Atmospheric Research 169 (2016) 73–85

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmos

A long term (1999–2008) study of radar anomalous propagation conditions in the Western Mediterranean

A.V. Magaldi [a],*, M. Mateu [b], J. Bech [b], J. Lorente [b]

[a] CONACYT Research Fellow - Instituto de Matemáticas, UNAM-Juriquilla, Querétaro, 76230, Mexico
[b] Department of Astronomy and Meteorology, University of Barcelona, Martí Franqués 1, 08028 Barcelona, Spain

ARTICLE INFO

Article history:
Received 5 June 2015
Received in revised form 18 September 2015
Accepted 27 September 2015
Available online 9 October 2015

Keywords:
Anomalous propagation
Weather radar
WRF model
Mediterranean sea

ABSTRACT

In this paper a study of the radio propagation environment of electromagnetic waves prevailing in the lower troposphere of the Western Mediterranean basin is presented. Deviations from atmospheric average or standard radio propagation conditions (anomalous propagation or AP) can affect significantly the quality of weather radar observations and other telecommunication systems. This is particularly important when ducting or superrefraction is present and spurious echoes resulting from the interaction of the beam with the ground or sea surface may appear. These AP conditions occur mainly when temperature inversions or strong moisture gradients are present. The period covered in this study ranges from 1999 to 2008 and conditions were derived from the Weather Research and Forecasting (WRF) modeling system, using the Japanese 25-year Reanalysis (JRA25) dataset as initial and boundary data. From the WRF model, we use the temperature, moisture, and pressure fields with a grid length of 30-km horizontal resolution and 250 m vertical resolution to compute several indices such as the Vertical Refractivity Gradient, Vertical Modified Refractivity Gradient and a Ducting Index. Results obtained show that on the Western Mediterranean coast the most favorable conditions for superrefraction are found in summer, while the most affected areas are the Gulf of Valencia, the Strait of Gibraltar and the Northern Gulf of Lion. Additionally, a comparison with radiosonde data recorded in Barcelona (NE Spain) is also performed indicating an overall agreement between model and observational data despite a tendency to decrease subrefractive events by the WRF model.

1. Introduction

The trajectory of the electromagnetic waves in the atmosphere depends mainly on vertical variations in the air refractive index n (Doviak and Zrnic, 1993; Bech et al, 2012). The air refractive index n is typically described by the magnitude known as refractivity N (see Section 2 for details), and its vertical gradient presents some degree of variability but also a predominant range of values known as standard or normal propagation conditions. In the area covered by weather radar, variations of N in the vertical scale are typically much more relevant than in the horizontal scale, so they are usually assumed constant within a radar domain. However, extreme cases have been documented for specific locations where normal propagation conditions are not met, often in coastal areas such as the Persian Gulf, Western Africa or the Mediterranean Sea (see for example Atkinson et al., 2001; Atkinson and Zhu, 2006; Kaissassou et al., 2015, or Viher et al., 2013) so it is important to study how frequently these situations happen and how intense they may be in order to assess possible impact on weather radars or other microwave based communication systems. Global average distributions of radio propagation conditions are described by the International Telecommunication Union (ITU) for communication system design applications — see for example ITU (2003) — and, similarly, a number of research studies have addressed in detail significant departures from normal propagation conditions (Lopez, 2009; von Engeln and Teixeira, 2004).

On the other hand, there are other important applications where atmospheric refractivity plays a fundamental role as in the use of Global Navigation Satellite Systems to retrieve integrated water vapor (i.e. precipitable water) from zenith total delay of satellite signals (Rohm et al, 2014; Wilgan et al, 2015) or through the employment of radio occultation techniques (Hajj et al., 2002) to estimate temperature and water vapor profiles as in the COSMIC/FORMOSAT mission — see for example the recent studies by Santhi et al (2014) or Dhaka et al (2015). As reported by Xie et al (2012) the possible presence of sharp refractivity gradients, mostly at the top of the atmospheric boundary layer, has been identified as one of the limitations of these radio occultation techniques.

The objective of this paper is to examine lower tropospheric radio propagation conditions in the Western Mediterranean basin, an area prone to anomalous propagation according to previous studies. The period considered covers 11 years and the analysis is performed using a Numerical Weather Prediction (NWP) system and a complementary comparison between model and radiosonde data in order to assess

---

* Corresponding author.
E-mail address: adolfo.magaldi@im.unam.mx (A.V. Magaldi).

http://dx.doi.org/10.1016/j.atmosres.2015.09.027

model results. Despite the focus of this paper is on weather radar applications, others such as those mentioned above can benefit from a detailed description of lower tropospheric radio propagation conditions in the region of study.

The rest of the paper is organized as follows. Section 2 provides the basic equations and magnitudes used in the study, Sections 3 and 4 introduce the region of study and data employed, Sections 5 and 6 presents results and the comparison between NWP and radiosonde data, respectively, and Section 7 contains a summary and concluding remarks.

2. Radio propagation characteristics

2.1. Relevant magnitudes

Because the refractive index n variations in the atmosphere are typically about 10^{-6}, the refractivity N is used instead (Bean and Dutton, 1968):

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

where P is the atmospheric pressure (hPa), e is the water vapor pressure (hPa) and T is the air temperature (K). A related magnitude, the modified refractivity index M (ITU (2003) is defined for a given height level as:

$$M = N + 157z \tag{2}$$

where z is the altitude (m) of the level considered. Refractivity is dimensionless, but sometimes N values are expressed in "*N units*". The vertical derivative of N (dN/dz), denoted here as the Vertical Refractivity Gradient (VRG) is a key magnitude to characterize propagation conditions in a given atmospheric layer and is calculated as the difference in refractivity between the base and top of the layer. Typically the first kilometer of the troposphere is considered, i.e. the difference between refractivity values at surface N_S and at 1000 m above the ground level N_{1000}, according to International Telecommunication Union (ITU) standards (ITU, 2003):

$$VRG = N_{1000} - N_s \tag{3}$$

Based on climatological atmospheric conditions, normal or standard propagation is defined when the VRG is about -39 to -40 N units km^{-1}. When this condition is satisfied, the beam path of the radiowaves is curved toward the terrestrial surface, with a smaller curvature than the earth surface curvature. When this condition is not fulfilled, two anomalous situations are possible: subrefraction, when refractivity increases with height ($VRG > 0$) and electromagnetic waves are curved away from the ground; and superrefraction, when the electromagnetic waves are curved toward the ground more than usual. This condition may lead to an interception of the radar beam with the terrain or the sea surface. In practice, a threshold of -79 N units km^{-1} is usually taken to distinguish normal from superrefraction conditions. Ducting, which is an extreme case of superrefraction, occurs when the VRG is about -157 N units km^{-1} or less. Deviations from standard conditions are usually related to the presence of sharp moisture gradients or thermal inversions, which present an important variability at a global scale (von Engeln and Teixeira, 2004; Brunke et al., 2015). Clutter echoes produced under superrefractive conditions are known as anomalous propagation echoes. The variability of VRG and associated effects in radar observations was studied by Alberoni et al. (2001), Fornasiero et al. (2006a,b) and Bech et al. (2007a,b). In an analogous way, we can define the vertical modified refractivity gradient $VMRG$ (dM/dz) as the difference between the modified refractivity at 1000 m M_{1000} and surface modified refractivity M_s

$$VMRG = M_{1000} - M_s \tag{4}$$

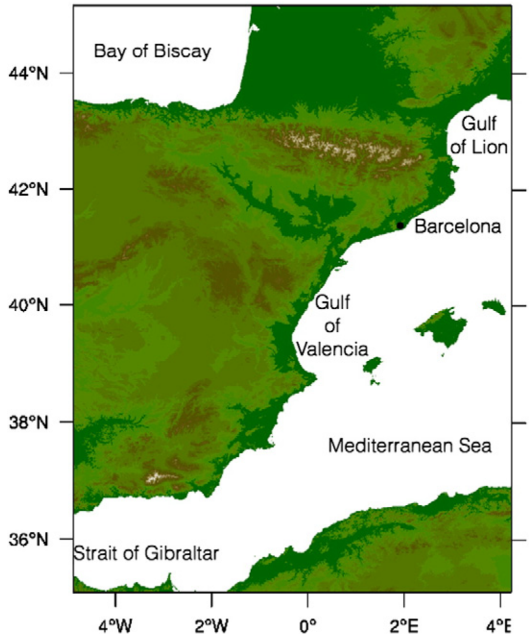

Fig. 1. Region of study indicating the topography and main geographic locations cited in the text.

Another quantity used here to describe propagation conditions is the ducting index D_I defined as the maxima of (Johnson et al., 1999):

$$D_1 = \max\{78(z_i - z_0) - (M_i - M_0)\}, \mathrm{i} = 1\ldots, \mathrm{n} \tag{5}$$

meaning that the modified refractivity gradient is evaluated for all layers from the ground level (z_0) up to 3 km (z_n), thus covering typical heights of a base level radar Plan Position Indicator. Units of z are in km and the constant 78 has units of km^{-1} so that the ducting index is dimensionless. Table 1 summarizes the different propagation characteristics under relevant ranges of dN/dz, dM/dz and D_I.

2.2. AP detection implementation

Several instruments can provide temperature, pressure and humidity data to retrieve refractivity vertical profiles. In the past many observational radio propagation studies have been performed using radiosonde data, such as Stagliano (2008) and Bech et al. (2000). Bebbington et al. (2007) and Bech et al. (2007a) use an NWP model to forecast the

Table 1
Effects on radar beam propagation under different ranges of dN/dz, dM/dz and D_I (adapted from Bech et al, 2007a).

Characteristic	dN/dz (km^{-1})	dM/dz (km^{-1})	D_I
Ducting parameterization	dN/dz ≤ −157	dM/dz ≤ 0	$D_I \geq 78$
Superrefraction	−157 < dN/dz ≤ −79	0 < dM/dz ≤ 79	$78 > D_I \geq -1$
Normal	−79 < dN/dz ≤ 0	79 < dM/dz ≤ 157	$-1 > D_I \geq -79$
Subrefraction	0 < dN/dz	157 < dM/dz	$-79 > D_I$

Table 2
WRF parameterization and scheme setup used is this work.

Parameterization or scheme	Reference
WSM5 microphysical parameterization	Hong et al. (2004)
Kain–Fritsch convective parameterization	Kain (2004)
Five-layer thermal diffusion scheme for the land-surface parameterization; YSU planetary boundary layer scheme	Noh et al. (2003)
Dudhia shortwave radiation	Dudhia (1989)
Rapid Radiative Transfer Model for longwave radiation	Mlawer et al. (1997)