

Analysis of daily precipitation based on weather radar information in México City

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RESUMEN

En México hay una red de 12 radares meteorológicos para monitorear sistemas convectivos intensos. Los datos del radar Doppler del Cerro de la Catedral, a 40 km al noroeste de la Ciudad de México, se han usado para obtener estimaciones de razón de precipitación durante eventos de precipitación intensa. Los resultados muestran que aunque las estimaciones son cercanas a lo observado en una red de estaciones de superficie, es necesaria una nueva configuración del sistema de radar para capturar mejor las características de las tormentas intensas, particularmente al pie de las montañas del oeste. La comparación entre las estimaciones del radar y una densa red de pluviómetros muestra que tal deficiencia puede estar relacionada con errores sistemáticos debidos al bloqueo del radar, pero también a problemas de muestro del radar y los pluviómetros. La calibración por sí misma puede no ser suficiente ya que con el radar en una montaña alta pero relativamente distante hay un bloqueo significativo. Tal ubicación limita la capacidad de muestreo para hacer una buena cobertura vertical. Las características actuales de la elevación del haz evitan que el radar estime la cantidad de precipitación en los niveles bajos de las nubes, cerca de la base de la nube. Se propone una nueva configuración del sistema de radar de la Ciudad de México tomando en cuenta la cobertura espacial y los efectos de propagación sobre una atmósfera estándar en un campo de reflectividad horizontalmente constante.

ABSTRACT

In México, there is a network of 12 meteorological radars to monitor intense convective systems. Data from Cerro de la Catedral Doppler radar, 40 km northwest of México City, have been used to obtain precipitation rates estimates during intense precipitation events. Results show that although estimates are close to the observed precipitation in surface stations, a new configuration of the radar system is necessary to better capture the characteristics of intense storms, particularly at the foothills of the western mountains. The comparison

between the estimate from the radar and a dense network of rain gauges shows that such deficiency may be related to systematic errors due to blockage (radar), but also to sampling problems (radar and rain gauge). The calibration by itself may not be enough since there is significant blockage with the radar at the peak of a high elevation but relatively distant mountain. Such location limits the scan capacity from making a good vertical coverage. The present characteristics of the elevation of the radar beam prevent the radar from estimating the amount of precipitation in the lowest part of the clouds, near the cloud base. A new configuration of the radar system for México City is proposed taking into account spatial coverage and propagation effects upon a standard atmosphere in a horizontally constant reflectivity field.

Keywords: Radar precipitation, extremes hydrometeorological events.

1. Introduction

For many years, México City has suffered hydrometeorological disasters associated with flash floods (Domínguez, 2002), resulting from convective storms in the western mountains of the México Valley watershed. Although a better understanding of the evolution of these storms is necessary to reduce vulnerability, only a few studies have looked at the mechanisms that control such events (Jáuregui and Romales, 1996). The effects of intense precipitation increase the risk of landslides and floods due to the large number of irregular settlements in the western part of México City (Magaña and Neri, 2007). For a better understanding of the processes associated with intense precipitation over the México valley, it is necessary to have better estimates of precipitation to characterize the evolution of the storms, from the moment they appear in the eastern part until they intensify in the western part of the valley. A weather radar constitutes the most adequate tool for such monitoring of intense convective systems in large metropolitan areas. In México City though, there are still problems to operate the radar as a nowcasting tool. This problem has to be solved since the number of intense precipitation events has increased in recent decades due to the rain-island effect (Huff and Changnon, 1973).

México City is around 2250 m above mean sea level, and is surrounded by high elevation mountains with peaks up to 4000 m above mean sea level. The rainy season spans from May through October with a well defined gradient in precipitation from the northeast, where annual precipitation may be around 500 mm, to the southwestern-western region where precipitation is around 1200 mm/yr. This spatial distribution in precipitation reflects the orographic effect in precipitation from the western mountains. Only a few streams remain in the urban area and consequently intense precipitation leads to runoff that accumulates in urban areas over the valley, causing floods and landslides at times. This has made water managers and civil protection authorities more aware of the need of an improved system to monitor and forecast severe weather. Weather radars may play an important role in this task, due to their capacity to visualize the characteristics of intense storms with high spatial and temporal resolution. Most storms move across the México City Valley from east to west, where they appear to intensify at the foothills of the mountains. Radars constitute the best option for monitoring and mapping precipitation (Valdés-Manzanilla and Aparicio, 1997). Therefore, the best location for the radar to monitor intense storms is where it can detect the onset and intensification of the convective systems.

Daily precipitation in the México Valley watershed exhibits a well-defined diurnal cycle (Magaña *et al.*, 2003). There are usually clear skies before noon and storms in the afternoon and in the evening. In general, afternoon precipitation tends to occur relatively earlier in the eastern part than in the western part of the basin. Severe storms (> 20 mm/h) are more probable to occur after

16:00 h local time in the central-eastern part of México City, and late in the evening in the western mountains. There may be precipitation events in the early morning as well (between 5 and 6 local time), but their dynamics is not clear. Some reports from stations in the western mountains of the basin indicate that precipitation in the early morning hours may be as large as 5 mm/h.

There is a network of twelve C-band radars, mainly along the Mexican coasts, for the monitoring of tropical cyclones. There is also a weather radar called Cerro de la Catedral, located 40 km northwest of México City, to monitor severe weather over this region. The main characteristics of this radar are described in Table I. Although weather radars are important tools in the study of the severe weather, there are problems in Cerro de la Catedral radar that result in insufficient meteorological information in its day to day operation. Its coverage and the quality of precipitation estimates are inadequate due to topographic blocking and scanning practices. There are not nowcasting products and the data are rarely used for early warnings since precipitation estimates are seldom available. Consequently, most weather predictions for the México Valley are based on empirical methods, which make them of little use for taking measures for prevention in the civil protection system. Frequently, meteorological information is only used to explain the origin of natural disasters.

Table I. Configuration of Cerro de la Catedral radar in México.

Radar characteristics	Manufacturer
Antenna diameter (m)	Ericsson 4.2
Gain (dB)	44.7
Beamwidth (°)	0.9
Polarization	Linear, hor/vert
Frequency (GHz)	5.60-5.65
Wavelength (cm)	5.30-5.35
Peak power (kW)	250
Pulse length (ms)	0.5-2.0
PRF (Hz)	250, 900, 1200
MDS (dBm)	-114, -110, -109

The metropolitan authorities are aware of the need of an early warning system for severe weather based in an adequate diagnostic-prognostic system to characterize the mesoscale features of severe weather. Although there is a dense network of surface meteorological stations and rain gauges, satellite images, as well as numerical models to diagnose and predict mesoscale circulation, a weather radar is necessary for a complete and detailed coverage of the precipitation field and for very short range prediction of intense convective systems. Collier (1996) showed that weather radars play an important role in the structure of a forecasting system in the time range of one hour. Strong convective cells may be classified and tracked by the radar and prognoses can be performed with accuracy. However, the quality of the diagnosis and prognosis in the very short time depend on the radar characteristics, for instance its scanning position. In other words, it will depend of how the radar actually “sees” the storms.

The main objective of the present work is to examine the rainfall patterns over México City, as determined from Cerro de la Catedral radar, by looking at spatial characteristics (shape, position and magnitude) of precipitation across the valley such during case studies of intense precipitation. The diagnostic of the problems with this radar may help to propose a better configuration for this instrument that results in improved information for decision making. The analysis also constitutes a first step towards an improved understanding of storms over urban areas, particularly during the summer rainy season.

The structure of this work is as follows. Section 2 presents a brief description of the data and the methodology used in the present study, including the criteria to select case studies. Section 3 corresponds to a description of the summer precipitation regime over México City, to contextualize the case studies as characteristic of this season. In Section 4 a new design of a meteorological weather system is proposed to correct some of the problems with its current location. Section 5 present conclusions.

2. Data and methodology

Reflectivity data from Cerro de la Catedral radar were provided for the 1995-1998 period by the Mexican weather service. By means of a Marshall-Palmer relationship, reflectivity data was converted to precipitation estimates (Méndez *et al.*, 2006). To estimate precipitation from the Cerro de la Catedral radar reflectivity, the Marshall-Palmer ($Z = 200R^{1.6}$) distribution has been used, based on an analysis of historical data. The limited availability of data from the radar led to consider only a few case studies for episodes of intense precipitation. The rainfall data used for the present study comes from the rain gauge network operated by the Dirección General de Operación y Construcción Hidráulica of México City government. The data correspond to measurements of precipitation every 15 minutes during precipitation events in a network of 78 rain gauges across the México Valley basin (Fig. 1).

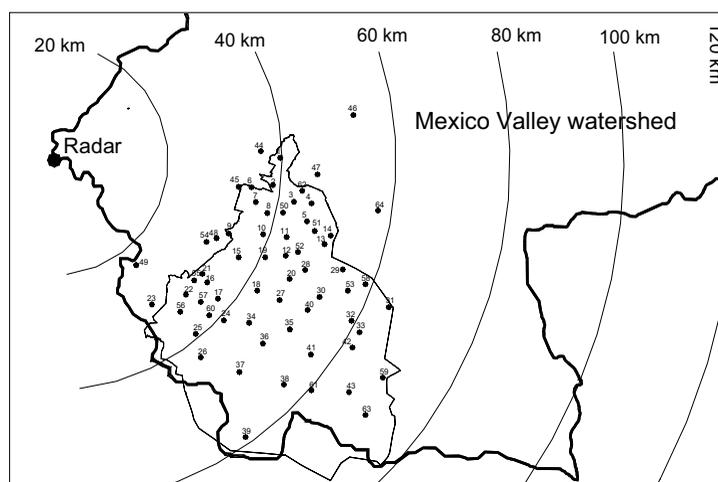


Fig. 1. Rain gauge distribution over México City and Cerro de la Catedral location. The numbers refer to the meteorological station id. The thick line is the watershed boundary; the thin line represents México City limits.

The analysis of severe storms was carried out by selecting case studies that exhibit the average characteristics of precipitation over the México Valley. On average, there are around 12 extreme precipitation events every summer in a particular location of México City, most of them related to easterly waves (Magaña *et al.*, 2003). By means of data from the rain gauge network, episodes of severe storms were selected. The criterion used for the case studies was such that at one rain gauge (González *et al.*, 1998):

$$hp_{24h,j}^k \geq 50 \text{ mm} \quad (1)$$

where $hp_{24h,j}^k$ is the accumulated precipitation over 24 h in the rain gauge j for the day k . The time evolution of rainfall over the valley may be analyzed by mapping data from the rain gauges for 13 storm cases occurring during summer time (Table II).

Table II. Periods of the selected events for radar and rain gauge analysis.

Case number	Date	Period (local time)
1	23 September, 1995	15:00 - 18:45
2	14 June, 1996	19:00 - 24:00
3	18 June, 1996	17:30 - 22:45
4	13 July, 1996	18:00 - 20:15
5	15 August, 1996	18:30 - 22:15
6	01 September, 1996	15:15 - 17:00
7	19 September, 1996	16:15 - 18:00
8	02 June, 1997	19:00 - 22:15
9	15 July, 1997	16:45 - 18:45
10	16 September, 1998	00:45 - 05:45
11	26 September, 1998	19:00 - 05:00
12	27 September, 1998	15:45 - 19:00
13	19 August, 2003	15:30 - 18:45

One of the main difficulties in comparing radar precipitation estimates and rain gauge measurements in random locations has to do with the spatial representation of rainfall patterns and their magnitude. The radar possesses a much higher spatial density of precipitation estimates with uncertainty in the magnitude. The rain gauge network possesses more accuracy at specific point but is more uncertain in estimating rainfall in gap regions, i.e., between measurement sites. In hydrology, many approaches have been developed to represent the spatial patterns of precipitation by means of rain gauges only, especially for rain events of short duration associated with severe convective storms. Point rainfall frequency is the most common technique used in studies of the temporal and spatial rainfall (Ramos *et al.*, 2006). This method assumes that the point measurement is representative of a large area around the gauge, considering the region as homogenous. However, there is no physical criterion for defining the extent of this area (Sen and Habib, 1998). So, the spatial variability of the storm is simply an average from various point measurements and is subject to errors, and the estimate depends on the density of the rain gauge network (Shah *et al.*, 1996).

In order to represent the spatial variability of rainfall, the aerial averaging of precipitation, developed by Thiessen (1911) is used for the present analysis. The method is used for non-uniformly distributed gauges and it consists of defining areas around each rain gauge. The ratio of the area of each zone of influence to the total area constitutes a weighting coefficient for the corresponding

area. Any attempt to map point rain gauge data as aerial estimates that represent the spatial variability of precipitation require some form of interpolation. There are two main interpolation techniques: deterministic (inverse distance weighted) and geostatistics (e.g. krigging). However, the spatial patterns are not completely accurate in inter gauge areas, among other things because point measurements from the rain gauges may not detect the intense core of the storm. In addition, interpolation methods frequently smooth out some of the rain rate maxima, which makes it difficult for an appropriate comparison with radar estimates. These difficulties in pattern comparison between radar and rain gauge, may lead to some error associated with the way we sample precipitation in space and time. Therefore, the comparison will be done by visually comparing precipitation in some specific regions of the valley.

3. Precipitation regime in the México Valley watershed

Central México exhibits a monsoonal type of climate, with a well-defined rainy season from late May until early October. Average precipitation varies from around 500 mm/year in the northeastern part of the México Valley, to almost 1200 mm/year, in the southwestern part. In summer, the interaction of the mountains with easterly winds determines, to a large extent, the characteristics of precipitation (intensity, timing, coverage, number of extreme events). Consequently, summer precipitation exhibits an east-west gradient, with more intense and frequent precipitation along the southern and western slopes of the basin due to orographic effects (Barros, 1994). According to the Mexican weather service, precipitation in excess of 60 mm in 24h is not unusual in the southwestern part of the city. Magaña *et al.* (2003) have determined that extreme events in the western part of México City should be more than 25 or 30 mm in 24 h, while for the eastern part of the city, more than 15 mm in 24 h already constitute an extreme event. The maximum historical record in the southern part of the city is 164.9 mm in 24 h on September 22, 1983. Intense precipitation events are becoming more frequent in recent decades. According to Jáuregui (2000), the number of severe storms (more than 20 mm/h) has increased from around four per decade around the 1940s, to almost 20 per decade in the 1980s.

By examining the average precipitation from the 13 case studies, it is found that precipitation is usually more intense in those locations over the western mountains of the México Valley (e.g. station number 21-25 or 55-58) than in the eastern part (e.g. 64-68) (Fig. 2a). Precipitation over the mountainous regions may be twice as large as the one observed in the relatively flat part of the basin. The diurnal cycle during these intense events indicates that the intense precipitation begins in the afternoon, around 16:00 h local time, generally in the eastern part of the valley, and propagate to the western part during the evening, reaching the other extreme of the valley by late evening and midnight (Méndez *et al.*, 2006). The sum of hourly accumulated rainfall during the 13 case studies shows that this characteristic of the diurnal cycle is captured (Fig. 2b). The analysis of the individual cases allows examining the rainfall patterns observed by the rain gauge network and the radar. Results are depicted in hyetographs, mostly for the México City area, since there are no rain gauges to the west of the mountains, and consequently the rainfall patterns in this region are not reliable for comparison with the radar estimates.

The precipitation event for September 23, 1995 corresponds to a case of intense rainfall over the western mountains of the México Valley. Rain gauge observations indicate up to 60 mm between 15:00 and 18:45 local time (Fig. 3a). The radar estimated rainfall also shows intense precipitation, of the same order of magnitude as the measured with the rain gauges, but with a much more refined

spatial structure (Fig. 3b). The radar also detects rainfall in some locations to the east of the basin that are not captured or are smooth out by the interpolation scheme used with rain gauge data. It can be noted that precipitation patterns, obtained from the rain gauges and radar are in agreement, except at some locations where the rain gauges fail to depict the correct pattern of precipitation, possibly due to sampling problems.

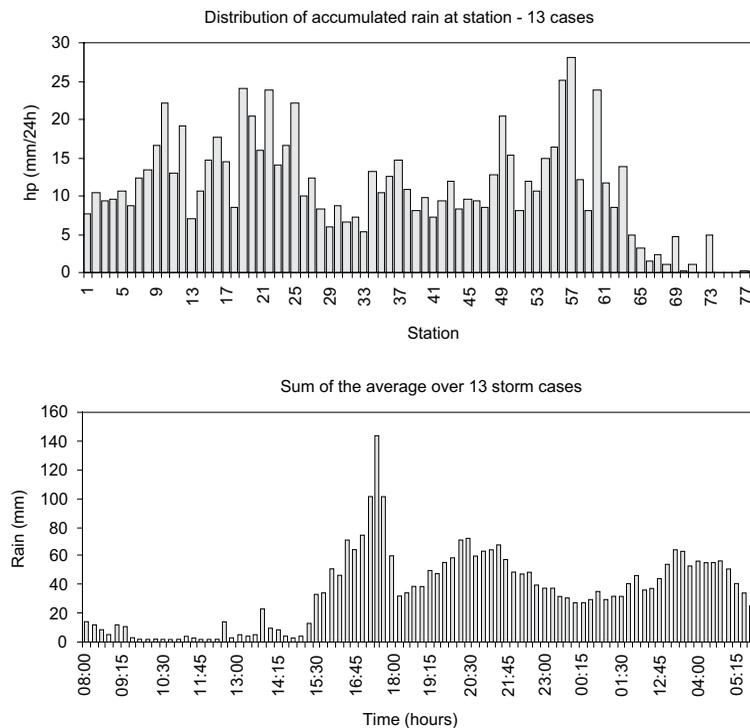


Fig. 2. a) Distribution of spatial average accumulated rainfall (mm/24 h) over stations. The numbers refer to the map of Figure 1; and b) temporal distribution of average accumulated rainfall (mm).

The case for June 14, 1996 also shows intense precipitation in the western part of the valley at the foothills of the mountains, with maxima in precipitation of the order of 50 mm between 19:00 and 24:00 h local time (Fig. 3c and d). The radar captures the structure of the rainfall pattern but the maxima is slightly displaced (around 5 km) to the central part of the region, not over the mountains, but over the valley. This part of the domain (foothills of the western part of the México City) exhibits systematic differences between radar estimates and rain gauge observations.

The case for June 18, 1996 from 17:30 to 23:00 h local time shows a pattern with intense precipitation to the southwest of México City, mostly in the mountains (Fig. 3e and f). The spatial structure from the rain gauge network and the radar is very similar in magnitude and shape. However, precipitation at the foothills of the western mountains shows that while rain gauges indicate between 25 to 30 mm of rain, the radar only estimates around 10 to 15 mm.

On the other hand, the case of July 13, 1996, between 18:00 and 20:15 h local time corresponds to a situation when intense precipitation (more than 50 mm) is estimated by the radar, but not clearly measured by the rain gauge network (Fig. 3g and h). There appears to be an overestimation on the amount of rainfall in the relatively homogeneous (urban and flat) region of northeastern México City.

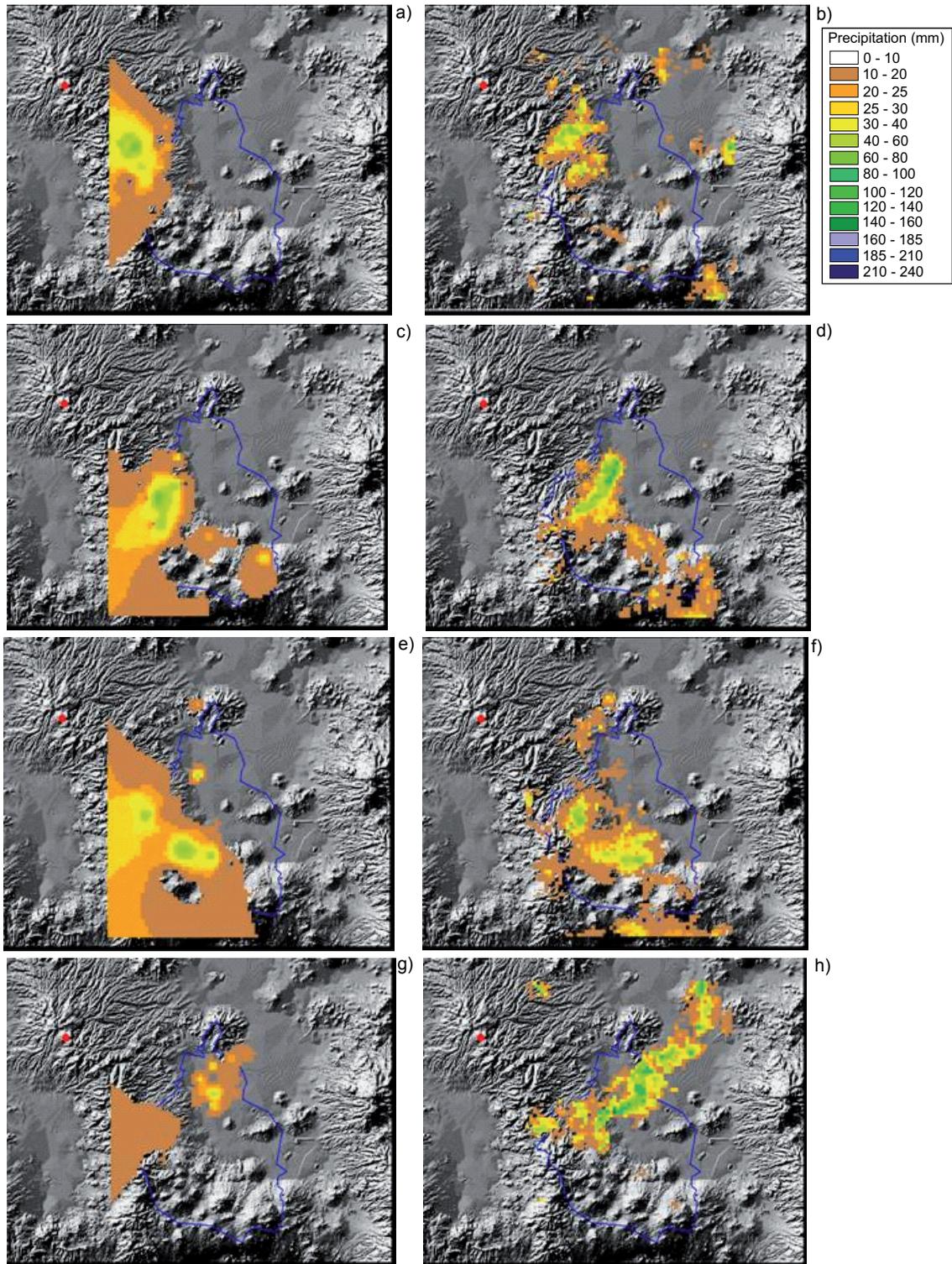
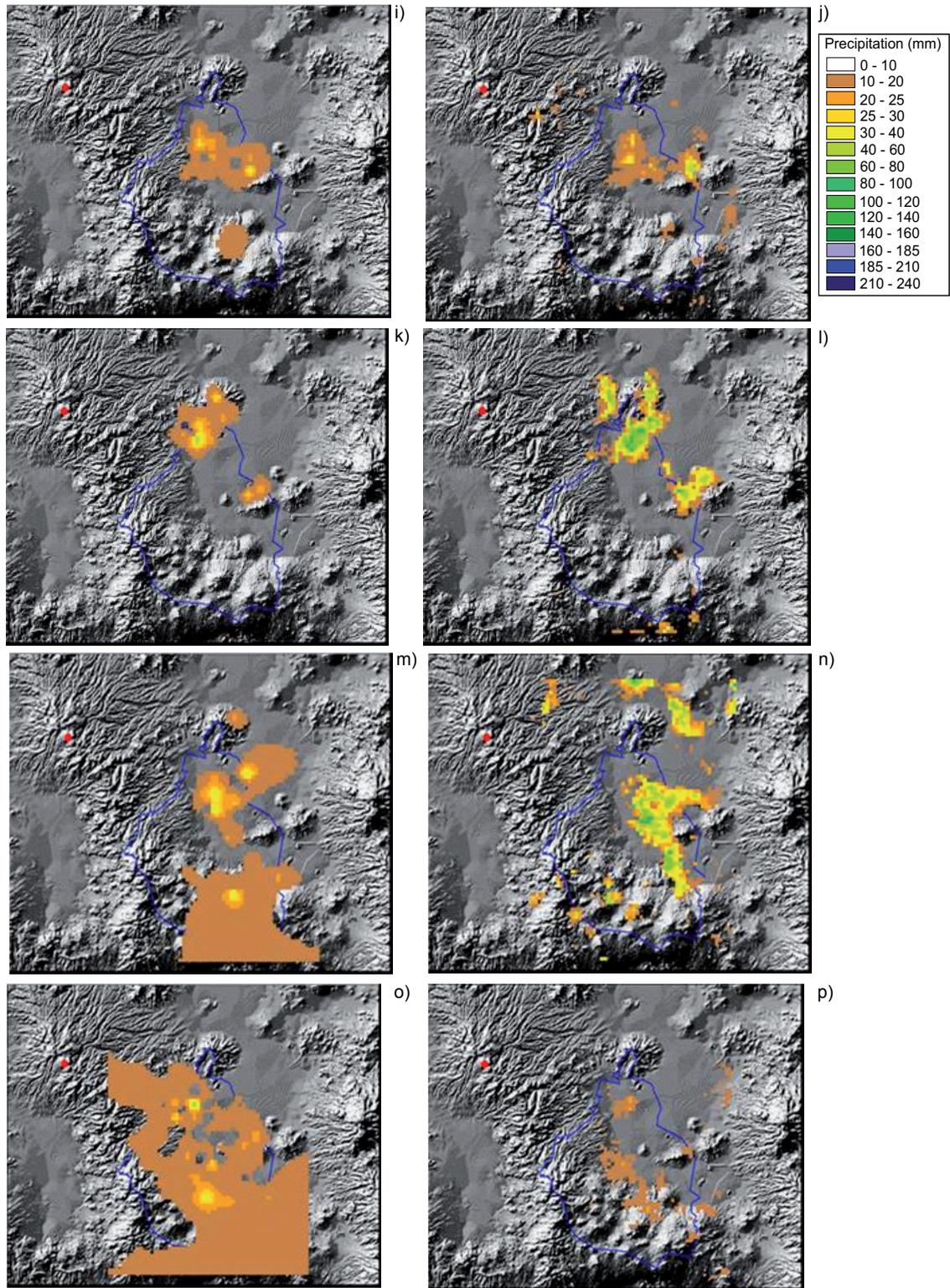
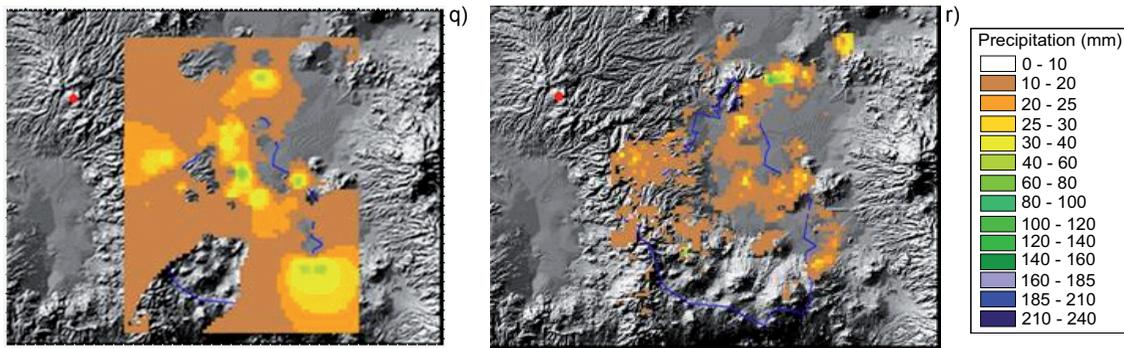


Fig. 3a-h. Interpolated precipitation from the rain gauge network (left) and estimates of precipitation from the Cerro de la Catedral radar (right) for nine out of thirteen case studies used in the present analysis. The intensity of precipitation is indicated in the color bar (see text for details). (Continues in the next page.)



(Fig. 3, i-p, continued.)



(Fig. 3, q-r, continued.)

The case studies for August 15, 1996 (18:30-22:15 h local time) (Fig. 3i and j) and September 1, 1996 (15:00-17:00 h local time) (Fig. 3k and l) show similar spatial patterns of precipitation, but with some overestimation in the magnitude of precipitation over the eastern part of the valley. The case for June 2, 1997 (19:00-22:15) (Fig. 3m and n) also shows that at the eastern part of the valley, the radar overestimates precipitation, but detects no rainfall right at the foothills of the western mountains of the city.

The situation on September 16, 1998 (00:45-05:45 h local time) (Fig. 3o and p) also shows how the radar tends to underestimate precipitation at the foothills of the western mountains of México City, just like the situation during September 26, 1998 (19:00-05:45 h local time) (Fig. 3q and r). Similar conditions are observed for the other case studies (not shown).

4. Proposal for a new radar system

Most of the analyzed cases show that intense precipitation over the eastern part of the basin occurs earlier in the eastern than in the western part of the México City watershed, generally after 16:00 h local time for the former and during the late evening and passed the midnight for the later. It is also found that while there seems to be an underestimation in the amount of precipitation over the western mountains of the valley, at the foothills, rainfall rates tend to be overestimated over the eastern parts. The origin of this problem may be partially related to the blockage effect from mountains between the current radar position and the basin.

The weather radar usually suffers partial or total blockade when it is located in mountainous regions. The current location of the Cerro de la Catedral radar can limit the coverage of the radar when it requires negative angles in the vertical measurements to monitor the valley, affecting the precipitation estimates (Joss and Waldvogel, 1990; Sauvageot, 1994; Collier, 1996; Smith, 1998). In the case of the México Valley, the cloud base is usually around 1000 m high with respect to the ground level. The current location of the radar makes it difficult to detect reflectivity from the lower part of the cloud, particularly around the foothills of the western mountains of México City (Fig. 4). In an 8 to 10 km deep cumulonimbus cloud, up to 0.5 km of the cloud cannot be sampled by the radar near the foothills of the western mountains of the México valley. This may lead to errors of around 5% or more in the estimate of the amount of precipitation. Therefore, it appears necessary to make use of some blockage corrections in the radar signal in order to get better quantitative estimates of precipitation, including all the column of precipitable water. The correction of systematic errors in the vertical may be combined with elimination of spurious echoes

by two- and three-dimensional analysis of the topography and the storm itself (Krajewski and Vignal, 2001; Steiner and Smith, 2002). However, these corrections may have a contrasting effect in the precipitation estimates in the western and eastern parts of the México Valley, since the calibration factors should be systematically applied in the entire domain and consequently, it may result in overestimation of precipitation in the eastern part of the basin and underestimation in the western mountains, particularly at the foothills. The previously described difficulties lead to consider the gradual change in the position of Cerro de la Catedral weather radar. It is necessary to make use of the radar as a tool not only for qualitative rainfall estimation, but to more quantitative rainfall measurements (Borga *et al.*, 1997). This concept may be implemented through a new configuration of the radar network, allowing for dual Doppler analysis of the wind fields in the analysis of the mechanisms for heavy precipitation.

The México City basin is a good example of complex topography, which increases the difficulty of choosing an adequate place to locate a radar system, as a mean for obtaining an appropriate coverage. The Cerro de la Catedral radar is located at 3785 m above sea level, approximately 1500 m above México City ground level, and it is the only one that covers most of the México Valley basin. Such elevation affects the precipitation estimates, mainly by creating blind regions near the very low troposphere (up to 1000 m high) mainly at the foothills of the western mountains. The inability of the radar to include shallow rains makes it necessary to set the elevation angles of the radar to negative values, of around -1.5° . However, this has the inconvenience of more blockage, clutter and loss of signal.

The scanning strategy for the correct observation of the clouds and precipitation close to the ground involve new managing strategies, including better radar scanning and change of its current location for better monitoring. Although moving the radar from its present position or acquiring a new system represents an opportunity to improve the coverage, some of the clutter problems or the multi-path and anomalous electromagnetic wave propagation problems may still remain. A unique solution is certainly not possible. In any event, a new configuration is necessary to correct the weaknesses of the present system. A complete three-dimensional coverage of México City can be achieved by moving the Cerro de la Catedral radar to either the north or south of the México Valley watershed, and perhaps by installing a second radar in the opposite extreme of the basin.

Several conditions of propagation either from the present radar or from two other possible positions were attempted to get the greater coverage area. By using the AREPS software from US Navy and 3 arc seconds topography data from Instituto Nacional de Estadística, Geografía e Informática (INEGI), México, it may be shown that the radar beam propagation with -1° of elevation, does not allow a good view of the layers close to the ground and most of signal is lost (Fig. 5). An alternative configuration, where there are new positions for two radars, one at the south of México City and the other one at the north of the city may constitute a new array, as illustrated in Figure 6. The radars at these positions are within the city and they are not as high as the current radar. The radar 1 is at 2281 m above mean sea level and the radar 2 at 2975. The rings, which were drawn are 10 km apart and illustrate the domain for both radars. Radar 1 is located at the south, at Universidad Nacional Autónoma de México (UNAM) campus, and radar 2 is at the north, at Cerro del Chiquihuite. Such combination of radars covers most of México City, without shading effects. The diamonds in the picture shows the overlapping regions and that the city is well covered by the radar. This new configuration can monitor the city at low elevations with a good mapping of the main rain patterns.

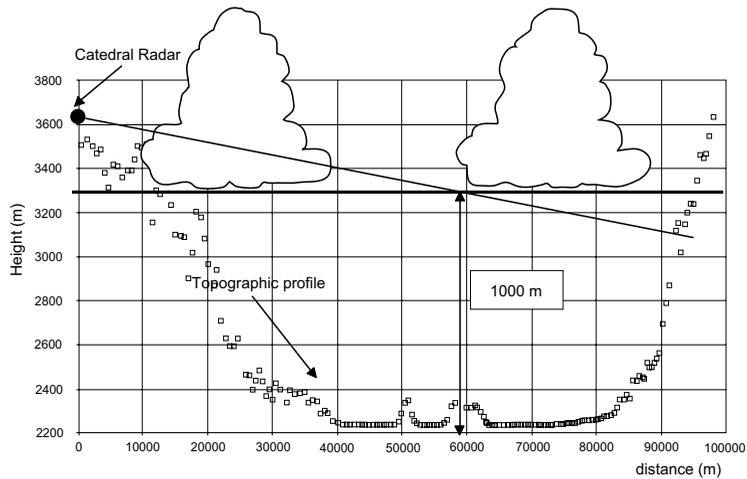


Fig. 4. Schematic diagram of the vertical cross section along the radar beam from northwest to southeast, showing the part of the clouds that is not visualized by the radar due to orographic blockage.

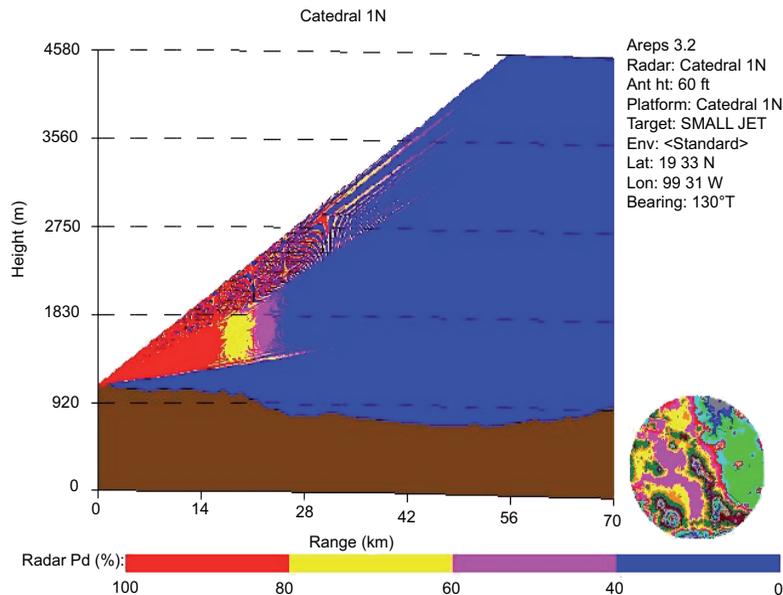


Fig. 5. The probability of detection for the Cerro de la Catedral radar, with the radar beam at -1° .

The new configuration of the radar system for the México City is taking into account spatial coverage and propagation effects, upon a standard atmosphere. Thus, the profile of refractive longitudinally was assumed constant, and the vertical profile does not vary from one location to another. Obviously, this design limits the study of propagation, but even under normal conditions of spreading, the radars are highly subject to problems of hidden beam, spread anomalous and signal attenuation (Fig. 7). This configuration minimizes these problems, resulting in an overlap of the volumes sampled by the two radars.

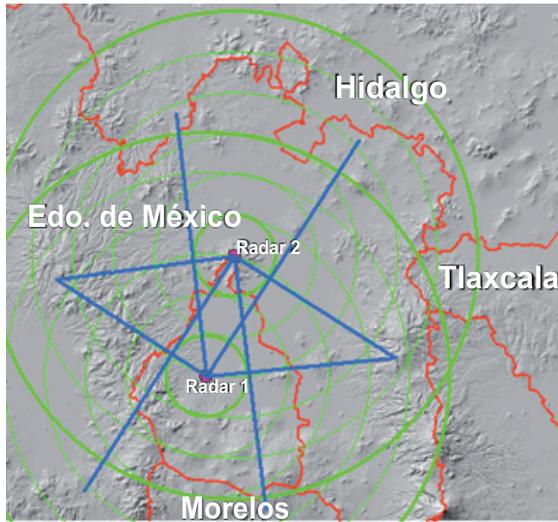


Fig. 6. Topography and idealized coverage with 2 overlapping radar systems. The diamonds represent the overlapping region for radar at UNAM (south) and Cerro del Chiquihuite site (north) and the circles are total expected coverage for radar placed at UNAM and Chiquihuite station site.

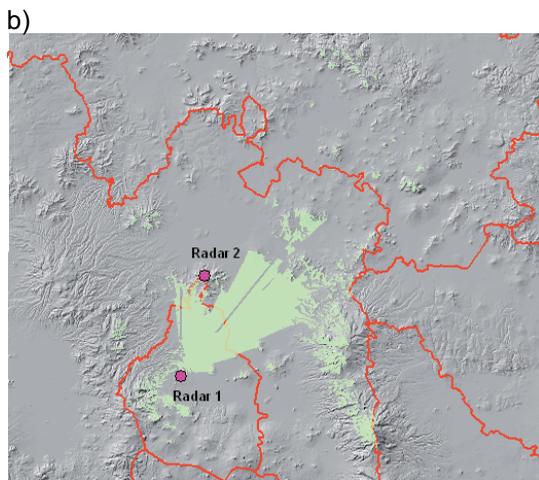
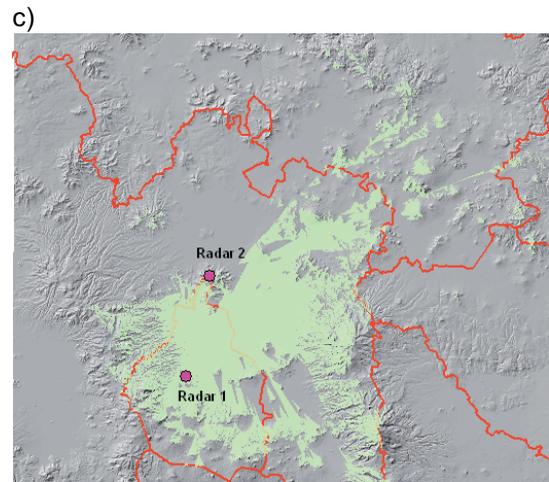
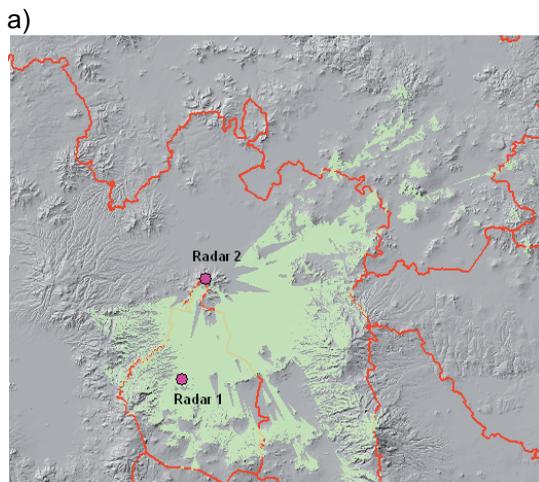


Fig. 7. Coverage of the proposed radar configuration, considering: a) the radar located at the north of México City, b) the radar located at south and c) the overlapping coverage from the two radar positions, at the south and at the north.

5. Conclusions

Radar hydrology, or the hydrological applications of meteorological radars, has become an important part of remote sensing in atmospheric sciences and disaster preparedness activities. By means of meteorological radars a description of the precipitation field with high temporal and spatial resolution, required in hydrological modeling (Sempere-Torres *et al.*, 2004), may be obtained. The advantages of radar derived rainfall data with respect to rain gauge networks are multifold (Collier, 1996; Joss and Waldvogel, 1990). Radar covers large areas and is of rapid access for real-time hydrological applications. An adequate combination of radar plus rain gauge data results of some of the best estimates of precipitation.

In this work an evaluation of rainfall quantification for México City by rain gauges and radar was conducted. While rain gauges provide accuracy in the magnitude, the radar provides spatial coverage. In México City most rainfall occurs during the afternoons of summer time with intense precipitation frequently developing from east to west. The comparison of rainfall patterns obtained from radar estimates and rain gauge (interpolation) analysis is not straightforward. However, in the present study it has been shown that the rainfall pattern location and shape are in close agreement over most of the domain. However, there may be large differences in magnitude of precipitation from each system, especially for those regions close to the mountains. Some differences may be due to sampling problems, but appear to be largely influenced by mountain blockage of the radar beam, and to some extent by poor spatial representation of rain gauges. In order to examine this problem, a radar propagation study was performed, by considering the actual radar position and a combination of two other sites in México City. It is suggested that this new configuration would improve the sampling of radar data, improving the representation of the raining areas over México City. The current location of the Cerro de la Catedral radar is not adequate to quantify heavy precipitation or when light precipitation is close to the ground and far from radar site.

The capacity of the Doppler radars of 2D and 3D scan of the storm gives a big advantage for flow and precipitation prediction and may be fundamental to understand the physics of storm intensification in the mountainous part of México City. This is the region where a higher risk of flash floods is faced in irregular settlements. Satellite and radar have the potential to provide good estimates of precipitation in these regions, leading to better spatial and temporal coverage.

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References

- Barros A. P., 1994. Dynamic modeling of orographically induced precipitation. *Rev. Geophys.* **32**, 265-284.

- Borga M., D. Da Ros, S. Fattorelli and A. Vizzaccaro, 1997. Influence of various weather radar correction procedures on mean areal rainfall estimation and rainfall-runoff simulation, in: *Weather radar technologies for water resources management*, Braga, B. J. and Massambani, O. (Eds.), IRTCUD/University of Sao Paulo, Brazil and IHP-UNESCO, 73-86.
- Collier C. G., 1996. *Applications of weather radar systems*. John Wiley and Sons, 2a. Ed., New York, 390 pp.
- Domínguez M. R., 2002. El sistema principal de drenaje del área metropolitana del valle de México. Instituto de Ingeniería, C1-22, 34 pp.
- González Villarreal F. J., V. Franco, G. E. Fuentes, B. Méndez A., G. Esquivel, 1998. Estimación de la precipitación en la cuenca del Valle de México a partir de datos de lluvia captados por medio de radar. Reporte Técnico, Instituto de Ingeniería, Proyecto 8353, UNAM, México.
- Huff F. A. and S. A. Changnon Jr., 1973. Precipitation modification by major urban areas. *Bull. Amer. Met. Soc.* **54**, 1220-1231.
- Jáuregui E., 2000. El clima de la Ciudad de México. Instituto de Geografía. (Plaza y Valdés, Eds.). México, D. F., 131 pp.
- Jáuregui E. and E. Romales, 1996. Urban effects on convective precipitation in México City. *Atmos. Environ.* **30**, 3383-3389.
- Krajewski W.F. and B. Vignal, 2001. Evaluation of anomalous propagation echo detection in WSR-88D data: a large sample case study, *J. Atmos. Ocean. Tech.* **18**, 807-814.
- Magaña V., J. Pérez and M. Méndez, 2003. Diagnosis and prognosis of extreme precipitation events in the México City basin. *Geofis. Int.* **41**, 247-259.
- Magaña V. and C. Neri, 2007. Eventos hidrometeorológicos extremos en el Valle de México. *Revista Ciudades.* 26-30.
- Méndez-Antonio B., R. Domínguez-Mora, V. Magaña-Rueda, E. Caetano and E. Carrizosa-Elizondo, 2006. Calibración hidrológica de radares meteorológicos. *Ing. Hidraul. Méx.* **20**, 43-64.
- Ramos M. H., E. Leblois and J.-D. Creutin, 2006. From point to areal rainfall: linking the different approaches for the frequency characterisation of rainfalls in urban areas. *Water Science and Technology* **54**, 33-40.
- Sempere-Torres D., C. Corral, R. Sánchez-Diezma, M. Berenguer, C. Velasco, M. Franco, X. Llorc, E. Velasco and J. Pastor, 2004. Are radar rainfall estimates ready for hydrological applications? Some reflections from the experience in Catalunya. European Conference on Radar in Meteorology and Hydrology (ERAD) – COST 717 Final Seminar. Abstracts Book, 30 p.
- Sen Z. and Z. Z. Habib, 1998. Point cumulative semivariogram of areal precipitation in mountainous regions. *J. Hydrol.* **205**, 81-91.
- Shah S. M. S., J. P. E. O'Connell and J. R. M. Hosking, 1996. Modelling the effects of spatial variability in rainfall on catchment response. 1. Formulation and calibration of stochastic rainfall field model. *J. Hydrol.* **175**, 67-88.
- Steiner M. and J.A. Smith, 2002. Use of three-dimensional reflectivity structure for automated detection and removal of nonprecipitating echoes in radar data. *J. Atmos. Ocean. Tech.* **19**, 673-686.
- Thiessen A. H., 1911. Precipitation for large areas. *Mon. Wea. Rev.* **39**, 1082-1084.
- Valdés-Manzanilla A. and F. J. Aparicio, 1997. The Mexican doppler radar network. 28th Conference on Radar Meteorology, Am. Meteorol. Soc. Austin, TX, EUA, 35-36.