12D.3 STEREO PHOTOGRAMMETRIC ANALYSIS OF OROGRAPHIC CONVECTION DURING THE NORTH AMERICAN MONSOON

J. A. Zehnder*
Creighton University, Omaha, NE

J. Hu and A. Razdan
Arizona State University, Tempe, AZ

1. INTRODUCTION

The elevated terrain in the desert southwest of the United States provides an ideal location in which to observe the onset and transition from shallow to deep convection. Thunderstorms associated with the North American Monsoon (NAM) occur on a fairly regular diurnal cycle, with shallow convection developing under often clear skies over the highest peaks a few hours after sunrise. The shallow convection builds as a series of successively taller turrets that rise through the remnants of the preceding ones, transitioning into cumulus congestus and eventually cumulonimbus.

The development of the deep convection is often slow, occurring over a period of hours despite the presence of sufficient CAPE. One possibility is that as the shallow turrets rise into the relatively dry air aloft, they evaporate by entraining the environmental air. Given suitable conditions, such as weak winds aloft, the shallow convection can moisten the column and the successive turrets grow through a moistened environment. Other mechanisms, such as an adiabatic adjustment of the temperature profile by gravity waves generated by nearby convection may also contribute to conditioning the atmosphere to support deep convection.

Observations of convection over the Santa Catalina Mountains in southern Arizona has been ongoing for several years. Using stereo pairs of digital cameras and automatic image processing techniques, a method for determining the three dimensional structure of convection has been developed. This preliminary work motivated a series of coordinated observations using a variety of platforms that took place in July and August of 2006. The CuPIDO (Cumulus Photogrammetric In-situ and Doppler Observations) field program employed a network of 10 surface meteorological stations, 4 of which were equipped to measure surface fluxes, two mobile GPS based radiosonde systems and two arrays of digital cameras that were used to generate time lapse movies and 3-dimensional cloud structures. In addition, the University of Wyoming King Air provided a variety of in-situ wind, thermodynamic and cloud physical data and a 95 GHz (W-band) airborne doppler radar.

The CuPIDO program consisted of a series of 15 intensive observing periods. The experiment design called for coordinated soundings and aircraft observations beginning just prior to the onset of the shallow convection and through the transition to cumulonimbus. This provided the opportunity to sample the pre-convective environment and determine changes that occur as the convection develops. Soundings were located upwind of the orography and taken at hourly and in some cases 30 minute intervals. Digital imagery and surface data were collected continuously through the period. Details of the experiment design are given in Damiani et al. (2008).

2. STEREO PHOTOGRAMMETRIC ANALYSIS

Stereo photogrammetric analysis has been used to study the evolution of convection for some time (e.g. Malkus, 1952, Warner et al. 1973). Holle (1982) discusses various aspects of obtaining information on thunderstorms from cloud photogrammetric techniques. These studies used photographs and manual methods of triangulating or obtaining quantitative information. Digital images provide a convenient method of navigating cloud features and facilitate the analysis of images.

Using the intrinsic (focal length and dimensions of the imaging chip) and extrinsic (location and orientation of the cameras) camera parameters allows the definition of projection matrices that relates points in 3-d space to the projection onto the image planes. Rather than using measured values of the extrinsic parameters, an iterative scheme based on minimization of a cost function is used to refine the measured values, which are treated as a first guess. The scheme was tested using known landmark points and calculated positions were accurate to within 50 meters at the 30 km distance of the peaks. A description of the method and definition of the projection matrices are given in Zehnder et al. (2007), along with sample 3d cloud retrievals while a detailed description of the algorithim is given in Hu et al. (2008).

* Corresponding author address: Joseph A. Zehnder, Creighton University, Department of Atmospheric Sciences, Omaha, NE, 68178. email:zehnder@creighton.edu

3. CASE STUDY: AUGUST 10 2006

A collection of 3-d cloud structures has been used to provide a context for in-situ and sounding data for one specific case of the evolution of deep convection. The case occurred on August 10, 2006 and was investigated during CuPIDO IOP #10 (see Damiani et al. 2008). Conditions on this day were typical of the NAM, with light (<20 kt) and variable winds from the surface to about 200 mb. The profile was moist aloft, with a moist adiabatic lapse rate above the 600 mb level. Half hourly soundings taken from a location about 5 km from the peak over which the convection begins showed a stable layer present at about 500 mb (~6000-8000 m asl) that capped the convection.

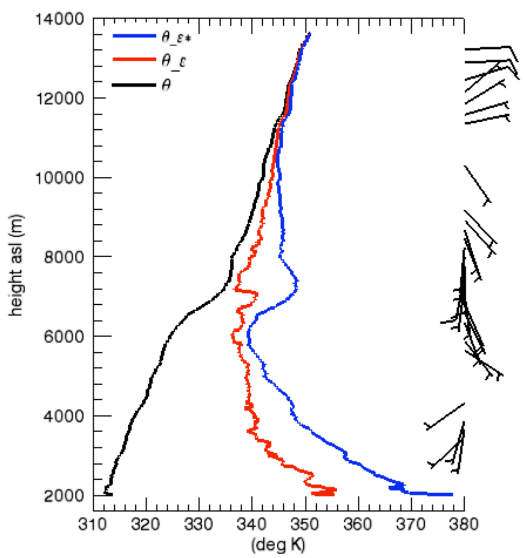

Figure 1: Plot of potential temperature θ, equivalent potential temperature θ_e and saturated equivalent potential temperature θ_e at 9:30am local time on 10 August 2006. Wind speeds are in m/sec. ½ barb = 5 m/sec.*

The shallow convection began at about 8:30am local time under mid-level stratiform cloud. Shallow convection developed and built as a series of towers aligned along the highest terrain. The tops of the cells remained limited at about 6000 m asl, as is seen in Fig. 2 which shows the convection at 10:30am local time. The convection persisted for a period of about 2 hours, fluctuating in intensity with the eventual development of towering cumulus and then cumulonimbus over the Mt. Bigelow (visible about 1/3 from the right edge of the image in Fig. 2 and 3).

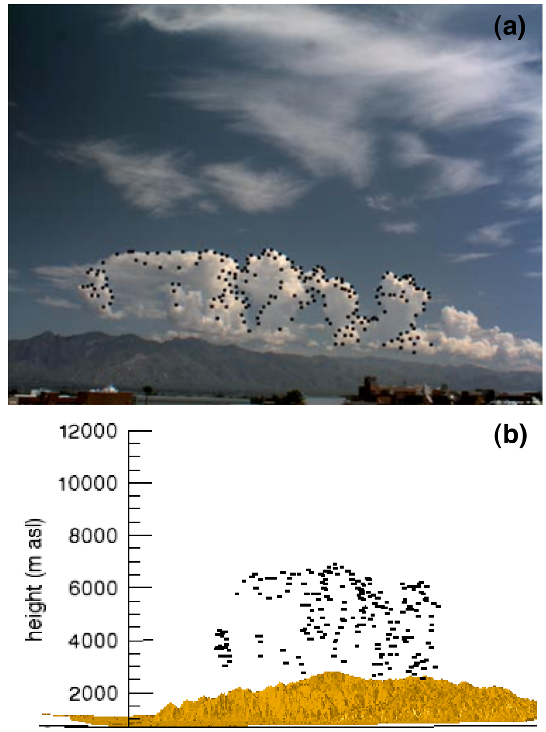

Figure 2: (a) Cloud image and (b) points determined from the 3d retrieval algorithm at 10:36am local time. Cloud tops are fairly uniform and capped at about 7000 m asl.

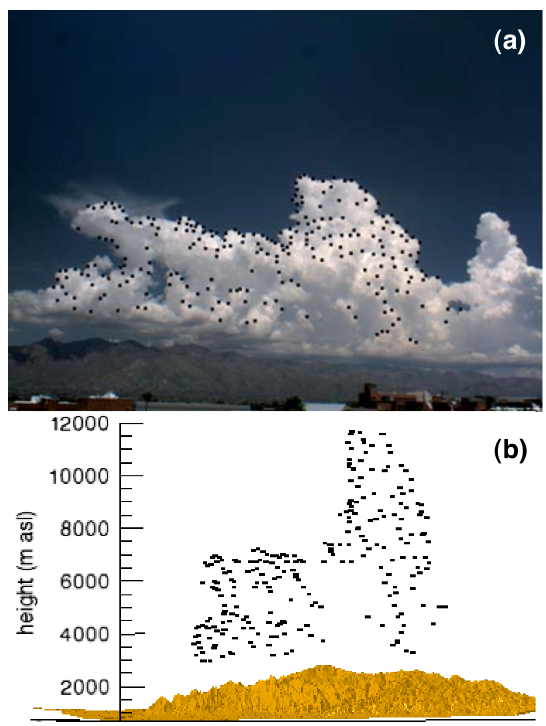

Figure 3: As in (2) at 12:39 pm local time. Convection still capped in foreground, with towering cumulus developing over Mt. Bigelow.

The onset of the deep convection coincided with a modification of the vertical thermodynamic profile. A stable layer such as that apparent in the θ_e* profile in Figure 1 has vanished, with the profile being saturated neutral between about 6000 and 9000 m asl as seen in Figure 4.

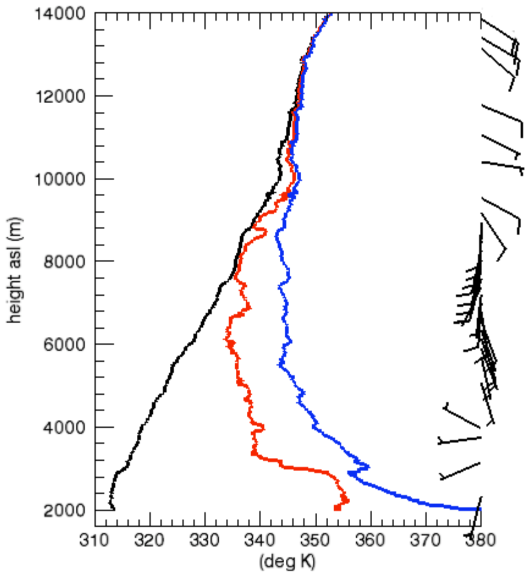

Figure 4: As in Fig 1, for a sounding at 12:30pm local time .

A comparison of Figs. 1 and 4 shows that there is little change in the θ_e profile between the two soundings, while there is a warming below the 7000 m asl and a cooling above in the θ_e* profile. This suggests that an adiabatic adjustment is responsible for the modification of the profile.

Plots of the in-situ temperature, represented as θ_e* in order to facilitate comparison with the soundings shown in Figs. 1 and 4, are given in Figure 5. These plots show sections of the flight track in clear air prior to and after the onset of the deep convection. The flight level, ~7500 m asl, coincides with the level where θ_e* is decreasing. The temperatures above the mountain top at the time the deep convection develops (Fig. 5b) are lower than any of the upwind values shown in Fig. 5a. This suggests some local modification of the temperature rather than the advection of cool air from the south.

A possible explanation for changes to the temperature profile is the influence of gravity waves generated by localized diabatic heating. The effect of gravity waves has been shown analytically using the hydrostatic, Boussinesq equations by Nicholls et al. (1994) and with a linear spectral model by Mapes (1998). The waves may be generated locally by convection over the Santa Catalina Mountains or by convection over an adjacent range (the Rincon Mountains the peak of which is about 30 km from Mt. Bigelow). Another possible source of gravity waves is orographic uplift associated with the weak southerly flow shown in Fig. 1. Further details of this case, and another that occurred during CuPIDO where moistening of the profile seemed to be the dominant mode of modification are given in Zehnder et al. (2008).

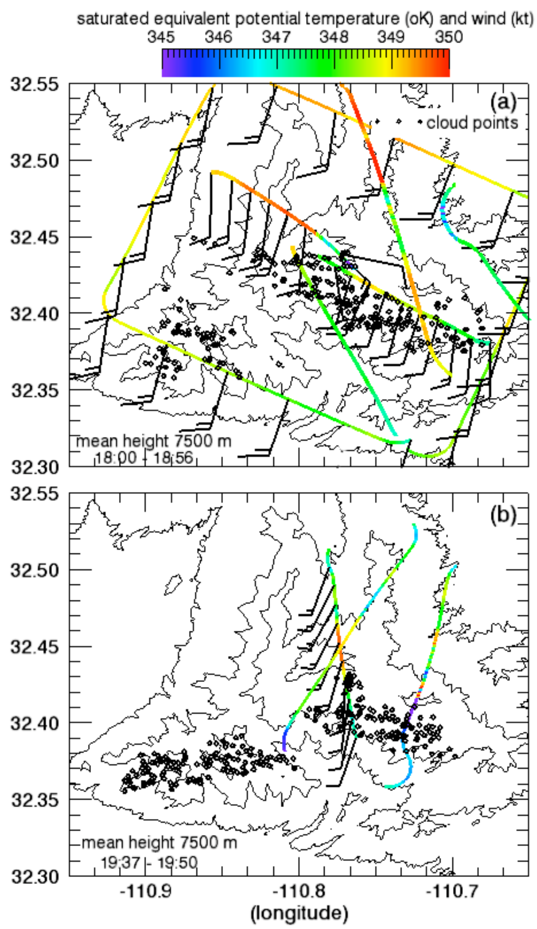

Figure 5: In-situ values of θ_e along flight track at a mean altitude of 7500 m asl for the periods 11:00am-12:00pm and 12:30-12:50 pm. Wind speeds are in kt and points indicate the location of convective cloud.*

4. CONCLUSIONS AND FUTURE WORK

A stereo photogrammetric technique that can be applied to digital images has been developed. This technique allows for extraction of 3d cloud structures from the images. Cloud images were collected as part of a series of coordinated observations of the onset and development of orographic convection associated with the North American Monsoon. The CuPIDO experiment design allowed for sampling of the pre-convective environment and monitoring changes to the thermodynamic profile during the transition from shallow to deep convection.

The case presented here showed clear evidence of a stable layer present in the mid-troposphere (6000-8000 m asl), the breakdown of which coincides with the onset of the deep convection. The mechanism that is responsible for the breakdown is as yet undetermined, but it is likely that gravity wave activity is responsible for the adjustment of the temperature profile. This will be addressed using high resolution numerical simulations in a future study.

Acknowledgements: Support for this work was provided through NSF grant ATM-0638788. The data was collected as part of the Cumulus Photogrammetric, In-Situ and Doppler Observations (CuPIDO). The primary sponsor of CuPIDO is the US National Science Foundation (NSF). The involvement of the NSF-sponsored Lower Atmospheric Observing Facilities from the University of Wyoming and those managed and operated by the National Center for Atmospheric Research (NCAR) Earth Observing Laboratory (EOL) is acknowledged. The data was downloaded from the CuPIDO Data Archive, which is maintained by NCAR EOL.

5. REFERENCES

Damiani, R., and coauthors, 2008: Cumulus Photogrammetric, In-situ and Doppler Observations: The CuPIDO 2006 Experiment, *Bull.Amer.Met.Soc.,* **89***, 57-73.*

Holle, R.H., 1986: Photogrammetry of thunderstorms. *Thunderstorms: A Social and Technological Documentary, Vol. 3,* 2nd ed., E. Kessler, Ed., University of Oklahoma Press, 77-98. [Available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402]

Hu, J., A. Razdan and J.A. Zehnder, 2008: Binocular stereo photogrammetry for 3D cumulus cloud measurements, *J.Atmos.Ocean.Tech., (submitted)*

Malkus, J.S., 1952: The slopes of cumulus clouds in relation to external wind shear. *Quart.J.Roy.Met.Soc.*, **78**, 530-542.

Mapes, B.E., 1998: The large-scale part of tropical mesoscale convective system circulations: A linear vertical spectral band model. *J.Met.Soc. Japan*, **76**, 29-55.

Nicholls, M.E., R.A. Pielke and W.R. Cotton, 1991: Thermally forced gravity waves in an atmosphere at rest. *J. Atmos. Sci.*, **48**, 1869–1884.

Warner, C., J.H. Renick, M.W. Balshaw, and R.H. Douglas, 1973: Stereo photogrammetry of cumulonimbus clouds. *Quart. J. Royal Meteor. Soc.*, **99**, 105-115.

Zehnder, J.A., J. Hu and A. Razdan, 2007: A Stereo Photogrammetric Technique Applied to Orographic Convection. *Mon.Wea.Rev.* **135**, 2265 – 2277.

Zehnder, J.A., J. Hu and A. Razdan, 2008: Evolution of the Vertical Thermodynamic Profile During the Transition from Shallow to Deep Convection during CuPIDO 2006. *Mon.Wea.Rev.* (submitted)