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Monthly and daily variations of radar anomalous propagation conditions: How “normal” is normal propagation?

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Abstract. Standard or normal propagation conditions of the radar beam (i.e. vertical refractivity gradients around -40 N units/km for the first kilometer above sea level) are considered to be the most representative, specially for midlatitude regions. However, it is not strange to find departures (anomalous propagation or anaprop) from those average conditions which may lead to significant errors in the height measurement of the echoes. In this work more than 2000 radiosonde observations recorded in Barcelona from 1997 to 2002 have been used to characterize radar propagation conditions. The main interest was to find variations in the conditions during the different months of the year and to assess their potential effects on a regional weather radar network currently under development. Most radars of the network will be located in coastal areas, which could be particularly prone to anomalous propagation. Calculations included statistics and seasonal variations of surface refractivity and vertical refractivity gradients for the first kilometer. On average, standard propagation was dominant but a marked super refractive minimum was found in August. During that month the variability of the vertical refractivity gradient also was the highest. In agreement with other authors, significant correlations between monthly averages of surface refractivity and vertical refractivity gradients have been found.

1 Introduction

The variation of the air refractive index plays a key role when characterizing the propagation conditions of a radar beam. In particular, the vertical profiles of the air temperature, moisture and pressure are mostly responsible for the way the radar energy will propagate in a given atmosphere. A number of assumptions on these vertical profiles are usually taken, assuming the so-called “standard propagation conditions” which are associated to the average state of the atmosphere accepted as the most representative. However, due to the inherent variability of the atmosphere, it is a well-known fact that propagation conditions may differ, sometimes significantly, from those considered standard resulting in anomalous propagation (AP).

Super refraction of a weather radar beam produces more bending towards the ground surface than expected for standard conditions and therefore increases and intensifies ground clutter echoes (AP or anaprop echoes). This situation is particularly negative for automated quantitative precipitation estimates (QPE) such as those required for operational weather surveillance and hydrological flood warning. Quality control procedures for QPE have traditionally dealt with anaprop and, in general, clutter echoes (see, for example, Kitchen et al., 1994; Joss and Lee, 1995; Anderson et al., 1997; da Silveira and Holt, 1997; Fulton et al., 1998; Archibald, 2000; Sánchez-Diezma et al., 2001, or Steiner and Smith, 2002, among others).

However, the fact that AP echoes may be detected and cleaned with techniques such as those above mentioned, does not prevent that radar observations may be affected because of the difference in their expected height. If this difference is important enough, any procedure which requires a precise knowledge of the echo altitude may be potentially affected by AP. For example, if radar data (either echo intensity or Doppler winds) are to be assimilated in a NWP model or if the radar echo intensity is corrected for beam blockage due to mountain sheltering (Bech et al., 2001), the effect may be relevant.

Since 1997, radiosonde observations have been made in Barcelona to support the operations of the regional government’s Subdirectorate of Air Quality and Meteorology. In this study, radiosonde observations are used to characterize radar anomalous propagation (anaprop) conditions and their potential effects on a regional weather radar network currently under development. Most radars of the network will be located in coastal areas, which could be potentially prone to anomalous propagation.

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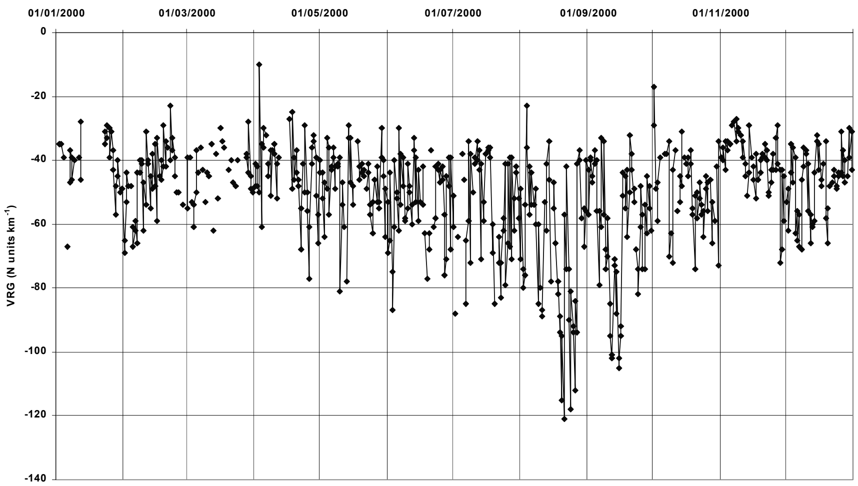

Fig. 1. Vertical refractivity gradient (VRG) for the first kilometer above ground level in Barcelona during year 2000. Points correspond to 00:00 UTC and 12:00 UTC data and only consecutive points are connected.

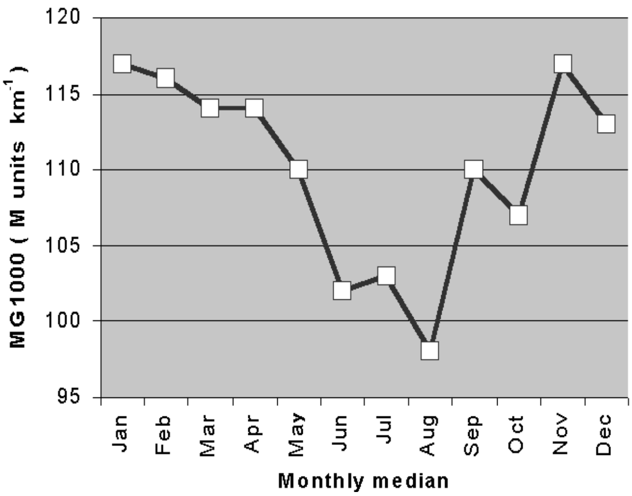

Fig. 2. Annual variation of the monthly median of modified refractivity vertical gradient for the first kilometer (MG1000) above ground level in Barcelona.

2 Methodology

2.1 Refractivity and modified refractivity

As anomalous propagation is due to relatively small variations of the air refractive index n, the magnitude known as refractivity N, defined as one millionth of n−1, is commonly used in anaprop studies. Bean and Dutton (1968) showed that N can be written as:

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

where T is the air temperature (K), p atmospheric pressure (hPa) and e is the water vapour pressure (hPa). A related magnitude is the modified refractivity M, which is defined as:

$$M = N + \frac{z}{10^{-6} r}, \quad (2)$$

where z is altitude and r is the radius of the Earth in m. Modified refractivity is very useful to characterize propagation conditions as for constant M the curvature of the ray path is that of the Earth's surface and, therefore, when there are negative M vertical gradients the ray path may be bent towards the surface and then radio waves get trapped like in a wave guide (ducting). Propagation characteristics may vary largely, depending on the type of air mass (Gossard, 1977). When characterizing the radio propagation environment it is usual to consider the vertical refractivity gradient of the air of the first kilometer above ground level to estimate propagation effects such as ducting, surface reflection and multipath on terrestrial line-of-sight links. However, the effect on weather radar beam refraction not only depends on the refractivity gradient of a layer but also on the angle of incidence between the beam and the trapping layer considered and the frequency of the electromagnetic wave. For weather radar applications, if the refractivity gradient of the first kilometer of the atmosphere is around $-1/4\alpha$ (i.e. -39 N units km^{-1} or 118 M units km^{-1}, where α is the Earth's radius) then standard propagation will occur for any angle of incidence (Doviak and Zrnic, 1992).

3 Vertical refractivity gradients statistics

The following analysis was performed using more than 2000 radiosonde observations collected between 1997 and 2002 in Barcelona, enlarging a smaller data set used in an earlier preliminary analysis (Bech et al., 2000). The data covers all months and was both collected at 00:00 UTC and 12:00 UTC (local midnight and noon, respectively). We have focused our analysis in the vertical refractivity gradient of the first kilometer above ground level. As an example, Fig. 1 shows the evolution of this parameter during the year 2000.

Considering the whole data set, a median gradient of modified refractivity for the first kilometer above ground was found to be of 111 M units per km. Annual variation of these monthly medians is shown in Fig. 2. Minimum values (the

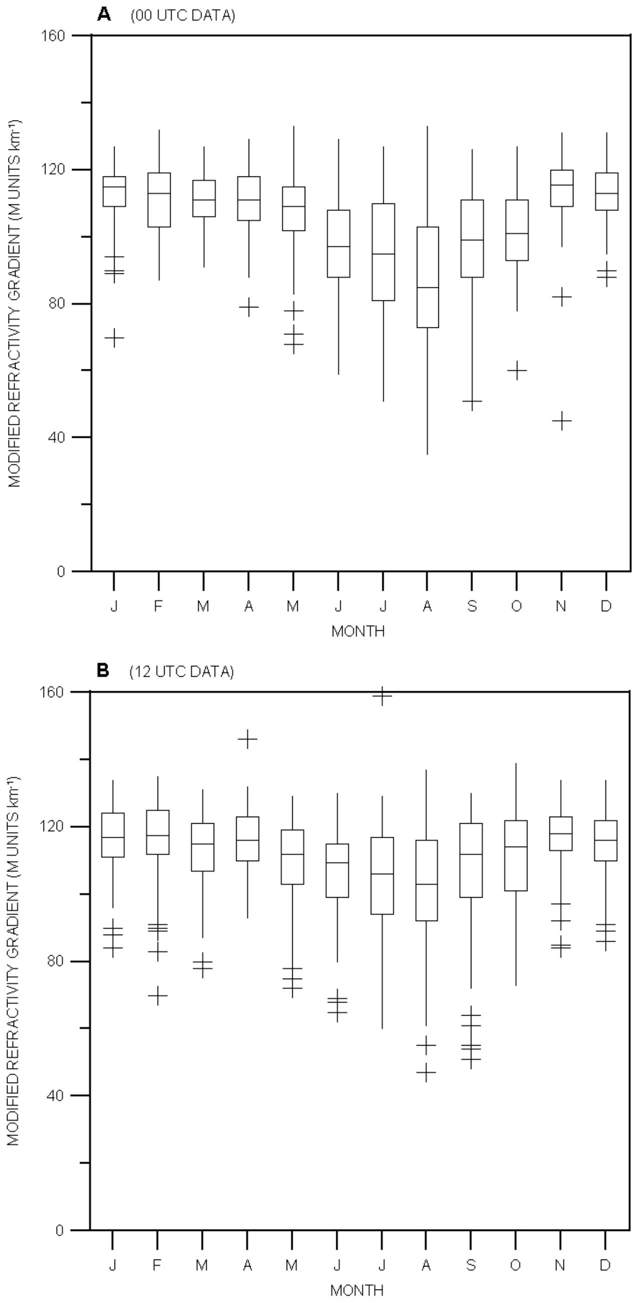

Fig. 3. Box whisker plot showing the first, second (median) and third quartile and outlier points of modified refractivity vertical gradient for the first kilometer above ground level in Barcelona for each month: **(a)** 00:00 UTC data and **(b)** 12:00 UTC data.

most super refractive) occur in August (98 M units km^{-1}), when summer surface temperatures are higher. During that month, the gradient is below 65 M units km^{-1} 10% of the time and below 76 M units km^{-1} 80% of the time. In the cold period ranging between November to April standard propagation conditions are predominant, with values around 113 to 117 M units km^{-1}. The rest of the year may be considered as made up of two transition periods before and after the summer peak.

The differences between 00:00 UTC and 12:00 UTC gra-

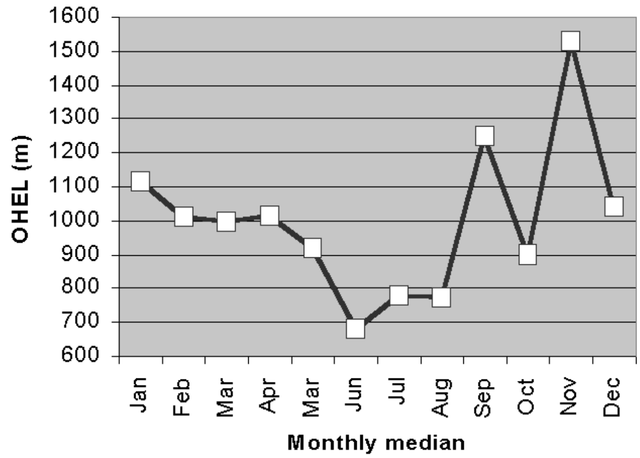

Fig. 4. Annual variation of Optimum coupling Heights for Elevated ducting Layers (OHEL).

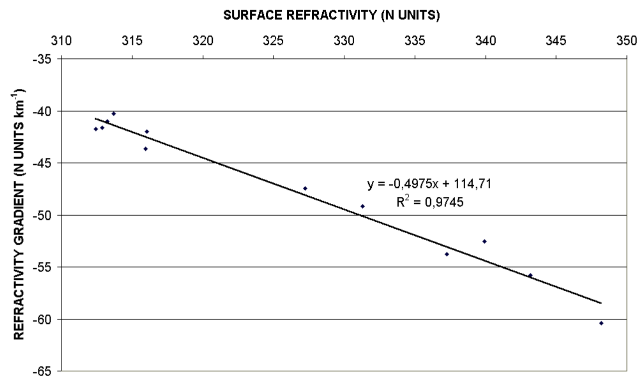

Fig. 5. Surface refractivity vs vertical refractivity gradient plot and the corresponding linear fit line.

dients during each month of the year may be explored in Fig. 3. It shows a box whisker plot built with the first, second (median) and third quartile, a vertical line extending from the first quartile less 1.5 times the interquartile range to the third quartile plus 1.5 times the interquartile range. Points falling outside the line are considered outliers and are plotted as crosses. Note that, as expected, midnight conditions are more super refractive than noon conditions, most probably because of the effect of nocturnal radiation inversions. This diurnal cycle may sometimes be observed in the clutter echoes (Moszkowicz et al., 1994). However, it seems that 12 UTC data presents more outliers than 00:00 UTC. In general, outliers occur much more often in the super refractive zone than in the sub refractive, where are almost inexistent. Moreover, both midnight and midday data, show the median annual minima in August; however the variability also is maximum during this month.

The vertical gradient of refractivity in the first kilometer takes into account surface trapping layers such as surface ducts and ducts associated to temperature and moisture gradients of the boundary layer which extend to the surface (Babin, 1996). Moreover, the existence of elevated ducts –

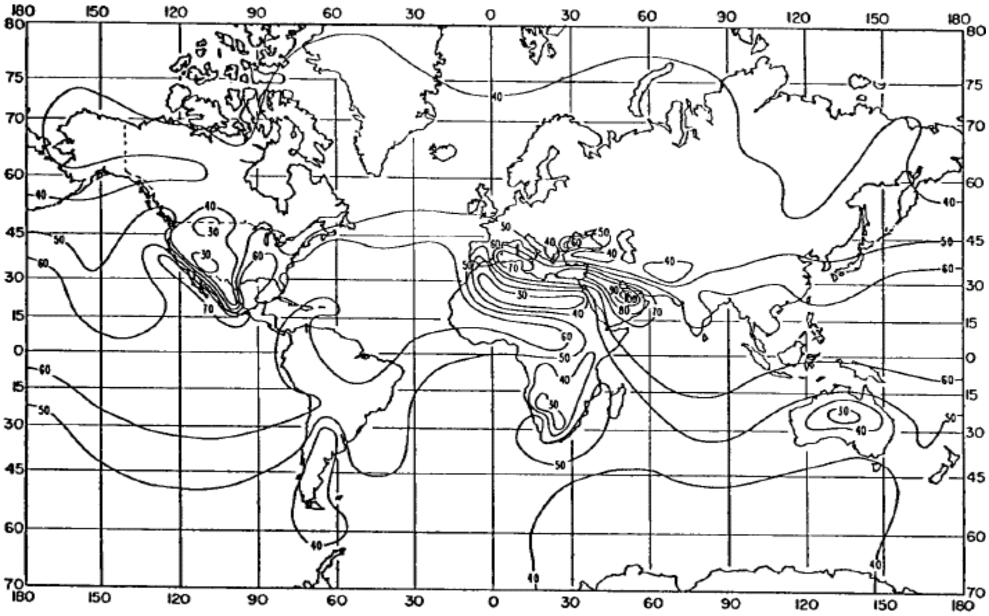

Fig. 6. World wide map of averaged vertical refractivity gradients for August (ITU, 1997).

when the bottom of the duct is above the surface – may also be significant from the point of view of the propagation environment.

Elevated ducts may be characterized for their vertical extension, the refractivity gradient, and also by the bottom of the trapping layer (where the modified refractivity gradient is zero). This height is also known as the optimum coupling height of the elevated duct. Figure 4 shows the monthly variation of median values of optimum coupling heights of the elevated ducts. It may be seen that they range roughly between 1500 m (November) to 700 m (June). From May to August, values are below the first kilometer above ground so elevated ducts contribute during this period to increase the vertical refractivity gradient above mentioned.

The relationship between surface refractivity and the vertical refractivity gradient for the first kilometer was investigated for data collected in the UK (Lane, 1961) and the US (Bean and Dutton, 1968) during the sixties. In both cases a high correlation was found for monthly averages of both magnitudes. For the data set considered, a correlation of 0.9745 was found (Fig. 5).

4 Summary and discussions

Seasonal variations of propagation conditions for Barcelona have been studied using radiosonde data collected between 1997 to 2002. Vertical refractivity median gradients for the first kilometer have been calculated and departures from normal propagation conditions were found in summer time, being most important in August.

The values obtained in this work may be compared with those shown by the International Telecommunications Union worldwide maps of vertical refractivity gradients (ITU, 1997). The maps provide a large scale overview of the vertical refractivity gradient. However, they agree relatively well. In particular, ITU suggested monthly mean values for February, May, August and November for the Barcelona area are 117, 110, 90 and 107 M units km^{-1} while the mean values we found were 116, 108, 96 and 117.

Figure 6, taken from ITU (1997), represents monthly mean values of vertical refractivity gradient, ΔN, for August, when the annual low is reached in the Barcelona area. Note that the intense super refractive area (below 60 N units km^{-1}) extends from the Persian Gulf – where the world extreme is achieved for that month with 100 N units km^{-1} – and the coast of North Africa to the Western Mediterranean.

The results shown confirm the occurrence of anaprop conditions which may have a significant effect on weather radar observations. In particular, quantitative precipitation estimates may be affected, and processing procedures assuming standard propagation conditions, such as radar beam blockage correction schemes, should be used with caution.

Another issue to be considered because of the maritime environment of the area studied is the representativity of the radiosoundings, as shown in several field campaign measurements (see for example Brooks, 2001). Taking into account that in the studied area there is a coastal range with heights around 400 to 700 m, and that several radar units are to be installed at those heights, the presence and type of elevated ducts has been considered. In particular, the variation of the optimum coupling height of elevated ducts shows that, depending on their intensity and extension, they could have effects on the lowest elevation radar beams.

From the results shown, it may be concluded that, on average, normal propagation conditions are dominant, i.e. "normal". However there are significant seasonal variations, including changes in both the median and the monthly dispersion of the vertical refractivity data which, in extreme cases, may produce significant variations in the height estimation of the radar echoes.

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