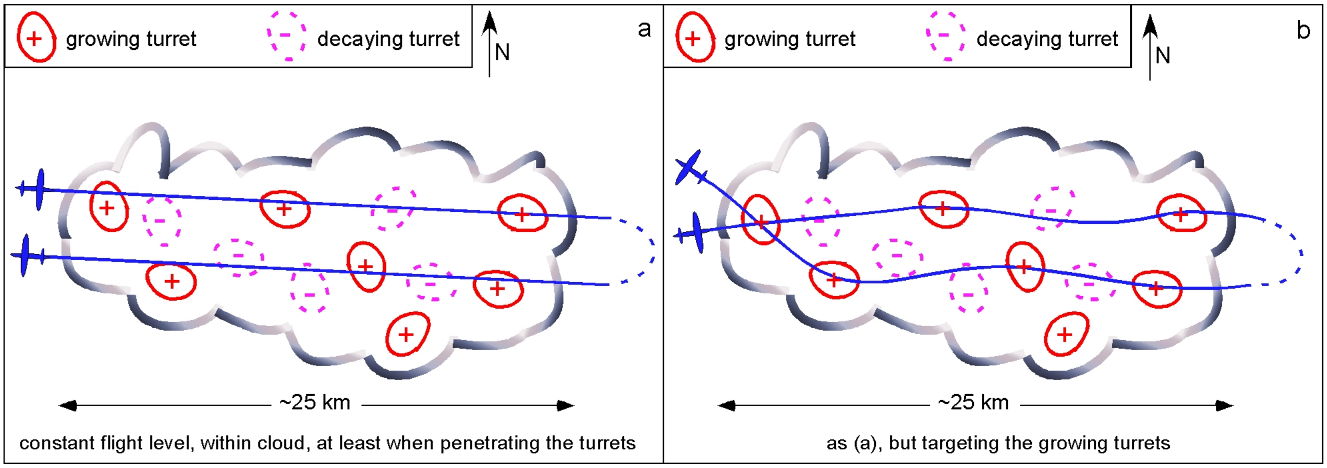


Fig 6.2. *Statistical sampling of cells in a cluster. The WCR operates in profiling and/or VPDD modes.*

6.2. WKA cumulus cluster dynamics flight patterns

The basic observational strategy for cumulus cluster dynamics flights is to directly measure the temporal evolution of the mesoscale pattern of kinematic, thermodynamic, and microphysical fields while profiling the cloud and precipitation structure. A target cluster will be approached at above-cloud altitude, in order to determine whether it is a suitable target, using visual clues and WCR echo and vertical velocity profiles, displayed in real time on board the WKA. A target is suitable if cumulus towers appear to be growing, many echoes are ascending, and high reflectivity values are found aloft, rather than at the surface. The flight then proceeds with a stepped transect through the cluster (**Fig 6.3a**), maintaining its most vigorous region in the center of each leg, at mid-levels, just below cloud base, and at the lowest feasible flight level (Fig 4.1). The lowest flight level is used to depict the thermodynamic and kinematic structure of the cold pool in the context of the echo and velocity structure aloft, to estimate evaporation rates, and to deduce variations in surface fluxes, the latter via indirect methods. All legs should extend beyond the cluster until a few kilometers beyond the outflow boundary, or, at higher levels, over the width of the cluster itself. Sampling of the environment is important to estimate buoyancy (Braham and Kristovich 1996) and other perturbation variables.

This sequence is repeated, with intervening soundings if other RICO platforms are not providing them, until the cluster decays or moves out of the S-POL 70 km range. The second stepped traverse becomes centered on the new towering cumuli wherever it forms (Fig 4.1). Because the convective signal is rather weak (Section 4.3), and because changes are rapid, a transect at one or two levels may be repeated many times.

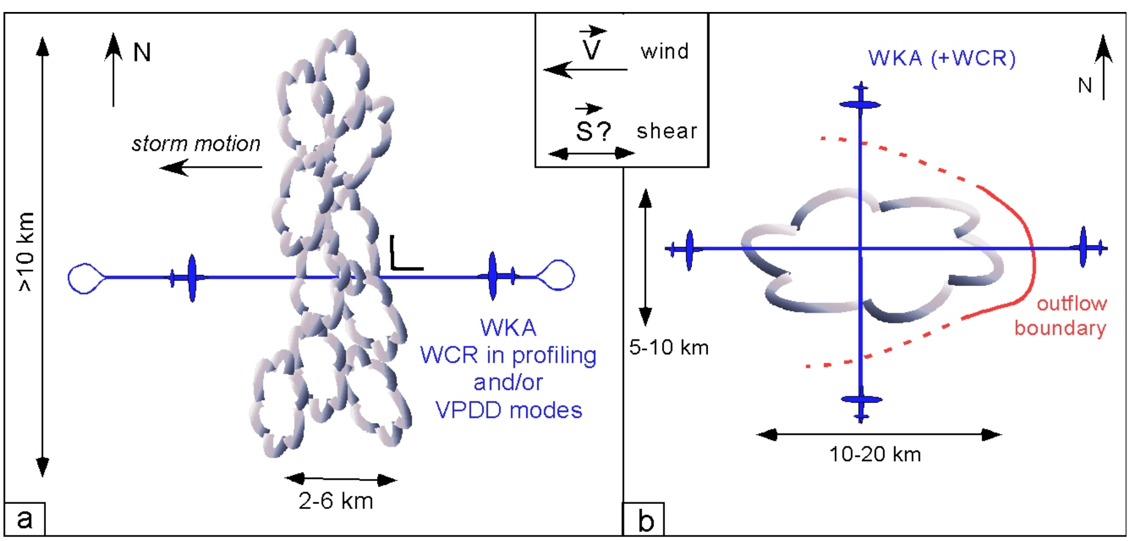


Fig 6.3. *Stepped traverse across a cumulus cluster. The frame of reference is relative to the cluster. S is the shear vector over the depth of the cumuli. (a) Strong linear organization; (b) a more amorphous cluster.*

Ideally the wind, shear, and line-normal direction are more or less aligned (Fig 6.3a). In that direction, the divergence field and the cold pool spreading are best defined, and the WCR profiles can be interpreted as a 2-D transects across a mostly 2-D structure. In the 'ideal case' of a long cumulus line, we may attempt fly a clockwise racetrack along the cumulus line, operating the WCR in HPDD mode, at the lowest flight level. The main objective of such racetrack is to contrast surface fluxes on the upshear and downshear sides of the line.

If the cluster is amorphous, the preferred transect direction is that of the wind and shear. If the main axis of the cluster tends to align with the wind and shear, then stepped transects should be conducted both along and normal to that main axis (**Fig 6.3b**).

7. Proposed research schedule

- **Jan –Nov 2004:** attendance at RICO preparation workshops; preparation of a proposal to enable electronic fast switching (Section 5.1); testing new data analysis tools resulting from HiCu03 work. Additionally, for Vali: analysis of HiCu03 data (current NSF grant) and the development of software emerging from that for use in RICO; for Geerts: preparation of a proposal to numerically simulate trade wind cumulus clusters, and to interpret model results in the context of WCR/WKA observations, in collaboration with Dr. Shu-Hua Chen (Section 4.4); for the radar engineer: installation of the WCR fast-switching capability (if separately funded), related software development, instrument integration, analysis of test flight data.
- **Dec 04 – Jan 05**: RICO field phase. The budget is based on full-time participation of Geerts, and half-time participation of Vali and a PhD student. Quick-look data will be examined to assess quality control processes and to offer preliminary interpretations, and to adjust the flight patterns where needed.
- **Feb-Dec 05:** correction of WCR data for aircraft motion; analysis of echo and vertical velocity structures, WKA data, and S-POL data; pursuit of all research objectives (see Abstract); graduate student guidance; presentations at a RICO meeting and at a conference.
- **Jan-Dec 06:** further in-depth analysis; conference presentation; publication in journals such as *J. Atmos. Sci, Mon. Wea. Rev., Quart. J. Roy. Meteor. Soc.*.

8. Educational initiatives

This proposal calls for the participation of two PhD level students. A first one will become involved in early 2004, and in the first year (s)he will take classes, become acquainted with the WKA and WCR data and software by means of the HiCu03 or other dataset, and possibly extend our preliminary analysis of satellite, sounding, and operational radar data of trade wind cumuli (Section 1.3). This person will also be a key participant in the RICO field phase. (S)he will contribute the WCR operation and data management and benefit from the RICO Graduate Seminar Series (see RICO SOD). A second graduate student will be included in early 2005. One PhD project will focus on the cloud-scale kinematics/microphysics, while the other will focus on the cumulus cluster-scale processes. Close collaboration with the PIs of this proposal, as well as with other RICO scientists will prepare these students for their professional careers.

As in previous field campaigns, the PIs will use data collected in RICO in their graduate courses, and they will make the data, preliminary analyses, etc, available on the web (see http://www-das.uwyo.edu/wcr/). Finally, the PIs will contribute, as appropriate, to the Graduate Seminar Series with lectures.

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