7B.4 THE IDENTIFICATION AND IMPACT OF AP/GC ON QUANTITATIVE PRECIPITATION ESTIMATES IN MOUNTAINOUS TERRAIN

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1. INTRODUCTION

Super-refractive anomalous propagation (AP) conditions can have a significant impact on weather radar observations by introducing ground clutter echoes (Bech et al. 2002). These conditions arise in atmospheres exhibiting large vertical refractivity gradients in the lower troposphere. The detrimental effect of severe super-refractive AP became apparent during the use of the National Severe Storms Laboratory (NSSL) Quantitative Precipitation Estimation and Segregation Using Multiple Sensors (QPESUMS; Gourley et al. 2001) system for the estimation of precipitation in Arizona. Frequent reoccurrences of AP over complex terrain have lead to false precipitation accumulations in radar-based QPE algorithms, despite the application of clutter removal routines.

The identification of anomalous propagation echoes that occur when the radar beam is refracted downward toward the earth's surface (super-refraction) is complex. Complications arise due to the beam path's dependence on the detailed thermodynamic structure of the atmosphere, primarily in the boundary layer. The mitigation of super-refraction impacts over complex terrain, on radar-derived precipitation estimates, is very difficult without adequate resolution of the boundary layer characteristics near or adjacent to radars.

Table 1. Refractivity type, gradient and condition

Type	Vertical Refractivity Gradient	Effect
Normal	-79 to 0 N/km	Slight variation on standard Radar beam path
Sub-refraction	> 0 N/km	Beam refracted away from earths surface
Super-refraction	- 157 to –79 N/km	Beam refracted downward toward earth surface
Ducting	< -157 N/km	Beam trapped by inversion to strike surface

Using a case study from Arizona the authors show that the occurrence of super-refraction causes radar beams to bend toward the ground to intersect mountains and result in AP echo. Potential identification and mitigation of super-refractive AP using radiosonde and RUC soundings is investigated. The potential utility of this technique in real-time radar processing is discussed.

2. BACKGROUND

The propagation of radio waves is strongly dependent on local meteorological conditions, specifically in the atmospheric boundary layer. Typical WSR-88D beam height calculations assume a standard atmosphere, which provides a 'normal' propagation path under standard refractive conditions. Anomalous beam propagation occurs due to variations in the refractive index n with height, which is often referred to by a scaled index of refraction known as refractivity N

$$N = (n - 1)10^6 = \frac{77.6}{T}\left(p + \frac{4810\,e}{T}\right) \quad (1)$$

where T is the air temperature (K), p is the atmospheric pressure (hPa) and e is the water vapor pressure (hPa) (Beam and Dutton 1968). Note the dependence of refractivity and derived beam path on water vapor. An accurate knowledge of vertical thermodynamic profiles in the atmosphere is necessary to calculate profiles of refractivity for determination of radar beam propagation (Doviak and Zrnic, 1993).

Beam propagation conditions are described in terms of normal refraction, sub-refraction, super-refraction and ducting. The refractivity slopes that allow the identification of these refractivity types are given in Table 1 (Beam and Dutton, 1968). The extent of refraction is dependent on both the refractivity gradient of the atmospheric boundary layer and on the elevation angle of the beam. The refractivity gradient in the atmosphere that is assumed for a standard beam path lies within the normal refraction range (Table 1) and produces "standard" propagation for any angle of incidence (Doviak and Zrnic, 1993). Super-refractive conditions occur as a result of inversions whereby the radar beam is caused to bend toward the earth's surface. An exceptional case of super-refraction is called ducting and occurs when the radius of the curvature of beam path becomes smaller than that of the earth. Ducting occurs due to a strong low level inversion when a cap of warm air exists in the lower troposphere overlying the very moist air. Under ducting conditions the beam may strike the earth's surface and undergo reflection causing AP echo (Beam and Dutton, 1968).

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3. CASE STUDY: WHITE MOUNTAINS, AZ; 01/10/03

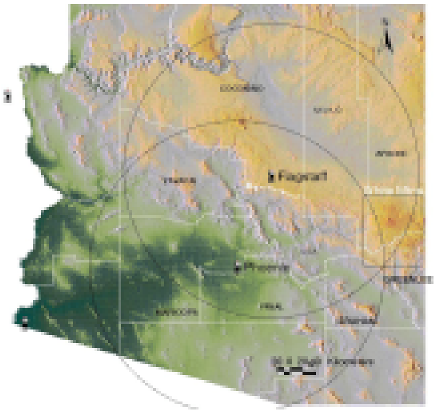
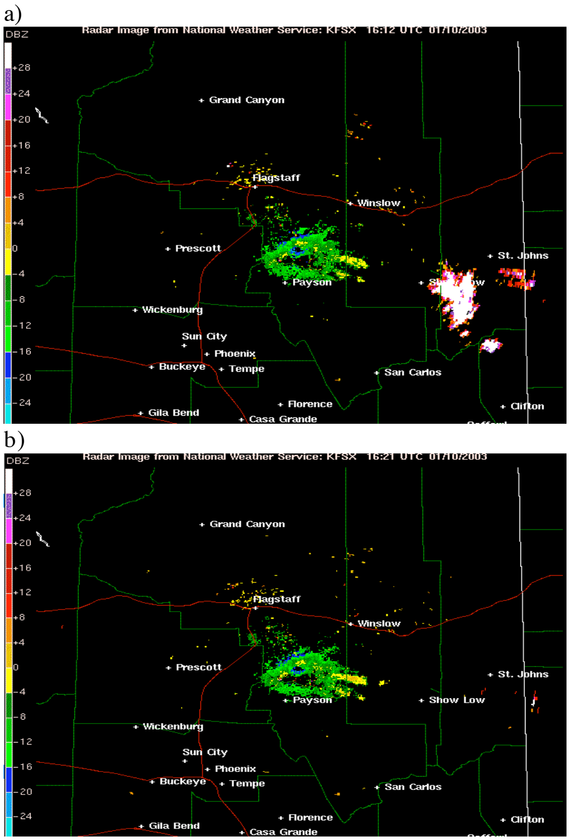


Figure 1: Shaded relief map depicting topography of Arizona. White Mountains are indicated by black box. Black circles are the 230 km range rings for Flagstaff (KFSX) and Phoenix (KIWA) WSR-88Ds.


a)

b)

Figure 2: KFSX 0.5 deg reflectivity over east central Arizona at a) 1612 UTC and b) 1621 UTC.

3.1 Radar observations

The topography of Arizona is indicated in Fig. 1. The White Mountain region is located in east-central Arizona. The elevation of terrain within the White Mountain region varies between approximately 1525 m above mean sea level (MSL) and 3050 m MSL, with its highest peak (Mt. Baldy) at 3400 m MSL. The White Mountains are one of two mountainous regions (the other being the Harcuvars) in Arizona where persistent clutter and/or AP have been identified in QPESUMS. The resulting false precipitation over the White Mountains, termed “rock rain,” is generally attributed to super-refraction of the lowest radar elevation angles.

Considerable AP over the White Mountains was observed on 10 January 2003. Figure 2 shows the AP echo from the Flagstaff WSR-88D (KFSX) at 1612 UTC that had reflectivity values up to 75 dBZ. This echo had been observed on several previous volume scans. The intense echo disappeared by 1621 UTC, just one volume scan later, suggesting that AP was the cause. Closer examination of the echo is shown in Fig. 3. High reflectivity is evident in both the 0.5 deg and 1.45 deg elevation angles suggesting that the echo could be true precipitation since there is some vertical continuity. Again, the sudden absence of intense echo (from Fig. 2b to 2c) implies that the echo is in fact due to AP.

3.2 Atmospheric observations

Radiosonde (FLG RAOB) and RUC2 soundings (NCEP operational 20 km RUC) were obtained between 1200 UTC and 1700 UTC on 10 January 2003, approximately 75 km from KFSX.

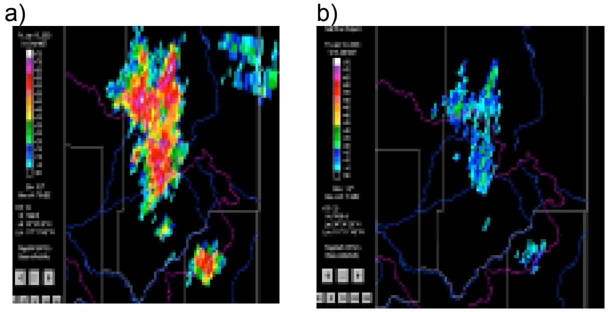

a) b)

Figure 3: Reflectivity from KFSX over the White Mountains at: a) 0.5 deg and b) 1.45 deg elevation angle.

KFSX is located on the Mogollon Rim 2.2 km MSL, approximately the same elevation that the RAOB was taken (2.17 km). The radar site is located ~137 km from the White Mountains at its closest proximity. The 1200 UTC RUC2 and RAOB soundings are shown in Fig. 4. The differences between the RUC2 and observed soundings are significant. The RAOB (Fig. 4a) shows a deep elevated inversion from 2909 m MSL to 3622 m MSL, with a moist layer below. In contrast, the RUC2 sounding (Fig. 4b) shows a shallow surface based inversion and no dry capping layer.

Refractivity profiles were computed using both 1200 UTC RUC2 and RAOB soundings to determine a) if super-refraction was evident and b) the potential utility of RUC2 sounding data to determine beam paths, versus RAOB. The “ray trace” program developed at the NSSL was used to determine radar beam propagation paths from calculations of vertical refractivity profiles using the available soundings. The program assumes horizontal homogeneity of the atmosphere. Given one thermodynamic profile and a beam elevation angle the ray is traced by the program until it reaches the terminal range specified.

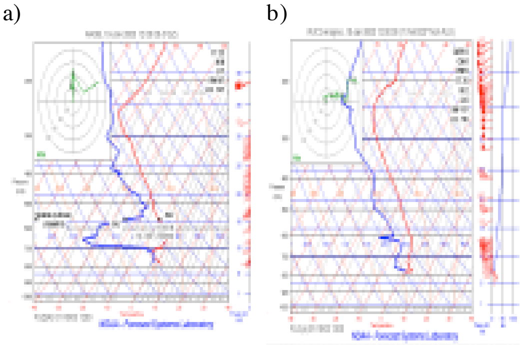

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Figure 4. Soundings from Flagstaff, AZ at 1200 UTC on 10 Jan 2003: a) RAOB sounding; b) RUC2 sounding.

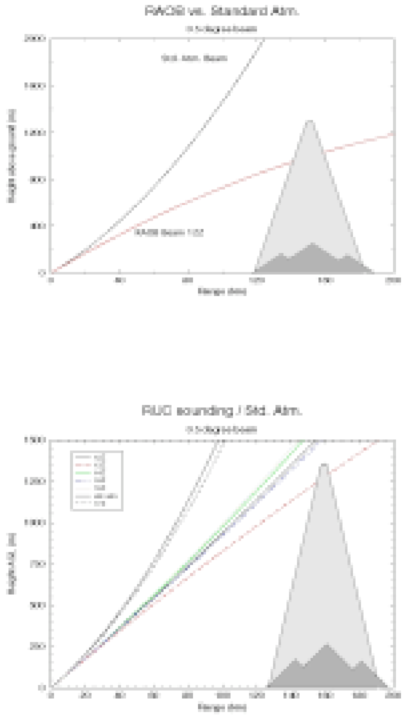
a)

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Figure 5. Output of the ray trace program showing the path of the KFSX 0.5 deg beam for a) 1200 UTC RAOB and b) 1200 UTC – 1700 UTC RUC2 soundings. The beam paths using standard atmospheric conditions are also shown.

Figure 5a shows the 0.5 deg beam path determined using the 1200 UTC RAOB data. The beam path is also plotted using standard atmospheric conditions (-39 N/km). The N profile corresponding to the 1200 UTC was –188 N/km indicating severe super-refraction of the beam. This situation would not normally result in AP as the beam would overshoot the mountains. However, the presence of the White Mountains in the path of the beam results in AP echo. The super-refraction of the beam occurs due to the large inversion and the moist layer below a much drier, warmer layer, as shown in the 1200 UTC RAOB sounding (Fig. 4b). The 0.5 deg beam also hits the White Mountains when RUC2 was used, yet only at 1300 UTC (Fig. 5b). At 1200 UTC the RUC2 data suggests a super-refractive beam path but no ducting. Note the large decrease in refractivity gradient between 1600 UTC and 1700 UTC in Fig. 6 (RUC2 data) that is due to mixing out of the inversion (see Table 2). As mentioned earlier this corresponds to the sudden disappearance of the AP echo (Fig. 2a).

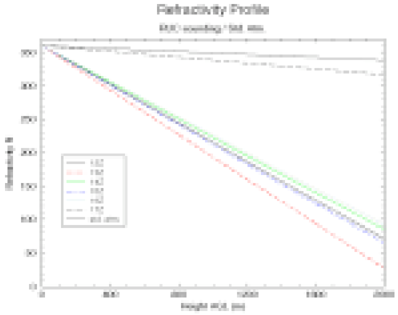

Figure 6. Refractivity profiles from 1200 UTC to 1700 UTC using RUC2 soundings. Standard atmospheric refractivity is shown for comparison.

Table 2. Refractivity profiles from various soundings

Sounding	Refractivity gradient
RAOB 12z	-184 N/km
RUC 12z	-144 N/km
RUC 13z	-170 N/km
RUC 14z	-139 N/km
RUC 15z	-148 N/km
RUC 16z	-134 N/km
RUC 17z	-40 N/km
Std. Atm.	-39 N/km

The ray trace program used in the study assumes that the atmospheric properties known at Flagstaff are preserved horizontally. This is not representative of the true boundary layer due to variations in terrain between Flagstaff and the White Mountains. This becomes problematic when considering the removal of the nocturnal inversion that is the initial cause of super-refraction. During daytime, warming allows the boundary layer to become mixed out reducing the extent of vertical gradients of water vapor and temperature. Due to the elevation and orientation of the mountains, the mixing proceeds at varying rates. In this case it is thought that nearer the mountains the boundary layer is shallower and is mixed out more quickly, i.e., the nocturnal inversion and its associated super-refractive effects are removed at an earlier time in comparison to flatter and lower terrain. This removal of the nocturnal inversion could explain why the enhanced echo region in Fig. 2 disappeared in late morning. The extent to which exceptionally high reflectivity was observed may have been caused by the beam intersecting a snow covered peak, which would enhance the echo returned more than bare rock.

4. DISCUSSION & CONCLUSION

Complex terrain poses a significant challenge for accurate radar QPE during the warm and cool season with the frequent occurrence of anomalous high precipitation amounts. This study examined an AP case from the White Mountains in Arizona on 10 January 2003. False echoes from the White Mountains with reflectivity as high as 75 dBZ were observed by the KFSX (Flagstaff) WSR-88D in the morning. In the latter hours of the morning the echo disappeared suddenly when a strong inversion was mixed out. Using refractivity profiles from 1200 UTC RAOB, the 0.5 degree beam path was calculated and shown to intersect the ground at the same range that the strong echo was observed. The RUC2 data, also used, showed a much weaker tendency for super-refraction. RUC2 calculation over the time period 1200 UTC to 1700 UTC showed that the sharpest reduction in refractivity gradient corresponded to the decrease in AP echo.

While the White Mountains AP is most likely a result of super-refractive anomalous propagation, determination of its occurrence and mitigating the impact is problematic. Using thermodynamic profiles from upper air sounding data allows the ray trace to be constructed and permits the identification of conditions that lead to super-refractive AP. However, radiosonde data is not readily available frequently or densely enough to provide much use operationally. The RUC2 data were qualitatively similar to the RAOB data but significant differences were noted between the 1200 UTC RUC and RAOB soundings. Thermodynamic data from RUC2 profiles would provide improved time sampling but appear to lack sufficient detail to determine the vertical profile with the required accuracy. It is evident from this brief investigation that the RUC2 model does not sufficiently portray detail in the boundary layer in order to accurately predict beam propagation paths, at least over complex terrain. However, sudden decrease in refractivity gradients from 1600 UTC - 1700 UTC suggests that the RUC2 model is capable of mixing out the boundary layer at the appropriate time, thus returning refractivity gradients closer to their standard conditions.

Further work will involve using multiple soundings to more accurately determine beam paths in a non-homogeneous environment. Due to the sparse network of upper air soundings it is inevitable that RUC2 data will be also used in these studies and any operational application of the ray trace procedure. Future studies involving AP mitigation schemes will utilize the fine-scale details from the 12-hourly radiosonde data in combination with the hourly evolution of meteorological variables from the RUC2 model.

5. REFERENCES

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