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The effects of vertical air motions on radar estimates of rainfall

J. J. Gourley[1] **and N. Dotzek**[2]

[1]Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, Norman OK, USA
[2]DLR, Institut für Physik der Atmosphäre, Oberpfaffenhofen, 82234 Wessling, Germany

Abstract. The effects of vertical drafts on radar rain rates from convective and stratiform clouds are studied using data collected over the state of Arizona, U.S. during the monsoon of 2003. The diurnal variability of rainfall is first studied by analyzing the spatial distribution of the hours in which maximum rainfall rates occur. The accuracy of these onset times and magnitude of maximum surface rain rates are shown to be dependent on the height at which they are sampled by radar. Convective clouds are generally well sampled by radar throughout their profiles immediately following initiation but can result in underestimated rain rates during mature and decaying stages. Convective downdrafts and weakening updrafts lead to downward precipitation mass fluxes which are not accounted for in standard reflectivity based rainfall estimation. At far range from radar, overestimation of stratiform rainfall may occur during early stages while underestimation is likely at mature and decaying stages. Corrections that utilize information from vertical profiles of reflectivity may need to consider storm types and their expected stage of storm lifecycle.

1 Introduction

The evolution of vertical drafts associated with deep, moist convection is studied here in the context of the effects on radar-estimated rainfall rates R. Dotzek and Beheng (2001) addressed this issue from an analytical perspective. They find that the prefactor a present in standard $Z-R$ relations increases when deep convective drafts are introduced. They conclude that rain rates in convective downdrafts may be double than what would be expected from measuring Z and estimating rainfall using $Z-R$ equations. A follow-on study by Dotzek and Fehr (2003) employs two cloud-resolving, mesoscale models to examine precipitation mass fluxes in the presence of convective drafts. They find that R can become highly negative early in convective cell lifecycles due to the influence of strong updrafts on hydrometeor fall speeds. These upward precipitation mass fluxes persist at upper cloud regions throughout storm maturity. Near the end of storm lifecycles, downdrafts dominate and result in downward precipitation mass fluxes reaching their maximum values at approximately 1 km AGL.

Several observation-based studies have pointed out this influence of convective downdrafts on rain rates derived from Z. Austin (1987), for example, showed that R can be increased by a factor of two, which is a finding that is supported by Illingworth and Blackman (1999). Despite these seemingly drastic impacts, traditional $Z-R$ relations are still found to hold in a statistical sense when considering the average over an entire cloud volume (Dotzek and Beheng, 2001). The study undertaken examines the spatial and temporal structures of radar-estimated rain rates for both convective and stratiform clouds. Particular attention is provided to the impact on quantitative precipitation estimates (QPEs) as a function of radar sampling height (or, equivalently, range).

2 Study Region and Data Methods

Arizona is characteristic of highly complex terrain with mountains and plateaus through the northern and eastern parts of the state with contrasting deserts in the lower elevations to the southwest (see Fig. 1). The region has two distinct precipitation peaks throughout the year – one in the summer and the other in winter. Summer precipitation is often referred to as a result of an extension of the "North American monsoon". A strong thermal low typically develops over the southwestern part of the state in response to very strong surface heating. This pressure gradient results in a northward flux of low-level moisture from the Gulf of California often through the action of surges (Douglas, 1993). Aloft, the region is typically characterized as being in a low-shear environment, with some easterly wind components on the south side of the continental ridge. Thunderstorms during July and

Correspondence to: J. J. Gourley
(gourley@ou.edu)

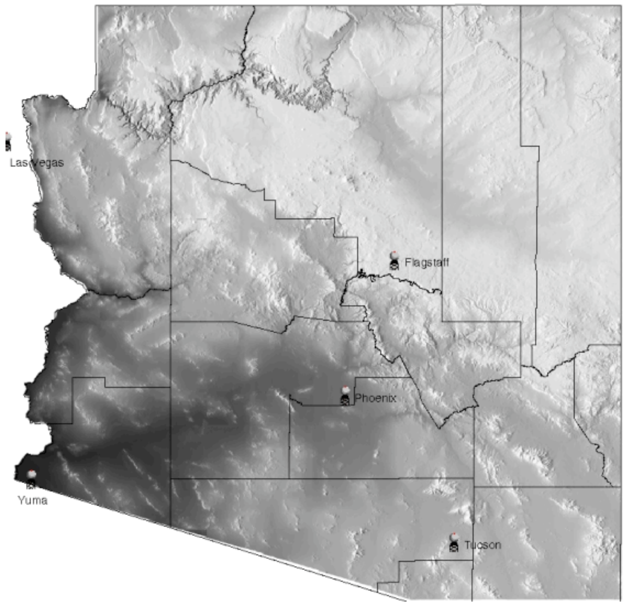

Fig. 1. Geographical map of the investigation area with shaded relief and radar locations shown.

August can almost be a daily occurrence over the high terrain, plateaus, and highlands. Occasionally, these storms persist as they transition down to lower elevations where there is more abundant moisture. This down gradient propagation of convective activity results in a nocturnal maximum of storm activity in low deserts, while higher elevation storms occur during times of maximum heating (Balling and Brazel, 1987; Watson et al., 1994).

During the summer of 2003, radar data from six WSR-88D radars covering portions of the state of Arizona (see Fig. 1) were supplied to an automated precipitation estimation algorithm (Gourley et al., 2001) and subsequently archived. A component of this aforementioned algorithm utilizes a convective-stratiform segregation technique discussed in Gourley et al. (2004). Radar-estimated rainfall and convective and stratiform cloud types are analyzed on a $1\times1\,\mathrm{km}^2$ grid covering a $544\,\mathrm{km}\times528\,\mathrm{km}$ region and are available every 5 min. Gridded rainfall amounts are aggregated for each hour during the two-month study period. Next, these QPEs are determined to be associated with either convective or stratiform clouds. If there has been any algorithm-identified convection during the past hour at the grid point in question, then the rainfall is assumed to be convective. Otherwise, the rainfall is stratiform.

The data set produced above is used to determine the hour of the day (in UTC) at which the maximum precipitation occurred, on average, throughout the summer. This analysis is performed for both convective and stratiform rainfall at each grid point. Additional analyses are performed to illuminate the relationships between the timing of maximum precipitation with radar sampling height. Time-height plots are used to show the frequency of grid points with maximum precipitation rates as a function of hour of day versus radar sampling height. Results are discussed for both convective and stratiform rainfall.

3 Results

3.1 Spatial Variability of Time of Maximum Rainfall

Figures 2a and b show the distribution of the timing of maximum monsoon rainfall during the summer of 2003. A climatological analysis was shown by Balling and Brazel (1987). Qualitatively, there is agreement between their Fig. 5 and our Fig. 2. Precipitation maxima are evident over higher peaks as early as 16:00 UTC. As daytime heating commences, several grid points over the higher terrain through the north and east reach their maximum rainfall values. As time continues, rainfall maxima appear to propagate to lower elevations. The nocturnal maximum in the middle of the state was discussed at length by Balling and Brazel (1987) and is represented in this analysis. It is interesting to note the differences between the analyses performed for convective (Fig. 2a) and stratiform rainfall (Fig. 2b). The distribution of timing of maximum precipitation for stratiform clouds has much more spatial continuity than with convective clouds. This result is not that surprising, as convection is often initiated over rather complex terrain in this region. Moreover, stratiform precipitation has often been noted to have greater spatial extents as compared to isolated, convective cells. The distribution of the timing of stratiform rainfall reveals a lag behind convective maxima at several grid points. Additional insights are gained from these maps by analyzing their relationships with radar sampling height.

3.2 Dependence on Radar Sampling Height

In the previous section, maps were produced to show the times at which each grid point typically receives its maximum rainfall rates from convective and stratiform clouds. The validity of these maps is based on the assumption that radars are capable of accurately measuring the magnitude and timing of surface rain rates R_0 throughout the study domain. Several studies (e.g. Smith, 1986; Kitchen and Jackson, 1993; Gourley et al., 2002) have shown that this assumption does not hold for cool season precipitation in complex terrain. These studies show that radar-based rain rates have a dependence on range where overestimation from bright band contamination is common at mid-ranges and underestimation from beams overshooting the precipitation profiles occurs at far-ranges. Time-height plots of R_0 are produced to reveal the dependence on radar sampling heights for both convective and stratiform rainfall. Radar sampling height can be thought of as equivalent to radar range when there are no significant beam blockages present.

Figures 3a and b show the number of grid points in the domain that have their maximum hourly rainfall rates in each time-height bin. These plots represent an ensemble of maximum rain rate profiles as a function of time. It must be noted,

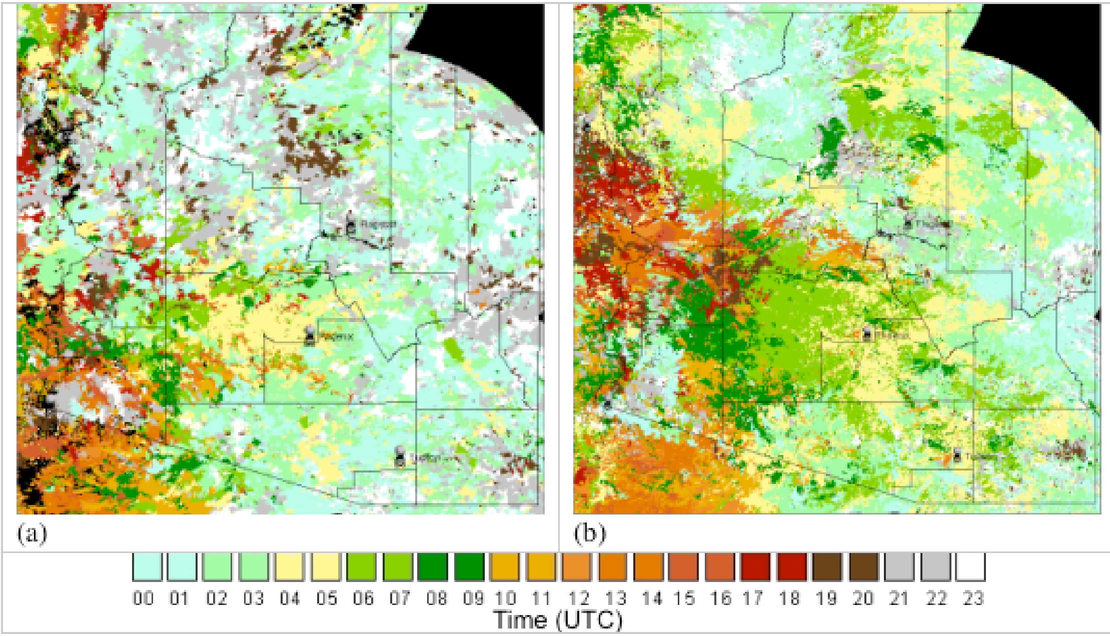

Fig. 2. Map showing the hours (UTC) in which the maximum rainfall rates occurred during July and August of 2003 from (a) convective clouds and (b) stratiform clouds.

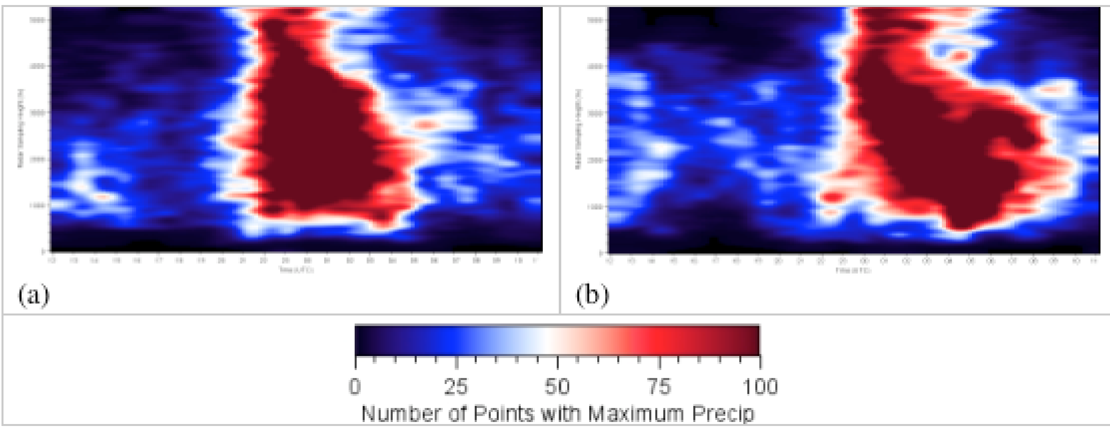

Fig. 3. Time-height plot showing the number of grid points that have their maximum rainfall rates at the hours (UTC) and radar sampling heights (m AGL) for (a) convective and (b) stratiform precipitation.

however, that the spatial variability of the timing of maximum rain rates is large, suggesting that storms are going through various stages of their lifecycles throughout the day. The evolution of these rain rate profiles bears a resemblance to the horizontally averaged rain rate profiles produced by a mesoscale model in Fig. 5d in Dotzek and Fehr (2003). The major difference is that the referenced figure is for a modeled, single-cell storm, whereas Fig. 3a applies to an ensemble of observed convective storms throughout the summer of 2003. Convective clouds are shown to begin producing maximum rainfall intensities between 21:00 and 22:00 UTC (Fig. 3a). As time continues after 00:00 UTC we begin to see the 100 contour decrease in altitude from 4000 m. Aloft, convective updrafts from the ensemble begin to weaken with time allowing hydrometeors to fall. At lower levels, the 100 contour increases in altitude with time from 800 m up to a height of approximately 1700 m at 03:00 UTC. As the convective downdrafts reach lower altitudes they begin to decelerate due to the formation of perturbation high pressure from airflows interacting with the surface.

Stratiform precipitation differs from its convective counterpart in that it lags initiation times by approximately two hours and persists for several more hours. The slanting shape of the 100 contour for stratiform rainfall indicates the ensemble of hydrometeors originate from heights around 5000 m, presumably from convective updrafts, and then slowly fall to lower heights with time. Stratiform clouds are not initiated in the same way as convective clouds, but are shown to be a result of convection. In this case, the weakening updrafts result in a downward precipitation mass flux. This evolution of updrafts with stratiform precipitation results in a distribution of precipitation mass that varies with time and height.

The evolution of these rain rate profiles has implications on radar-based QPE. Immediately following convective initiation, there are a similar number of grid points reaching their maximum rainfall values across a large range of radar sampling heights. This indicates that radars are capable of observing R_0 at close to far range at this particular time (21:00 to 23:00 UTC). It can be inferred that reflectivity values near convective initiation are approximately constant with height up to 5000 m AGL. From 23:00 to 03:00 UTC the increase in the downward precipitation mass fluxes (from weakening updrafts) makes the hydrometeors "less visible" to radars at far range. While radars at medium to far ranges indicate a decreasing trend of R_0, in actuality the hydrometeors are merely descending to lower heights and the true R_0 is actually increasing. Reflectivity data measured at low-levels (below 3000 m AGL) have a much better chance of capturing the time at which rain rates maximize. However, the magnitudes of these estimates will likely be underdone as the snapshots of reflectivity from radar fail to include the influence of convective downdrafts on R_0.

Rain rates for stratiform rainfall are shown to be even more dependent on time and radar sampling height. At earlier times between 23:00 to 00:00 UTC, radar observes high values of R_0 at far range. In contrast to convection, the reflectivity at these times increases with height. This profile suggests stratiform precipitation is actually overestimated by radar at far range at this stage of their lifecycle. The presence of weak updrafts delays the arrival of hydrometeors to the surface. As time progresses, the hydrometeors descend and provide for a more accurate estimate of R_0 from low-level samples after 03:00 UTC. At these times, the shallow nature of the profiles of rain rates suggests R_0 is underestimated for radar estimates at far range. In summary, the evolution of hydrometeors viewed as a function of time and height poses significant challenges for radar-based QPE. Adjustment procedures will need to account for precipitation type through polarimetric methods (Bringi and Chandrasekar, 2001, chapter 7), the time-height evolution of precipitation, potential enhancement caused by convective downdrafts, and horizontal displacement from wind shear.

4 Summary

Radar-based rain rates collected over an active monsoon period are examined in this study. Results are segregated for maximum rainfall rates produced from both convective and stratiform clouds. The presence of vertical drafts is shown to have an important influence on surface-based rain rate estimation. The diurnal weakening of updrafts with time results in downward propagating precipitation masses for both convective and stratiform clouds. The lack of low-level sampling by radar throughout the study region suggests the timing and magnitude of peak rain rates will be dependent on radar range. Furthermore, convective downdrafts can have the effect of increasing surface-based rain rates significantly over reflectivity-based estimates, even for low-level samples. Several attempts have been made recently to correct for the range-dependency of rain rates using vertical profile of reflectivity adjustments. This technique may yield some improvement, but needs to recognize that storms in different regions under the radar umbrella are likely in different stages of their lifecycles. Reference profiles may need to be constructed for different regions that consider their typical diurnal evolution, an area inviting future research.

5 Conclusions

Our study on the effects of vertical motions on radar estimates of surface rainfall in the state of Arizona concludes the following:

– The presence of updrafts and subsequent weakening with time leads to downward propagating precipitation mass fluxes for both convective and stratiform clouds.

– During early stages of storm lifecycles, surface rainfall from stratiform clouds will likely be overestimated at far range, whereas convective clouds have more constant reflectivity profiles with height.

– At later stages in storm lifecycles, underestimation is likely with convective clouds at close and far range. First, convective downdrafts may dramatically increase rain rates over expected values from reflectivity-based observations. Second, the precipitation profiles for both stratiform and convective clouds decrease with height making them less visible to radars at far range.

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References

Austin, P. M.: Relation between measured radar reflectivity and surface rainfall, Mon. Wea. Rev., 115, 1053–1070, 1987.

Balling, R. C. and Brazel, S. W.: Diurnal variations in Arizona monsoon precipitation frequencies, Mon. Wea. Rev., 115, 342–346, 1987.

Bringi, V. N. and Chandrasekar, V.: Polarimetric Doppler Weather Radar, Principles and Applications, Cambridge University Press, New York, 636 pp., 2001.

Dotzek, N. and Beheng, K. D.: The influence of deep convective motions on the variability of – relations, Atmos. Res., 59–60, 15–39, 2001.

Dotzek, N., Gourley, J. J., and Fehr, T.: Vertical profiles of radar reflectivity and rain rate: Observational and modeling results, ERAD Publ. Ser., 1, 243–249, 2002.

Dotzek, N. and Fehr, T.: Relation between precipitation rates at the ground and aloft – a modeling study, J. Appl. Meteor., 42, 1285–1301, 2003.

Douglas, M. W., Maddox, R. A., Howard, K., and Reyes, S.: The Mexican monsoon, J. Climate, 6, 1665–1678, 1993.

Gourley, J. J., Zhang, J., Calvert, C. M., Maddox, R. A., and Howard, K. W.: A real-time precipitation monitoring algorithm – Quantitative Precipitation Eestimation and Segregation Using Multiple Sensors (QPE SUMS), Preprints, Symp. on Precipitation Extremes: Prediction, Impacts, and Responses, Albuquerque, NM, USA., Amer. Meteor. Soc., Boston, 57–60, 2001.

Gourley, J. J., Maddox, R. A., Howard, K. W., and Burgess, D. W.: An exploratory multisensor technique for quantitative estimation of stratiform rainfall, J. Hydrometeor., 3, 166–180, 2002.

Gourley, J. J., Maddox, R. A., and Clarke, B. M.: A multisensor approach to partitioning convective from stratiform echoes, This volume, 2004.

Illingworth, A. J. and Blackman, T. M.: The need to normalize RSDs based on the gamma RSD formulation and implication for interpreting polarimetric radar data, Proc. 29th Int. Conf. On Radar Meteor., Montreal. Amer. Meteor. Soc., Boston, 629–631, 1999.

Kitchen, M. and Jackson, P. M.: Weather radar performance at long range – Simulated and observed, J. Appl. Meteor., 32, 975–985, 1993.

Smith, C. J.: The reduction of errors caused by bright bands in quantitative rainfall measurements made using radar, J. Atmos. Oceanic Technol., 3, 129–141, 1986.

Watson, A. I., Lopez, R. E., and Holle, R. L.: Diurnal cloud-to-ground lightning patterns in Arizona during the southwest monsoon, Mon. Wea. Rev., 122, 1716–1725, 1994.