Dynamical Processes of Orographic Cumuli

1. Airborne cloud radar studies of orographic cumuli: objectives and significance

1.1 CuPIDO

This proposal is linked to the CuPIDO (Cumulus Photographic Investigation and Doppler Observations) campaign over the Catalina Mountains in southern Arizona (**Fig 1.1**). The campaign, to be conducted in the summer of 2005, intends to describe orographic cumulus development during the morning hours at the meso-γ scale as well as the cloud scale, with an emphasis on boundary-layer evolution and the effects of entrainment, detrainment, and glaciation on individual convective towers that tend to develop in succession and culminate in the cumulonimbus stage. Questions on the cloud scale surround the evolution of cumulus buoyancy, i.e. its generation by latent heat release and its erosion by entrainment. On the meso-γ scale, the key questions regard the modification of convective available potential energy (CAPE) by topographically-induced convergence and surface heat fluxes, the modification of the mid-tropospheric detrainment layer by successive cumulus pulses, and the generation of precipitation-induced cold pools.

To address these questions, CuPIDO aims to field the following observational facilities: stereo digital cameras, several standard portable automated mesonet (PAM-III) stations, several integrated surface flux facility (ISFF) stations, one mobile and one stationary up/down GPS/Loran Atmospheric Sounding System (GLASS), and the Wyoming King Air (King Air for short). This proposal is in collaboration with Dr. J. Zehnder and colleagues at Arizona State University. Their efforts focus on digital stereo-photogrammetry from the Biosphere II site (Fig 1.1). High-resolution reflectivity and velocity data from scanning ground-based X- or C-band radars (single or dual) are being sought through a collaborative effort. In the absence of these data, the nearest operational S-band radar is some 70 km to the south of the Catalina Mountains. Another possible collaboration, with the University of Arizona, regards water vapor tomography by means of a dense network of GPS receivers.

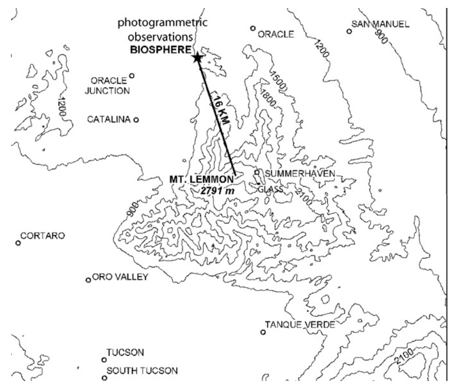

Fig 1.1. *Topographic map of the Santa Catalina mountains.*

Of particular importance to this proposal is the King Air. It will carry the Wyoming cloud radar (WCR) in addition to a state-of-the-art array of cloud, atmospheric state, wind, radiation, and flux probes (http://flights.uwyo.edu/base/InstList.pdf). The WCR is a 95 GHz (W-band) multiple-antenna radar, providing high-resolution reflectivity and dual-Doppler 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 ~40 m resolution, mainly above and below the aircraft, constitutes a powerful synergy for cloud dynamical studies. Pencil-line in situ data can be placed in the context of the cloud vertical and horizontal structure; radar reflectivity and velocity patterns can thus be interpreted by means of airborne thermodynamic and cloud measurements.

1.2 Significance

Shallow to deep convection is well-known to develop over mountains during the warm season. The 'sky islands' in the American Southwest are a preferred *natural laboratory for cumulus studies*, given the spatially and temporally regular development of cumuli driven by surface heat fluxes and mesoscale circulations. Cumulus convection is of fundamental importance to the atmospheric circulation. It transfers heat, moisture and momentum across isentropic surfaces in the troposphere. It profoundly impacts the local and large-scale radiation balance and is responsible for much of the warm-season precipitation. A number of contrasting conceptual theories exist for the dynamics of cumulus convection, yet thorough observational evidence remains rather sparse. The combination of airborne in situ data with cloud radar measurements adds a new dimension to the study of cumulus dynamics.

The proposed work will yield insights not only into the fundamental dynamics of cumulus convection, but also into *the orographic forcing of cumulus clouds*. This is a multi-scale process, and the synergy between topographically-induced mesoscale circulations and cumulus convection over mountains is poorly understood.

Cumulus convection operates on a range of horizontal and vertical scales. These scales are generally not resolved by operational numerical weather prediction (NWP) models. Thus the simulation of its impact is most challenging, and convective parameterization remains one of the greatest uncertainties in NWP models. Currently the ETA model runs at a horizontal grid spacing of 12 km in the conus domain. The Santa Catalina Mountains are roughly 20 km in diameter, less than three grid spacings, which are needed for the mountains to be resolved. Even if current- or future generation NWP models are able to resolve the mesoscale circulations associated with the Western mountain ranges, the effect of cumulus convection will continue to be parameterized. We do not propose to directly validate parameterization schemes, but our observations and interpretation of orographic cumulus dynamics should ultimately lead to a more accurate representation of the effect of cumulus convection on the resolved scales of NWP and general circulation models.

1.3 Orographic cumulus environment

To gain an impression of the cumulus patterns and associated temperature and moisture profiles to be expected during CuPIDO, we examined the Tucson (EMX) WSR-88D and 12 UTC radiosonde data for July and August 2003. Our qualitative findings plus two years of forecast experience in Arizona ('96-'97) concur with observations by R. Maddox (quoted by Zehnder 2003) that suitable Arizona summertime soundings can be grouped into three categories:

1) The most common sounding has a deep, well-mixed convective boundary-layer (CBL), with a shallow stable layer (at 12 UTC), a poorly defined CBL top (usually between 700-550 mb), and high relative humidity above the CBL. Over the plains this type of environment can have considerable convective inhibition (CIN), especially if the lifting condensation level (LCL) is well above the CBL top, in which case cumuli remain absent or shallow all day. The 12 UTC EMX CAPE (calculated based on mixing in the lowest 50 mb) is typically small (<1000 J kg^{-1}). Time lapse photography shows that orographic cumulus development will occur in stages, typically starting around 10 am local time, and successive towers appear to condition the environment in which they grow, as they detrain CBL air above the LFC. The larger or 'final' tower will come close to the level of neutral buoyancy (LNB), develop a large anvil and possibly heavy precipitation, and yield a well-defined low-level cold pool.
2) As (1), but drier air aloft. Successive development will occur over the mountains as before, but this succession of convective towers may never come close to the LNB and the cumulonimbus stage, especially if wind shear is present aloft.
3) A tropical moist sounding. Minimal CIN exists, thus thermals readily reach the LFC. Also, cumulus erosion by entrainment should be less effective. Under weak wind shear, topographic control and diurnal modulation are strong, and deep-convective development is rapid but short-lived. Under stronger shear, topographic control becomes weak and the precipitation may organize into mesoscale convective systems that are most vigorous in the evening. Tropical moist soundings are rare in Arizona. They are associated with a strong low-level moisture surge from the south, and are most common late in the monsoon season.

We plan to investigate morning cumulus convection in any of these three environments. We focus on the first one, because it is the most common and most interesting type.

1.4 Key objectives

Broadly speaking, we aim to describe the vertical and horizontal structure of the airflow and radar reflectivity fields within orographic cumuli, and relate the fine-scale cloud structure observations to flight-level measurements of microphysical and thermodynamic properties of these cumuli and their environment. We then aim to explore the linkages between the evolution of a cumulus tower, that of successive cumulus towers, and the environment in which the cumuli initiate, deepen, glaciate, entrain, and detrain. Thus the objectives are twofold, but interconnected:

Objective 1 (see Section 3): to describe the echo and kinematic structure of orographic cumuli at a scale of about 40 m, sufficient to resolve the primary entrainment processes; and to interpret this in light of microphysical and thermodynamic data, in order to gain new insights into the fundamental dynamical mechanisms controlling the evolution of cumuli.

Objective 2 (see Section 4): to examine spatial and temporal changes in the environment in which orographic cumuli develop and decay, in order to gain insights into the synergy between towering cumulus convection and orographically-induced mesoscale circulations.

1.5 *Relevance of other CuPIDO instruments to this proposal*

Our exploration will focus on the King Air probes, in particular the WCR. But other instruments are relevant. Most important is the stereo-photogrammetry, which provides a continuous depiction of the cloud edges as seen from the north side of the mountain (Fig 1.1) at a resolution at least comparable to that of the WCR. The geo-located cloud-edge maps, inferred from the digital stereo-images, will complement the WCR observations since the cloud base, some edges, and earliest stages of cumulus development are not detected with a cloud radar (see Section 5). We plan to map the cloud edges, where available, on the horizontal and vertical WCR transects. Knowledge of the cloud base is especially important as it determines the adiabatic liquid water content in the cumulus. Also, time-lapse photography provides the temporal context for the aircraft transects.

Ambient soundings will be used as well. Radiosonde data upstream of and over the mountains will be used to reveal changes in vertical structure due to pre-convective convergence, mid- & upper-level moistening, and post-convective cold-pool development. The soundings, plus aircraft data at various levels, will be used to estimate the CBL depths over the plains and the mountains, the stability above the CBL, the wind shear, cumulus buoyancy, and entrainment sources in the cumuli (Paluch method).

Changes in surface energy balance on the mountain top and slopes, due to solar heating, subsequent cloud shielding (Liu and Orville 1969), and precipitation will be inferred from the three ISFF stations. And the PAM-III stations distributed around the mountains will reveal changes in surface pressure, temperature, humidity, and airflow.

2. Summary of prior relevant research

2.1 *Current and prior relevant NSF support during the last three years*

(a) *An Airborne Radar Study of Cloud Structure and Composition* (Drs. G. Vali and R. Kelly, PI). NSF Award ATM-0094956, $606,215, 02/01/2001-02/29/2004. During its first year this grant supported participation in DYCOMS-II (Dynamics and Chemistry of Marine Stratocumulus), conducted in July '01 a few hundred km southwest of San Diego. The WCR operated on the NSF/NCAR C-130 aircraft, in vertical-plane dual-Doppler (VPDD) mode (Section 5). The DYCOMS field study and initial findings from it are summarized in Stevens et al. (2003). Additional studies are reported at www-das.uwyo.edu/~vali/ dycoms/ dy_rept.html. The grant further partially supported the High-Plains Cumulus (HiCu) campaign, conducted with the WCR and the King Air near Flagstaff AZ (summer '02) and Laramie WY (summer '03). The HiCu campaign has similar objectives to CuPIDO and thus constitutes an important learning experience ahead of CuPIDO. HiCu preliminary results, essentially the doctoral work of Rick Damiani, are summarized below (Section 2.2).

(b) *Fine-scale Description of Shallow Atmospheric Boundaries during IHOP* (Dr. B. Geerts, PI) NSF Award ATM-0129374, $350,462, 1/1/2002-12/31/2004**.** The IHOP (International Water Vapor Project) campaign, conducted in late spring 2002 in the central Great Plains, aimed to study the variations of water vapor at all scales, in order to improve warm-season QPF (quantitative precipitation forecasting). We used the WCR aboard the King Air to study the optically clear CBL. This rather unorthodox use of a cloud radar has yielded new insights into dry convection in the CBL and the vertical structure of radar 'fine-lines', which are believed to be due to high concentrations of small insects. Geerts and Miao (2004a) describe the structure of the fair-weather CBL and interpret the presence, persistence, and vertical velocity characteristics of echo plumes. As a tangent, Geerts and Miao (2004b) describe the rather surprising WCR observations of insect flight behavior, and finally Geerts and Miao (2004c) interpret these findings by means of a simple numerical model of CBL circulations. Work is in progress on a manuscript that places the observed echo plume kinematic, thermodynamic and moisture characteristics in the context of CBL dynamics (Miao and Geerts 2004). Also, we are about to submit a paper to *Mon. Wea. Rev.*, as part of a special issue on convective initiation in IHOP (Geerts et al. 2004). In that paper we describe the structure of an atmospheric density current in unprecedented detail, and discuss how it affects thunderstorm development. More details on our IHOP work can be found at http://www.atmos.uwyo.edu/wcr/projects/ihop02/.

(c) *Cloud and Dynamical Processes of Precipitating Warm Cumuli during RICO* (Drs. G. Vali and B. Geerts, PI) NSF Award ATM-0342597, $476,695, 1/1/2004-12/31/2007. This grant will support our participation in RICO (http://rico.atmos.uiuc.edu/), scheduled for Dec '04 - Jan '05. RICO in general aims to gain insight into the precipitation formation mechanisms of ice-free cumuli over the tropical oceans. We aim to explore the linkages between the kinematic evolution and precipitation development in warm marine cumuli, as well as between the cloud microphysical and the dynamical processes that sustain precipitating cumulus clusters. As part of the RICO effort, the WCR is being upgraded to allow fast electronic switching between the various antennae aboard the King Air, and thus simultaneous horizontal-plane and vertical-plane radar dual-Doppler scans (Section 5).

2.2 Recent investigations of cumulus congestus over the High Plains (HiCu03)

In this section we summarize some relevant findings of the HiCu03 experiment. Here, for the first time, WCR transects revealed the airflow field in cumuli at unprecedented detail. [WCR-inferred vertical velocities in cumuli have been described before, by French et al. (1999, 2000).] HiCu03 was conducted in the southeastern corner of Wyoming in July-August over terrain ranging from 1.2 to 2.4 km in altitude. The HiCu03 cumuli may have had roots over higher terrain, but the terrain influence was not studied in HiCu03. Cloud bases were about 5.0 km MSL. Cloud depth extended up to 3 km, with freezing levels around 4.4 km MSL. The horizontal aspect ratio of the clouds was very close to one, with diameters on the order of 2-3 km. The nearest available 00 UTC soundings reveal well-mixed temperature and humidity profiles below 600 mb on most days. Better proximity soundings were obtained during the King Air climbs, by means of the on-board instruments. Illustrations from five HiCu03 flights are shown below.

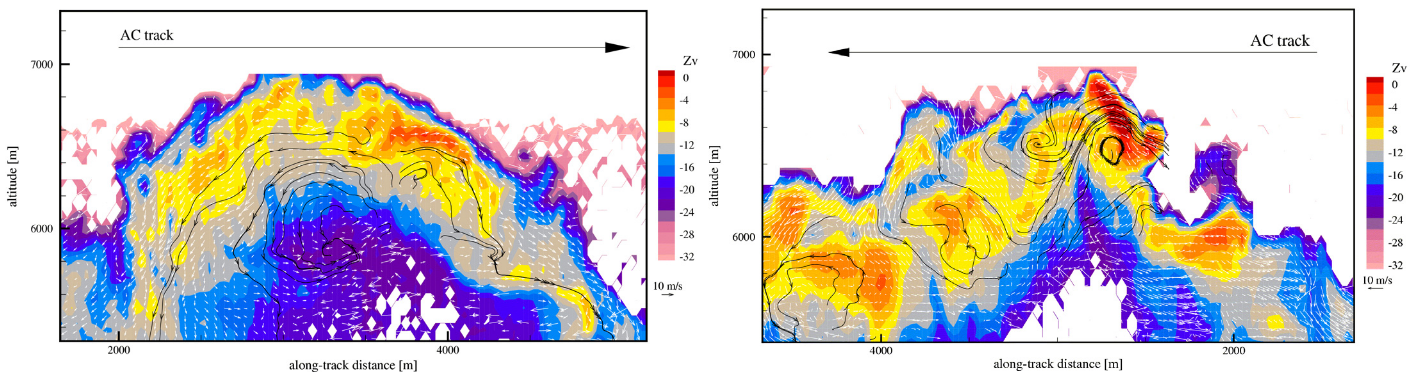

Fig 2.1 *Two VPDD (see Section 5) passes at the top of an isolated cumulus, on Aug. 26th, 2003, at 18:20 UTC (left) and 18:23 UTC (right). Shown are WCR reflectivity in color (Zv, dBZ), 2D vector field (mean wind subtracted), and select quasi-instantaneous streamlines (black lines with arrows). The flight level is indicated by an arrow. Grid resolution: 30x45 m^2. The 'reflectivity' is the equivalent reflectivity, i.e. it is assumed that the scatterers are water spheres. The WCR vertical velocity is the particle vertical motion: the particle terminal velocity (ranging between 0-3 m s^{-1}, according to the in situ cloud probes) is too uncertain to derive the vertical air motion field, but relatively small.*

The observed (equivalent) reflectivity and velocity fields in **Fig 2.1** confirm the conceptual model of shedding thermals (Blyth et al., 1988). HiCu03 data show that the upper portion of a cumulus thermal often consists of a rising vortex ring. Entrainment can occur near the ascending cap, consistent with the cloud-scale vorticity field: entrained air, engulfed by fine-scale shear instabilities at the upper boundary, may be carried downward along the side without penetrating into the ascending core because of strong horizontal divergence at the top. Instead, the mixed or even purely ambient air is more likely to be transported into the center of the thermal by the convergent flow at the vortex ring base. At a smaller scale (~100 m), both intrusions and extrusions can be seen, in which the velocity field is generally consistent with the streamwise reflectivity gradient, suggesting a short cloud microphysical response time.

This picture is consistent with the numerical simulations by Zhao and Austin (2004). They confirm the presence of undiluted parcels at the very front cap of the ascending thermal and in a narrow stem below it. Hydrometeors also may be drawn back into the updraft via this recirculation. This may be occurring at the base of the counterclockwise rotor in the left image of Fig 2.1, for instance. Such recirculation may lead to rapid precipitation growth: ice crystals may grow via Bergeron process when re-injected into an ice-supersaturated region; and larger droplets may find themselves in an environment favorable for coalescence. In other words, the vortex circulation may augment the effective particle residence time, thus facilitating both ice nucleation and riming/collisional processes.

The two VPDD analyses in Fig 2.1 are separated by ~3 minutes. Low reflectivity values are found in the center of the growing cumuli, while larger values occur at the summits and edges of the cloud. During HiCu03, growing cells systematically show centrally located updrafts, flanked by descending regions. This suggests a toroidal circulation: upward motion in the center of the cloud, overturning and horizontal divergence at the top, and descending flow carrying larger hydrometeors along the sides. The arching pattern in the reflectivity structure can be partly due to the lateral displacement of previously formed hydrometeors caused by the divergence at the top of the thermal.

The vortex ring core updraft carries aloft new generations of small droplets (mean diameter <15µm), yielding weaker echoes. Vortex ring tops and edges appear to be areas favorable to ice nucleation. Evaporative cooling following mixing may contribute to droplet freezing. Coalescence or riming may be promoted at the summit of the ascending parcel, if this parcel follows the path of a previous updraft, and a new generation of droplets is forced against 'older' precipitation. Reflectivity maxima were measured to increase by about 10 dBZ in 10 min in the growing cumulus of Fig 2.1. Such rapid increase was commonly observed in HiCu03 cumuli. Even at temperatures around -18ºC, LWC (liquid water content) values close to adiabatic were found in growing cumuli, above WCR-detected updraft shafts. When the central updraft becomes cut-off from its source (as was the case for the cumulus shown in Fig 2.1, a few minutes after the right image), then the cumulus rapidly glaciates. This causes a rapid reflectivity increase (5 to 10 dBZ), and the development of ample downdraft regions.

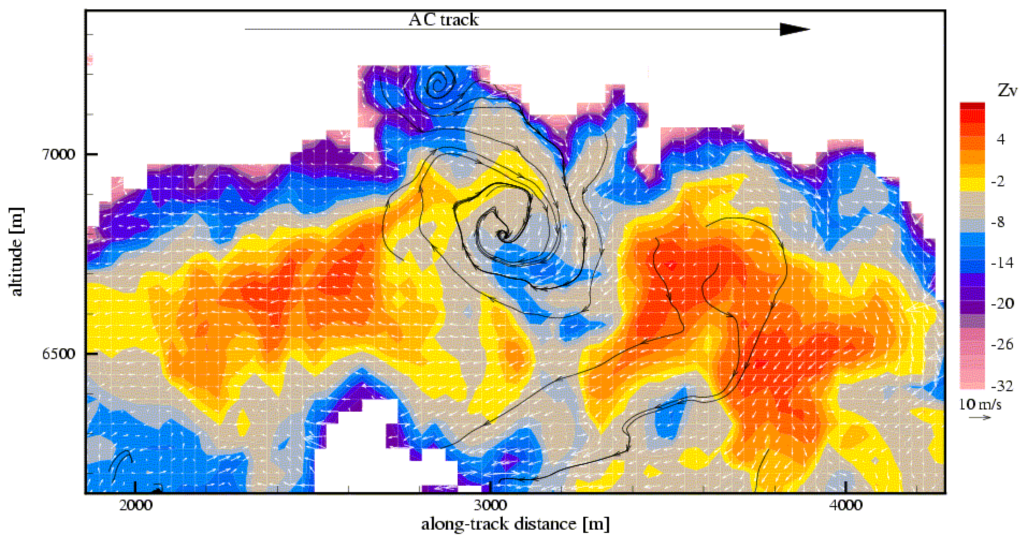

Fig 2.2 *As Fig 2.1, but for a VPDD pass at the top of a congestus, Jul. 17th, 2003 at 21:42 UTC. Grid resolution: 34x31 m^2. Note the two vertically-stacked counter-rotating vortices at the top, and the entrainment region forced by the vorticity structure.*

Fig 2.2 offers a VPDD synthesis for the upper region of a congestus under significant vertical shear (directed from left to right in the Fig). The ascending thermal just left of the center (near x=2700) is tilted by the action of the main shear. Two areas of strong reflectivity emerge separated by low values in the middle. Two intense vortices are evident at the top. They appear to be part of the same vortex ring that is tilted and sheared. The lower vortex is characterized by an arching pattern of the reflectivity, with lower values on the downshear side, and stronger on the upshear one. Apparently hydrometeors have been advected to the right, but the vortex-induced downdraft enhances entrainment from the top, severing the strong reflectivity region in the middle. LES simulations carried out by Zhao and Austin (2004) show an ascending cloud top characterized by a similar internal circulation, with strong horizontal divergence at the top and convergence at the bottom. The authors describe the vortex ring as being tilted in its ascent by the action of shear, with mixing and downdrafts enhanced on the downshear side of the cloud, whilst circulation is weakened on the upshear one.

Circulation driven entrainment is illustrated further in **Fig 2.3**. Fig 2.3A presents in situ and WCR measurements in up/down profile mode (see Section 5). Again vertical kinematics can explain the overall mushroom shape of the cumulus. The Doppler field shows an updraft located in the central portion of the cloud, near its base (the precise cloud base is undetected), and tilted to the left in the upper levels. Vertical plane wind vectors reveal the overturning of the thermal: a counterclockwise circulation is visible in the left sector of the cloud with convergent flow towards the center at flight level. Stronger reflectivity echoes are evident within the downward motion region. Some dry air appears to be captured by the circulation on the left: low reflectivity values intrude the cloud from the side and bottom. Note how the flight-level LWC drops to zero where this entrained air is encountered, near x=3600.

Fig 2.3B illustrates a VPDD synthesis of another cumulus top. Again an intense vortical structure is identifiable on the right, with potential entrainment manifesting in the reflectivity dent, consistent with a LWC minimum at flight level, well to the left of the cloud edge. During the next pass, six minutes later, the cloud was in decay; ice was widespread across the cloud and the maximum LWC was ~1/3 of that measured in the previous pass.

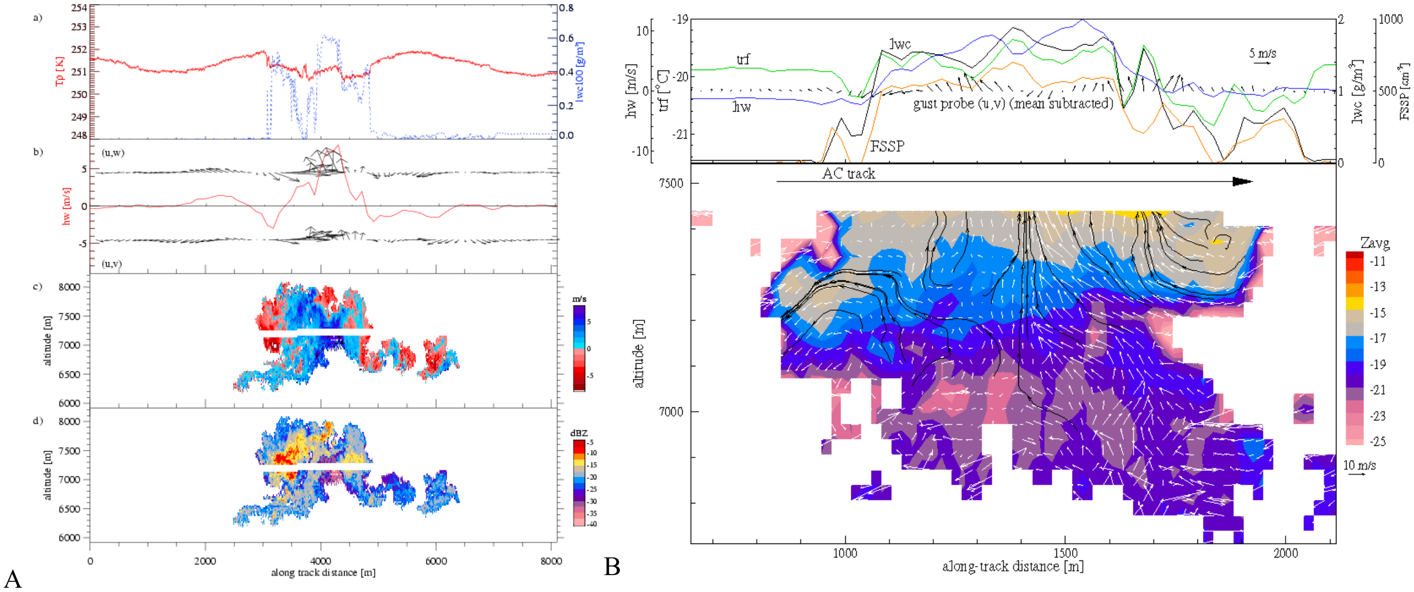

Fig 2.3 *A) In situ and WCR analysis of an isolated congestus, July 13, 2003, 20:58 UTC. a) density temperature (Emanuel, 1994) (T_ρ) and liquid water content (lwc); b) air vertical velocity (hw) and gust vectors (deviations from the mean horizontal wind) in the vertical transect (u,w) and the horizontal (u,v); c)Doppler vertical velocity above and below flight level (the white stripe is the radar blind zone); d) reflectivity. B) As Fig 2.1, but for a young congestus on July18, 2003, 20:43UTC; upper panel shows in situ data: air temperature (trf), air vertical velocity, liquid water content, FSSP cloud particle number concentration (FSSP), and gust vectors in the horizontal plane.*

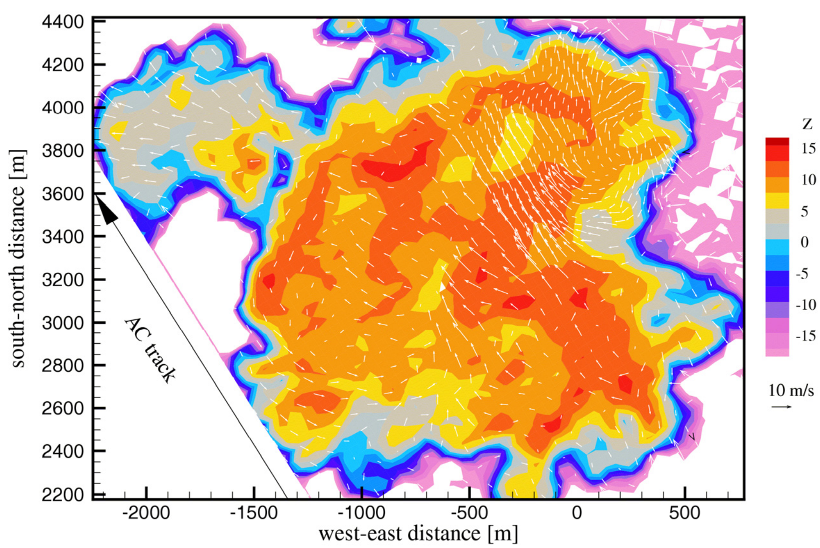

Fig 2.4 *As Fig 2.1, but a horizontal-plane dual-Doppler (HPDD, Section 5) analysis of a congestus on July 12, 2003.*

Fig 2.4 offers a horizontal view. Two large counter-rotating vortices are visible in the upper right and lower left. The large dent in the cloud boundary on the right illustrates entrainment driven by the cloud-scale circulation, while the divergent flow in the upper left cloud patch, away from the main cloud, suggests that that patch is detraining. Horizontal-plane vorticity, deformation, and divergence are comparable to those observed in vertical transects, which is consistent with the ~1:1 cumulus aspect ratio. Clearly the 3-D vorticity vector shows no preferential orientation in the vertical, and can be readily tilted into the horizontal; e.g. the counter-rotating vortex pair in Fig 2.4 may be due to the tilting of ring-core vorticity by the ambient wind. Vertical vorticity is frequently found at the edges of the updraft core.

During HiCu03, clouds appeared characterized by a pulsating nature, with periods of 'inactivity' alternated by arousal of coherent and vigorous updrafts. **Fig 2.5** shows a side/down (see Section 5) scan of a cumulus cluster being reinvigorated by the arrival of new thermals, after showing prevailing downward motion only 4 minutes earlier. The Doppler field shows that two broad areas of ascending motion are present with downward flow at their edges. They could be the result of a larger updraft being separated by older precipitation in the middle. Fig 2.5 demonstrates how the horizontal plane flow field varies in response to updraft cores: the strong updraft on the right (x=1000) exhibits confluent horizontal flow at flight level (directed towards the central portion of the cumulus); the one on the left (x=3300), whose top has not reached flight level yet, exhibits flow away from the updraft.

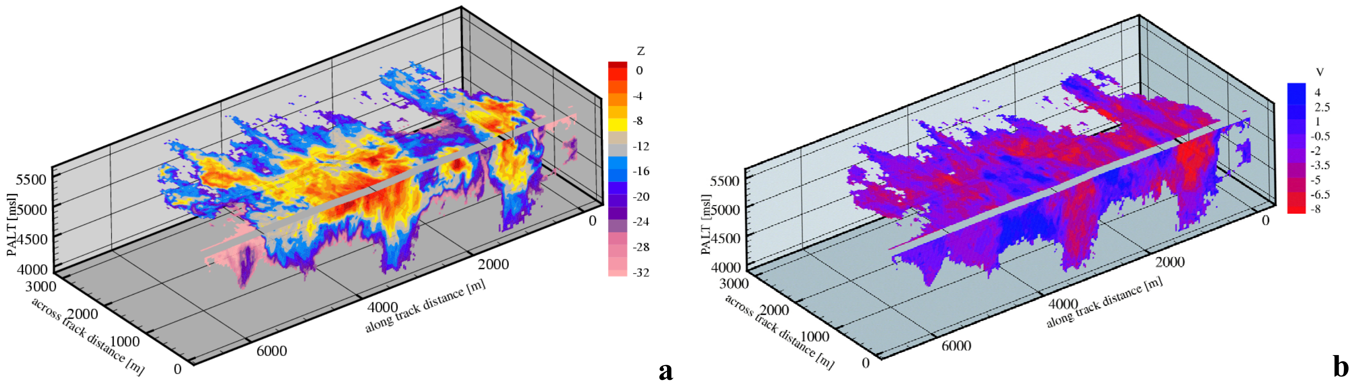

Fig 2.5 *An example of a two-plane simultaneous scan, for a cumulus on 18 July 2003. a) reflectivity [dBZ] in a horizontal plane to the right of the aircraft track and in the vertical plane below it; b) corresponding Doppler velocity [m/s], positive is upward and away from the flight track centered in the 200 m blind zone.*

These illustrations highlight the complex 3-D nature of entrainment mechanisms and cloud development processes. The WCR is a formidable tool to tackle these problems, especially when combined with in situ cloud, thermodynamic, and velocity data. We are currently analyzing these data in order to confirm and extend the conceptual model of cumulus dynamics, ultimately to improve convection parameterization schemes.

3. Cumulus dynamics and entrainment

The primary objective of this study is to investigate cumulus dynamics at a scale that largely resolves entrainment (Section 1.4). We propose to perform a detailed analysis of the WCR-inferred kinematics in vertical and horizontal cloud cross-sections, in combination with in-situ King Air data, as illustrated in Section 2.2.

Observational studies of cumulus dynamics have been hampered by the complex 3-D structure and rapid evolution of cumuli. Until recently airborne analyses have relied on 1-D (flight-level) data alone (e.g. Braham et al. 1951, Raymond and Wilkening 1982, Hobbs and Rangno 1985, Blythe and Latham 1993). Cumulus research using ground-based X- to S-band Doppler radars (e.g. Braham et al. 1951, Knight and Miller 1993, Knight et al. 2002) can describe the echo volume at high temporal resolution, but these radars may be affected by Bragg scattering and mainly see the product of convection (i.e. precipitation), not the cumuli themselves. Lhermitte (1987, 1988) and more recently Kollias et al. (2001) have shown the potential of a ground-based W-band Doppler radar for cloud research. Our airborne cloud radar adds a new dimension to cumulus research, given its fine resolution, its high sensitivity, its multi-plane 'scanning' capability, and the proximity to cloud and thermodynamic data. Damiani et al. (2004) demonstrate the capabilities of the WCR airborne configuration in providing a more complete spatial view of cumuli, in terms of both small-scale and cloud-scale dynamical features.

Given the rapid evolution of cumuli, it is difficult to relate a sequence of aircraft penetrations to cumulus evolution (e.g. Blyth and Latham 1993). Consecutive radar transects more readily reveal cumulus evolution and allow in-situ data to be interpreted in that context (e.g. Fig 2.1). Temporal evolution is parti-cularly important in the understanding of orographic cumuli, interacting with the mesoscale environment (Section 4).

We mainly seek to examine the existence and characteristics of vortex-ring type structures in the ascending cloud-caps. The importance of such features is threefold. Foremost, they are thought to be key players in the entrainment mechanisms (Blyth et al. 1988, Carpenter et al. 1998, Damiani et al., 2004). Secondly, a toroidal circulation displaces hydrometeors towards the sides of the updraft, initiating a spatially preferential arrangement of particles, and it may recycle hydrometeors back into the thermal core (Fig 2.1, Damiani et al., 2004). Thus it may directly affect precipitation development. For instance, ice crystals may grow rapidly through the Bergeron process if the vortical dynamics drive ice crystals back into a saturated updraft region. Growth by riming or collision-coalescence may also be enhanced by the re-ingestion process. We will assess whether WCR particle re-ingestion signatures are supported by in situ data. Thirdly, the mechanics associated with a rising vortex ring implies a 'bubble' rate of rise of about half the core updraft speed. This has consequences for the droplet residence time at a given altitude and thus on the forecasting of the lifetime of a cumulus cloud, its growth and maximum rise, and its precipitation.

3.1 Connections to earlier studies

The basic kinematics and dynamics of buoyant plumes and cumulus convection has received much attention, from the initial lab experiments (Scorer and Ludlam 1953) to more recent high-resolution numerical simulations (e.g. Grabowski and Clark 1993, Zhao and Austin 2004).

Reuter (1986), and more recently Blyth (1993) and Zhao and Austin (2004) present a thorough review of cumulus entrainment studies. Blyth (1993) underlines the importance of better understanding the entrainment of dry air into developing cumuli, and how this process still is an unseized key to the enormous fluctuations in the observed microphysical variables, making it difficult to parameterize cumulus processes in models. Entrainment, in fact, may profoundly impact not only the dynamics of cumuli, but also ice nucleation and secondary particle production rates, the onset of precipitation, electrification, the production of acid rain (Chandler et al., 1988), and cloud radiative properties.

The first descriptions of the dynamics and microphysical structure of cumuli are by Stommel (1947), Squires (1958), and Warner (1977). Their work was based on in-situ observations collected by means of several aircraft penetrations of cumuli. Large fluctuations in the velocity field were reported in the horizontal, and microphysical properties were found to be highly heterogeneous. Observations also indicated that horizontally averaged LWC values were less than the adiabatically predicted values (Stommel 1947, Braham and Draginis 1960). At the same time, the formation and fall-out of hydrometeors was recognized to play an important role in the circulation within buoyant cells (Byers and Braham 1949). A thermodynamic model alone was clearly not enough to describe the interaction between the rising warm, moist air and the environment. An analytical treatment of thermals, based on similarity theories, was first proposed by Schmidt (1941). Such treatments assume that the entrainment rate is proportional to the vertical velocity of plumes and inversely proportional to their radius (see Emanuel 1994, chapter 2, for a review of the proposed models for both laminar and turbulent convective entities). Entrainment was supposed to occur through the lateral sides of the thermals.

It was soon realized that an understanding of the dynamics of convective plumes is not only important to quantify vertical transport of heat and moisture, but also to understand cloud microphysical processes in convection. Much of the debate still is on the cause/effect relationships, the scales, and the altitudes of entrainment and mixing in cumuli. Stommel's assumption (1947) that lateral mixing alone explains the departure from adiabatic was soon abandoned. This hypothesis was initially developed based on the view that convective elements are '*steady-state jets*' (or 'plumes'). Plume theories discard any possible mixing of cloudy and environmental air at cloud top and ignore cumulus evolution. Since then, Squires (1958), Paluch (1979), and Emanuel (1981) have highlighted the importance of penetrative downdrafts as means of substantial entrainment, shifting the principal focus of the mechanics from the horizontal to the vertical plane. Paluch's observations (1979) supported the idea of mixing originating at cloud top, and Betts (1982) confirmed that cloudy air is the result of a mixture of ambient air from cloud-top and cloud-base. Findings of undiluted parcels at different levels in the clouds (Heymsfield et al. 1978, Austin et al. 1985) and lack of systematic variation in properties across the cloud, further questioned the validity of the bulk-entraining plume model.

Scorer and Ludlam (1953) and Scorer (1957) carried out tank experiments showing that entrainment and mixing occur both at the top and in the wake of the ascending thermal. The latter was envisioned as a single rising entity detaching from its original heat source. This 'bubble' approach was later refined into the '*buoyant vortex ring*' model (Levine 1959, Turner 1957). Analytical solutions for Hill's spherical vortex, an idealized vortex ring case, are found in Lamb (1949) and Telford (1988). Single-bubble theories, however, fail to justify the often-observed flat cloud bases, which seem to rely on steady updrafts driven by continuous heat source. Moreover, when coupled with self-similarity theory, thermals entrain dry air at such a rate that unmixed parcels should not exist at high levels in congestus clouds, which disagrees with the results of Heymsfield et al. (1978), Musil et al. (1986, 1991), Jensen et al. (1985) and others. Sanchez et al. (1989), however, found that thermals entrain ambient fluid at a much smaller rate than self-similarity theories predict, though retaining the characteristic toroidal circulation.

Turner (1962) proposed the '*starting plume*' model, which combines characteristics common to both bubble and jet theories. A plume cap, in this case, dilutes only about one third as rapidly as an isolated bubble for a given size, as half of the incoming flux comes from the plume below.

Most of the tank experiments and computational fluid dynamics simulations, upon which analytical models are constructed, rely on the similarities between the leading front of a buoyant parcel and the upper boundary of a growing cumulus. The Reynolds, Rayleigh, Prandtl and Froude numbers should be accounted for, in order to validate atmospheric observations against tank experiments via similarity theory (Emanuel 1994). Tank experiments and real clouds nevertheless differ for a number of reasons (aside from scale): the variation of buoyancy during ascent, the treatment of phase change, and environmental shear.

Parcel thermodynamic and microphysical properties determine the parcel density, and, in the context of the ambient stratification, the parcel buoyancy. Generally speaking, storms derive their energy mainly from latent heat release of condensation and freezing; hence the dynamical evolution is quite sensitive to water phase and water content. Even on a small scale, e.g. at the cloud top, the freezing of water may affect the dynamics. Evaporative cooling, following mixing with environmental dry air, may give rise to small-scale circulations that may grow through the depth of the cloud (Squires 1958).

Other factors complicate the study of convection. Cumulus is believed to grow mainly on the upshear side and detrain on the downshear side (Malkus 1954, Ackerman 1958, Scorer 1958, Kitchen and Caughey 1981, Rogers et al. 1985, Perry and Hobbs 1995), thus wind shear should be accounted for. Atmospheric turbulence in the inertial subrange affects convection. The birth of a convective element is most likely to be within a turbulent boundary layer. Thus the details of the initial disturbance profoundly affect the convective evolution (Johari 1992, Klaassen and Clark 1985). The outcome is a series of possible behaviors that can hardly be classified as a 'bubble' or a 'plume'. Nevertheless, observations of pulsating cumuli suggest a 'thermal' character in the nature of the convection. For instance, the lifespan of a cumulus eddy is on the order of a few tens of minutes; this is comparable to the time required for a parcel to rise from its source to its buoyancy equilibrium level (Doswell 2001).

As mentioned above, field observations have demonstrated that mixing is likely to occur at the cloud upper boundary (e.g. Paluch 1979, Betts 1982), but it cannot be limited to the cloud top. Blyth et al. (1988) and Blyth (1993) describe cumulus clouds as *shedding thermals*, with entrainment occurring near the ascending cloud-top with mixed parcels descending around the edges of the thermal updraft core. Although penetrative downdrafts may very well cause substantial descents [up to ~2.5 km from the level at which entrainment occurred (Squires 1958, Paluch 1979, Emanuel 1981)], detailed analyses of the kinematics reveal other features acting in the mechanism of entrainment. It appears that buoyancy reversal is more likely to be the effect and not the cause of entrainment. Cooper and Rodi (1982), examining the statistical properties of several collected droplet spectra and air velocity data in summer cumuli, depict mixing as a highly inhomogeneous process occurring first at cloud top. The result is pockets of negatively buoyant fluid that partially penetrate into the rising thermal. Some of these pockets are displaced laterally to form downdrafts at the edges of the rising core. These descending parcels eventually are recaptured in the wake of the central cap region. This overturning process may aggregate negatively buoyant air at the bottom of the rising core, leading to deep downdrafts.

Klaassen and Clark (1985) and Grabowski and Clark (1993) use numerical simulations to conclude that buoyancy reversal following evaporative cooling only plays a minor role in the generation of downdrafts, compared to dynamical effects. Blyth et al. (1988) identify the thin mixing region immediately above the ascending cloud top as the main entrainment source region; in their model, the mixed parcels descend along the edges of the thermal core into the turbulent trailing wake. Jonas (1990) and Stith (1992) support the idea of lateral mixing following the transport of environmental air from cloud-top via thin subsiding layers. Recent experiments (Johari 1992) confirm the hypothesis of a vorticity-induced velocity field which causes ambient fluid to be entrained from the bottom of the ascending parcel. Our HiCu03 analysis (Section 2.2, Damiani et al. 2004) gives credence to the shedding thermal model (Blyth et al. 1988), but clearly both lateral and top edges are potential erosion sites, given the complex 3D flow structure of cumuli.

3.2 Research Questions

The WCR data from HiCu03, combined with flight-level thermodynamic and cloud properties, are yielding new insights into the dynamics of cumuli (Damiani et al. 2004, Damiani 2004). However the analysis is hampered by a poor knowledge of the growth stage of sampled clouds, of the cloud base height, and of ambient stability and shear.

These variables should be known more accurately in CuPIDO. In this study of orographic cumuli, we aim to study the kinematics in both vertical and horizontal planes in the context of entrainment, the least understood factor in cumulus development. We will describe the scales and shapes of entrainment/detrainment circulations in various stages of cumulus growth, interpret these dynamically, look for signs of precipitation recycling, and assess/improve time-dependent models of cumulus evolution. The specific questions we will address as part of the CuPIDO cumulus dynamics study are:

- What conceptual model best describes the formation stages of a convective cloud?
    - Is orographic convection pulsating, and if so, what is the pulsation frequency, and how does the depth and/or width, and relative spatial location, change in successive pulses?
    - How does the cloud-top ascent rate compare to the core's updraft speed? Which element does the updraft mostly resemble: steady jet, starting plume, shedding thermal? We expect to find more evidence for the shedding thermal model inside the orographic cumuli, which may grow faster than the HiCu03 cumuli. The description of the evolution of a single convective entity within a cumulus or cumulus cluster is the basis for understanding cumulus dynamics and precipitation, as well as for the accurate parameterization of the effect of cumuli in NWP models and GCMs.
- What are the typical fine-scale flow and vorticity patterns within a cumulus congestus?
    - Are there secondary circulations along the main updraft column? Does the ascending cap show indications of horizontal or tilted vortex rings?
    - What are the space and intensity scales of vortices in the horizontal plane? Where is the vertical vorticity concentrated with respect to the main updraft? Fig 2.4 shows evidence for the existence of large vortices in vigorous congesti. Investigation of the coupling between the two planes will lead to a 3-D interpretation of cumulus dynamics, possibly shedding light on the vertical vorticity generation mechanism. The latter aspect is poorly understood in shallow and mid-size convection.
    - How do the horizontal airflow patterns influence the turbulent meandering of the updraft and affect the particle residence time? What is their role in possible secondary entrainment? We will attempt to answer these questions by correlating reflectivity structures to 2-D flow properties, such as vorticity and divergence, and by relating these to flight-level data, such as gust-probe traces and FSSP records.
    - Does helicity affect the strength and persistence of towering cumuli? Etling (1985) and Lilly (1986) suggest that helicity (cross-product between velocity and vorticity) is important for the development and lifespan of atmospheric flow structures. We intend to assess whether or not rotating updrafts (if present) demonstrate more coherence and resilience to dissipation.
- Are there indications of significant hydrometeor re-ingestion into the updraft core? If so, how is the recycling of hydrometeors affected by the depth and strength of the cloud-top vortex ring, and how is precipitation production affected? Damiani et al. (2004) confirm that the cloud-top toroidal circulation can affect the spatial distribution of hydrometeors. The WCR reflectivity field, combined with the WCR flow field, reveals clues about hydrometeor advection and growth/decay in specific sectors of the cloud.
- Where and at what scales does entrainment occur?
    - What is the role of major and secondary circulations in the entrainment? How does the toroidal circulation, often found in the ascending cloud top (Damiani et al. 2004, Blyth et al. 1988, Carpenter et al. 1998), affect entrainment? How do the droplet size spectra in entrained air (as inferred from WCR imagery) compare? Previous studies hint at inhomogeneous mixing in cumuli (French et al. 2000). We seek confirmation of these findings and will focus on the dynamical impacts of microphysical changes due to entrainment.
    - How do radar entrainment signatures at all scales evolve as a cumulus tower grows? The interfacial shear at the edge of the main updraft, or between up- and downdraft, may affect entrainment rates, as well as precipitation development and charge separation.
    - Do undiluted parcels persist in some cloud regions?
- Can cloud top instability nodes be discerned with WCR data? Grabowski and Clark (1993) attribute cloud-environment interface instabilities near cloud top to baroclinic vorticity production, i.e. by horizontal gradients of

buoyancy. The former as well as shear instabilities along the sides of the cloud may be responsible for entrainment in the upper cloud region, with cloud edge perturbations growing in scale. A related question is how turbulent kinetic energy and shear stresses vary with height in the cloud. Buoyant cores, entraining eddies, or zones of interfacial shear between up- and downward flow are expected to be source locations of turbulence.

- How important is the vertical wind shear in the evolution of the characteristic flow structures associated with the convective parcels? Vortex ring tilting due to vertical shear has recently been postulated (Damiani 2004). How does shear, and associated cloud-scale pressure perturbations, affect the flow field and entrainment processes in shallow to moderate convection? A comparison between low and strong wind shear cases will be performed.
- Where and when does glaciation occur? The question is important because the latent heat release by freezing may deepen the towering Cu, possibly leading to the Cb stage (Koenig 1963). Dye et al. (1986a, b) and Hobbs and Rangno (1985) report that the largest concentrations of ice particles occur at the edges of the updrafts and near the cumulus summits where intense small-scale entrainment may occur. The consequent mixing may enhance ice nucleation, due to lower temperatures and higher supersaturation. Ice nuclei have been shown to be more active for a given temperature at higher supersaturation (Huffman 1973, Berezinskiy and Stepanov 1986). Also, secondary ice formation mechanisms could be promoted by the larger drops forming at high levels of supersaturation (Blyth 1993).

4. Orographic circulations and cumulus development

4.1 Connection to earlier studies

Cumuli are well-known to first develop over mountains. Pick a visible satellite image loop for almost any summer day over the Southwest, and it is apparent that as the CBL develops during the morning hours, cumuli form and grow over the mountains. Almost every day around noon, mountains appear to become local conduits of CBL moisture (and thus also heat and momentum) into the free troposphere. Few field campaigns have aimed to describe the origin of orographic cumulus development, and the interaction between cumuli and the mesoscale orographic flow. Using a network of surface stations around the San Francisco Peaks in Arizona, Fujita et al. (1962) found a pressure drop during the morning hours mainly on the heated southeast side, leading to convergence and cumulus convection. Todd (1964) documents the deepening and increasing lifespan of successive cumulus towers over these same mountains, and verifies that a single updraft can be identified in sequential aircraft traverses, at least in the deeper cumulus towers.

A number of experiments have focused on airborne observations over the Magdalena Mountains in New Mexico, site of the Langmuir Laboratory (e.g. Braham et al. 1951, Braham and Draginis 1960, Raymond and Wilkening 1980, Raymond and Wilkening 1982, Dye et al. 1989, Raymond and Blyth 1989, Blyth and Latham 1993). Several studies also utilized photogrammetric techniques and multiple ground-based Doppler radars. Several of these papers deal with the initiation of ice and/or large droplets, and with the source levels of entraining air. Braham and Draginis (1960) describe the orographically-induced mesoscale ascent (the 'convective core') and distinguish this from updrafts in individual cumuli. None of the studies examine the dynamic interaction of the deep moist convection with the mesoscale orographic circulation.

In the early morning drainage flow may be present on a small scale, probably confined to the valleys emanating from the Santa Catalina Mountains, but the larger-scale flow has a Froude number close to one, depending on the upstream wind speed (U). The internal Froude number $F = U/NH$ is a measure of how a stratified airmass, with Brunt-Väisälä frequency N, interacts with an obstacle of depth H (e.g. Walter and Overland 1982). Prior to the onset of cumulus convection the ambient N value is close to zero ($<10^{-2}$ s^{-1}) over the depth of the mountains (H~1000 m). If the wind speed exceeds a certain value (e.g. 12 m s^{-1} if $\partial\theta/\partial z$ =1 K km^{-1}), then F >1 and the flow should go over the mountain. Under the more common weaker wind regimes (or higher static stability), the flow should go around the mountain, and a high should be present on the upstream slopes, a low on the downstream slopes. Thus orographic uplift and the triggering of summertime cumuli are not likely to be controlled by the ambient wind.

In fact by the time of cumulus formation, vertical motions and pressure perturbations can no longer be understood by an F argument, since the low-level stratification around the mountains essentially disappears. Rather, the circulations are controlled by a combination of mesoscale convergence (anabatic flow), which is sustained, and convective processes, which are highly transient. The mesoscale convergence is driven by differential heating above the mountains, thus it can be affected by latent heat release in convection. A range of scales is involved, depending on the size of the mountain, the CAPE, and the ambient shear. Raymond and Wilkening (1980) find that the heat-island circulation over the Magdalena Mountains is about 20 km in diameter, and the convective eddies are ~ 3-4 km in size.

The CBL over a mountainous terrain is far more complex than over a flat area. The basic dynamics of a solenoidal circulation resulting from a sloping CBL, and the low-level mesoscale convergence over an isolated mountain, are well understood (e.g. Orville 1964). This dry, thermally-direct mesoscale circulation, trapped by the CBL top over the high terrain, is well documented (e.g. Banta 1984, Raymond and Wilkening 1980). Less is known about how this convergence alters the CBL depth over the mountain and reduces the CIN. Under suitable ambient stratification, which is quite common during the monsoon season, cumulus towers (convective eddies) penetrate into the free troposphere, and this may drive a deeper, larger solenoidal circulation. The transition to a circulation over the depth of the troposphere occurs well before the shallow topographically-induced circulation matures.

In case of dry convection over a mountain, large negative heat fluxes occur in the upper part of the convective core, which serves to slow the solenoidal circulation (Raymond and Wilkening 1980). A succession of towering cumuli detrains 'rich' CBL air (high in θ_e[1]) into the middle troposphere, between the LFC and the LNB. From an energy budget perspective, water vapor convergence around the mountain, and precipitation over the mountain, implies that the latent heat release due to condensation should exceed the evaporative cooling below cloud base. Thus the heat deposit by detraining cumuli, as well as precipitating cumulonimbi, should cause net heating in a column of air above the mountain, and thus reduce surface pressure hydrostatically. This would at least temporarily enhance low-level convergence, consistent with the deep mesoscale circulation we postulate to exist. Yet observations in a small sample of orographic cumuli do not confirm this: surface pressure observations by Fujita et al. (1962) indicate that a low forms on the sunny mountain side until about local noon, and that is dissipates by the time of the first Cb formation, well before a cold pool forms. An analysis of aircraft data by Raymond and Wilkening (1982) also indicates that deep cumulus clouds do not significantly affect the strength of the low-level convergence. It is possible that any column warming is offset by cooling due to ascent in the stable free troposphere, associated with the deep mesoscale circulation. Clearly the synergy between mesoscale circulations and cumulus convection over mountains is poorly understood.

Related to the question of how cumulus clouds affect the orographic circulation is the question of how detraining cumulus eddies affect the evolution of subsequent cumuli. If the advective time scale is small relative to the lifecycle of a cumulus tower, then the free troposphere becomes locally enriched in moist static energy by detrainment of dissipating cumuli, and thus the observed deepening of successive cumulus towers may be due to the decreasingly negative buoyancy imparted by ambient air entrained into the cumulus. A stepwise development of new turrets through the remnants of their predecessors has certainly been observed (e.g. Roessner et al. 1990; J. Zehnder, Pers. comm.). The growth of cumulus towers to the cumulonimbus stage may be enhanced by a sudden glaciation and associated latent heat release (e.g. Ludlam 1952, Koenig 1963), but this does not explain the stepwise deepening of successive towers even above the -10ºC to -15ºC level, where glaciation generally occurs (Blyth and Latham 1993).

4.2 Research Questions

The above discussion brings us to a number of specific questions. These are phrased in terms of measurable quantities, inferred from the King Air and other CuPIDO platforms. They complement those raised in Section 3.2. They address the dynamical synergy between mesoscale circulations and cumulus convection over mountains.

- Is convective initiation driven by local surface heat fluxes over the mountain, and/or by mountain-scale convergence of air and moisture? How does this convergence change in intensity and in vertical extent during the orographic cumulus development phase?
- How does the moisture and heat content of the air over the mountain compare to that of the surrounding air at the same pressure level, especially in the pre-convective stage at low levels, and how does that affect CAPE/CIN?
- Does the free troposphere, above the CBL, warm over the mountain as a consequence of the cumulus convection? In assessing changes in the 'environment' in which a sequence of cumulus towers detrain, care needs to be taken to discriminate both horizontal and vertical advection: an increase in θ can be due to detrainment of 'parcel' air, or to compensating subsidence.
- Does the water vapor over the mountain increase as a consequence of the cumulus convection, i.e. do successive waves of cumulus significantly detrain moisture, as suggested by Perry and Hobbs (1996)?

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

- Is the gradual deepening of successive cumuli leading to the Cb stage caused by this detrainment, rather than by the continued warming along the mountain slopes?

5. Wyoming Cloud Radar measurements in CuPIDO

The centerpiece of this proposal is the WCR aboard the King Air. The in situ cloud and thermodynamic data, 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 shallow to towering cumuli. The WCR was developed in the early 90's (Pazmany et al. 1994) and has participated in 12 field experiments since then (http://www-das.uwyo.edu/wcr/). An array of possible research applications for this polarimetric radar is discussed in Kropfli and Kelly (1996).

5.1 WCR Configurations

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

- one oriented towards nadir,
- one looking ~30º forward of nadir in the vertical plane,
- one looking sideways or upward [depending on the position of a mirror in a faring on the aircraft frame], and
- one looking ~35º forward from the lateral beam in the horizontal plane.

The first (last) two antennae 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, two beams 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 (Damiani et al. 2004). The usual WCR range resolution is about 30 m, depending on the pulse width. The beamwidth is very narrow (about 0.7º for the various antennae), thus the across-beam resolution is even better than 30 m at all ranges of interest (< 3 km). For purposes of dual-Doppler synthesis the useful radar range interval is about 100 m to 3000 m. The minimum detectible signal is about -25 dBZ at a range of 1 km and about -16 dBZ at 3 km, depending somewhat on the selected operating mode and antenna. During CuPIDO a range resolution of 75 m may be used in the horizontal plane, resulting in increased sensitivity and larger maximum range. More detailed radar specifications can be found at http://www-das.uwyo.edu/wcr/.

Several antenna pairs can be operated at one time, each operated in a pulse-by-pulse interleaved fashion, resulting in a quasi-simultaneous data stream from the selected antennae. The key pairs are: VPDD (down/foreward-down); HPDD (side/foreward-side); single Doppler profiling (up/down); and single Doppler side/down. The VPDD mode is more sensitive than the HPDD mode, mainly because the down-pointing antennae are larger. We expect that at the time of CuPIDO, a new fast switching network and control system will be in operation, allowing simultaneous operation of all four antennae listed above, at the cost of some loss in sensitivity. This system will be capable of: quasi-simultaneous interleaved HPDD/VPDD (denoted DPDD, Dual-Plane Dual-Doppler); side-forward/down/up profiling mode, by which a vertical plane above and below, and a horizontal one starboard of the aircraft will be scanned in single Doppler mode. In addition to all the configurations, the side/up-pointing antenna can be used for polarimetric studies.

5.2 Reflectivity

All antennae are carefully calibrated, with a residual uncertainty ± 2 dBZ. The WCR reflectivity is almost entirely due to particle scattering. Small cloud droplets (<10 μm) typically produce too weak an echo. Cloud particles up to about 300 μm scatter in the Rayleigh regime. The cloud-free CBL produces a weak clear-air echo due mainly to small insects (Geerts and Miao 2004a). As CBL air is drawn into young cumuli, so are insects, and the transition from insect to mainly cloud particle scattering remains unknown (e.g. Wakimoto et al. 2004). Unlike for S-band radars, Bragg scattering is insignificant for W-band radars, hence the visual cloud edge should be close to the WCR observed one, at least in regions where cloud particles are large enough, e.g. near cloud top (Section 2.2). 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). The WCR cannot detect cloud base, because of contamination by insects (and later by rain), and because the cloud droplets tend to be too small.

The use of radar reflectivity Z to diagnose cloud LWC is not rigorously possible in Cu. In drizzle-free Sc a relatively simple LWC-Z relationship pertains (Vali and Haimov 2000): the one-way attenuation coefficient at 95 GHz is 4.6 dB/Km per g/m^3, plus about 0.3-0.6 dB/km due to water vapor (Lhermitte 1990). Drizzle-free conditions prevail near the Sc top (Vali et al. 1998) and methods can be devised for differentiating between cloud and drizzle (Wang and Geerts 2003). In continental cumuli, the drop size distribution is more complex and ice may occur, making reflectivity assignments more difficult. Some relief is available in the immediate vicinity of the aircraft, where reflectivities can be compared to in situ particle probe observations. Further away from the aircraft, vertical Doppler velocity can give selective information about particle types. Finally, the WCR signal rapidly attenuates in the presence of rain or large frozen hydrometeors, and the inference of path-integrated attenuation itself from two antennae in the same plane (HPDD or VPDD), as a way of characterizing the hydrometeor content (e.g. Guyot and Testud 1999), appears impossible in cumulus. In short, the interpretation of WCR reflectivities in cumuli is difficult.

5.3 Velocity

WCR Doppler velocities, after removal of aircraft motion (Damiani et al., 2004) correspond rather well with the motion of scatterers. The mode of operation and desired resolution dictate the pulse repetition frequency (PRF) to use. Experience testifies that velocity aliasing can be easily removed, hence we will privilege lower PRF's in order to reduce velocity noise (errors) and second trip echoes. Vertical and horizontal dual-Doppler velocities along straight and level legs will be synthesized according to the software package built by Damiani and Haimov. The WCR velocity measurements are affected by several sources of errors: for single Doppler data, these are signal to noise ratio of the distributed target, and King Air motion correction errors due to uncertainties in the INS and GPS data and in aircraft attitude. Geometrical interpolation and regridding are additional error sources for dual-Doppler winds. Based on previous experiments such as IHOP and HiCu03 (Section 2.2), the standard deviation of aircraft attitude variations (in roll, pitch and yaw) can be kept below 3º along dual-Doppler legs through convection. This results in errors of the in-plane velocity of about 1 m s^{-1}, which compare to the level of uncertainties in the wind measurement from the gust probe (Brown 1993). We estimate overall errors in the retrieved wind field to be in the order of 1 m s^{-1} for signal-to-noise ratios of 0 dB. Examples of the fine-scale (30x45 m) circulation in vigorous cumuli are presented in Section 2.2.

The main uncertainty in deriving vertical air motion from WCR radial velocities is the hydrometeor fallspeed. Two echo types will be distinguished, those with precipitation hydrometeors, and those with just cloud particles. 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. Reflectivity can be estimated from the King Air cloud physics probes (e.g. Wang and Geerts 2003), and this can lead to further fine-tuning. In cloud-only regions high confidence exists in the vertical air motion, since the fallspeed of cloud droplets is negligible. In precipitation, the drop fallspeed V_t can be estimated from 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 empirical Z-V_t relationships for orographic cumuli, relationships that may vary with altitude in cloud, cloud age, etc. The method uses the nearest gates of up and down WCR reflectivities and velocities, ~100 m from the aircraft. These measurements are centered on the aircraft, which measures vertical air motion (Geerts and Miao 2004a). The accuracy of the resulting vertical air velocity profiles remains uncertain.

6. King Air/WCR operations in CuPIDO

Temporal (rather than just statistical) sampling of cumulus towers is essential to assess conceptual models of cumulus growth. Owing to the orographic locking of the convection, we should be able to perform multiple rapid traverses of the same cloud at increasing flight levels (Todd 1964, Blyth and Latham 1993). Temporal sampling of a sequence of towering cumuli in various stages and over various depths of course is also statistically meaningful. Our objectives dictate the following flight patterns:

1. A shallow sounding to above the CBL and a low- to mid-level mesoscale circumnavigation around the mountains.
2. Stepped traverse cloud penetrations over the mountains, starting just above mountain top, then some 200 m below cloud base, then some 200 m above cloud base, and then ascending as the cloud tops deepen, up to 9 km MSL at most. The flight legs are 10-15 km long. Both at an early and at a late stage, 40 km long legs will be flown at two levels, one near cloud base and one at the estimated level of maximum detrainment, in order to assess how the cumuli affect the environment. The flight legs should maintain the same orientations, along the shear vector if shear is present. If a stepped traverse has been completed without Cb development, we repeat the cycle starting at (1). The cloud traverses assess the following: the in-cloud WCR airflow field in both vertical and horizontal planes, and the ambient flow; thermodynamic quantities at different levels, compared to ambient values; and the reflectivity structure variability within vertical and horizontal planes, together with in situ cloud measurements.

A weather briefing will be conducted daily at 6 am local time PDT (13 UTC), starting with a call to the Tucson NWS office and an examination of the 12 UTC EMX sounding. If a go-ahead is decided, GLASS soundings are to be launched regularly starting at 7 am LT, and the King Air will take off between 7 and 9 am LT, well before the initiation of convection, in order to first conduct a shallow sounding and to circumnavigate the mountains.

Early convection typically is topographically locked. The first (dry) thermals, a few 100 m deep, develop about two hours after sunrise (Geerts and Miao 2004a), the first shallow cumuli and mesoscale convergence may develop one hour later (9-10 am LT) and the first cumulonimbus anvil develops some two-three hours afterwards (J. Zehnder, pers. comm.). Cumulus traverses will terminate before the Cb stage is reached, because rain attenuates the WCR return and because lightning is hazardous. Typically aircraft operations will then cease, after circumnavigating the mountain one last time. The endurance of the King Air with WCR is 4-4.5 hours, which corresponds well with the period of interest. Similar missions have been flown before over the Magdalena Mountains with the NCAR King Air (Blyth and Latham 1993). Lightning impact does not affect the King Air flight performance, but it does require an expensive and time-consuming engine inspection (A. Rodi, pers. comm.).

In their initial stage the continental cumuli will likely be only marginally detectible by the WCR, and the incorporation of photographically-detected cloud edges is important. The WCR will be run in up/down profile mode (see Section 5) 200 m below cloud base, in order to connect the first cumuli to buoyant updraft plumes in the CBL, if there are enough biotic scatterers. The sampling of the subcloud air mass will determine the adiabatic liquid water content and the characteristics of an undiluted air parcel, in order to assess entrainment rates from cloud measurements at higher flight levels. Later on, low in the cloud, the WCR will be run in side-down profile or side-forward/down/up modes (see Section 5). As the cloud towers, traverses at increasingly high levels will be executed near cloud top in VPDD and/or HPDD modes. Alternating between HPDD and VPDD, an up/down WCR view is needed for the spatial collocation of the various features in the horizontal plane with respect to the updraft/downdraft regions.

7. Proposed research schedule

CuPIDO is proposed to be conducted in the summer of 2005. The photogrammetry effort, the soundings and surface stations are scheduled for field deployment for two months starting 1 July 2005. The King Air including WCR will be requested for one month within that period, for a total of 60 research flight hours. The King Air, including WCR, is part of NSF's Lower Atmosphere Observing Facilities (LOAF) pool, and its data have a proven record of accessibility, accuracy and reliability. The WCR antenna selection system is being upgraded in the next few months (Section 5), and a separate proposal has been submitted for a new WCR data acquisition system with digital receiver.

If the King Air is not available in summer 2005, then a delay of CuPIDO till summer 2006 will be requested, however Dr. Zehnder's group would have to obtain an extension on their current grant. Either way, Drs. Zehnder and Geerts will continue to make contacts to enhance the mesoscale observing facilities in CuPIDO, especially mobile ground-based scanning radars (Section 1).

One of the investigators (Damiani) is expected to defend his PhD dissertation on HiCu03 no later than spring 2005. He is expected to assume a post-doctoral appointment following the defense. The tools for WCR velocity corrections, dual-Doppler synthesis, and combined WCR/King Air data analysis have been developed over the past two years, and we have tools for GLASS and PAM data analysis, so the analysis of King Air, WCR, and other CuPIDO data can progress rather quickly following the field phase. A PhD student (probably Dr. Nandana Amarasinghe) will be working in close collaboration with Damiani, under supervision of Dr. Geerts.

Three years of support are requested, in order to enable the field work and preliminary data processing (Year 1), the detailed data analysis including presentations at meetings such as the AMS Conferences on Radar Meteorology and Mountain Meteorology (Year 2), and the preparation of several manuscripts for publication in journals such as the *J. Atmos. Sci.*, *Mon. Wea. Rev.*, and *Quart. J. Roy. Meteorol. Soc.* (Year 3). In Year 3 we also allow time and travel support to prepare a future proposal, building on our CuPIDO work.

8. Educational initiatives

This proposal calls for the participation of a PhD-level student, both during the field phase and in the subsequent data analysis. The King Air aircraft is too small to seek active undergraduate student participation in the airborne operations in CuPIDO. However, if the deployment of GLASS and PAM facilities is supported, then we will coordinate with NCAR ATD to write an REU (Research Experience for Undergraduates) proposal to fund at least two University of Wyoming undergraduate students in the field, in order to install and run the facilities.