Atmósfera 25(2), 155-170 (2012)

Mesoscale convective systems during NAME

A. VALDÉS-MANZANILLA
División Académica de Ciencias Biológicas, Universidad Juárez Autónoma de Tabasco, Carretera Villahermosa-Cárdenas Km 0.5, 86100 Villahermosa, Tabasco
Corresponding author; e-mails: arturo.valdes@dacbiol.ujat.mx, avmanzanilla@hotmail.com

V. L. BARRADAS MIRANDA
Instituto de Ecología, Universidad Nacional Autónoma de México, Circuito Exterior s/n, Ciudad Universitaria, México D. F., 04510

Received March 3, 2011; accepted November 24, 2011

RESUMEN

Este trabajo examina los Sistemas Convectivos de Mesoescala (SCM) ocurridos durante el Experimento del Monzón de Norteamérica (NAME) usando datos de instrumentos desplegados en el noroeste de México como radar y sondeos atmosféricos, y satélite meteorológico. Imágenes infrarrojas de satélite fueron usadas para definir estos fenómenos meteorológicos durante el periodo julio-agosto de 2004 en el área núcleo del NAME. Se observaron 82 SCM durante el NAME, en una estación veraniega ligeramente más activa de lo normal, debido probablemente a una posición de la dorsal más al sur de lo normal. Vientos del suroeste a niveles medios dominaron en la región durante los periodos inactivos de formación de los SCM y vientos del este dominaron durante los periodos activos. La hora de inicio de los SCM fue mayormente entre la tarde y noche; mientras que su hora de término fue después de medianoche con una duración media de 7.46 horas. La mayoría de los SCM durante el NAME se formaron asociados a dorsales y vaguadas invertidas. Pocos de ellos se relacionaron a ciclones tropicales. La mayoría de las líneas convectivas analizadas fueron clasificables (70%), siendo una gran parte de ellas paralelas al cortante del viento (69%). No sólo la magnitud y dirección de los vectores de la cortante del viento a niveles medios y bajos son importantes para la morfología de los SCM, como se observa en las imágenes de radar, sino también el ángulo entre estos dos vectores de la cortante del viento. Los parámetros cinemáticos fueron más importantes para la morfología de los SCM que los termodinámicos.

ABSTRACT

This work examines Mesoscale Convective Systems (MCS) observed during the North American Monsoon Experiment (NAME), using data of deployed instruments in Northwest Mexico like weather radar, atmospheric soundings and weather satellite. Satellite infrared images were used to define these meteorological phenomena during July-August 2004 period on the NAME core region. Eighty two MCS occurred during NAME in a summer season lightly more active than normal, due probably to a ridge position more to the south than normal. Southwesterly midlevel winds dominate in the region during inactive MCS formation periods, while easterly winds dominate during active periods. MCS initiation time was mostly between afternoon and evening, while their termination time was after midnight with an average MCS duration of 7.46 hours. Most of NAME MCS formed associated to synoptic ridges and inverted troughs. Few of them related to tropical cyclones. Most of the analyzed convective lines in this region were classifiable (70%), being most of them shear-parallel lines (69%). Not only the magnitude and direction of the midlevel and low-level wind shear vectors were important to MCS morphology, as is seen in weather radar images, but also the angle between these two wind shear vectors. Kinematic parameters were more important to MCS morphology than thermodynamic ones.

Keywords: North American Monsoon Mesoscale Convective System.

1. Introduction

One of the most important meteorological phenomena in northwestern Mexico and southwestern United States are the mesoscale convective systems (MCS), as shown by Lang *et al*. (2007), who estimated that ~75 % of the rainfall is produced by organized convective systems during disturbed regimes.

Mohr and Zipser (1996) also found that NW Mexico is one of the areas with more occurrences of MCS in the world and observed many of them along the Sierra Madre Occidental (SMO), when they studied global distribution of MCS using 85-GHz ice scattering signatures of the Special Sensor Microwave/Image onboard the Defense Meteorological F-11 satellite.

One of the main objectives of the North American Monsoon Experiment (NAME) carried out in northwestern Mexico during 2004 was to study warm season convective processes in this complex coastal region (Higgins *et al*., 2003). A large quantity of meteorological instruments were deployed in its field campaign like meteorological radars, wind profilers, radiosondes and research planes to have a better description of the meteorological conditions of this region. That provided a unique opportunity to carry out research in convective systems in northwestern Mexico.

A prolific literature on convective systems in northwestern Mexico was produced in the last two decades, due to the high frequency of MCSs in this region, but most studies were based on satellite imagery, synoptic and sounding data, such as Douglas *et al*. (1986), Howard and Maddox (1988), Smith and Gall (1989) and Farfán and Zehnder (1994).

Some recent studies used the available instrumentation deployed during NAME, such as Lang *et al*. (2007) who studied all sizes of convective systems in a specific area covered by three meteorological radars, but not in the entire NAME core region. This work covers the entire NAME core region but only one type of MCS.

Some research questions about MCS in Northwestern Mexico have only been partially answered, specially for other types of convective systems, or not yet answered, like the following questions:

a) What synoptic systems influence MCSs formation in this region?

   Douglas *et al*. (1986) found that the 500 hPa subtropical ridge influences the formation of MCC, a kind of MCS, in Northwestern Mexico. On the other hand, Lang *et al*. (2007) found that tropical easterly waves also influence the genesis of convective systems in this region. Our hypothesis is that other synoptic conditions, like inverted troughs (as was suggested by Finch and Johnson (2010)), may produce favorable conditions for the formation and development of MCS. In this study, we quantified what synoptic systems had influence in MCS formation in this region.

b) What is the influence of kinematic and thermodynamic parameters in the organization of convection of MCS in Northwestern Mexico?

   Lang *et al*. (2007) found some differences in low-level wind shear in their different precipitating regimes, but they did not study specifically MCS. Our hypothesis is that not only low-level wind shear but also midlevel one are very important in the organization of convection of MCS in Northwestern Mexico.

c) What is the influence of the position of 500 hPa subtropical ridge in the number of MCS formed in northwestern Mexico during NAME and in their intraseasonal variability?

   Douglas *et al*. (1986) found that a subtropical ridge located more to the south than normal was associated with a greater number of MCC, a type of MCS. Our hypothesis is that the position of this ridge not only influences how many MCS form in this region but also when there are active periods.

d) What is the influence of the diurnal cycle in MCS formation in this region?

   The strong diurnal cycle of convection is considered as one of the main characteristics of North American Monsoon (Higgins *et al*., 2003). Lang *et al*. (2007) found that rainfall associated with organized systems had two peaks around midnight and sunrise. Our hypothesis is that the diurnal cycle influences strongly MCS formation and dissipation in this region.

Finally, our study adds new knowledge to the topic of Mexican MCS, because we classify MCS, for the first time, according to low-level and midlevel wind shear and determined what synoptic systems are more influential in their formation. In addition, we studied other MCSs characteristics like their frequency of occurrence, tracks and diurnal variation.

2. Data and methodology

We used GOES-12 infrared satellite images to track MCS, because they covered totally the NAME core region. The Mexican weather service (Servicio Meteorológico Nacional, SMN) provided these images from its satellite receiving station with a format of 640 × 472 pixels, 4 × 4 km by pixel. The area of study covered the NAME core region from 20º N to 35º N and between 105º W and 115º W (Fig. 1). The period of study was from July 1 to August 31, 2004.

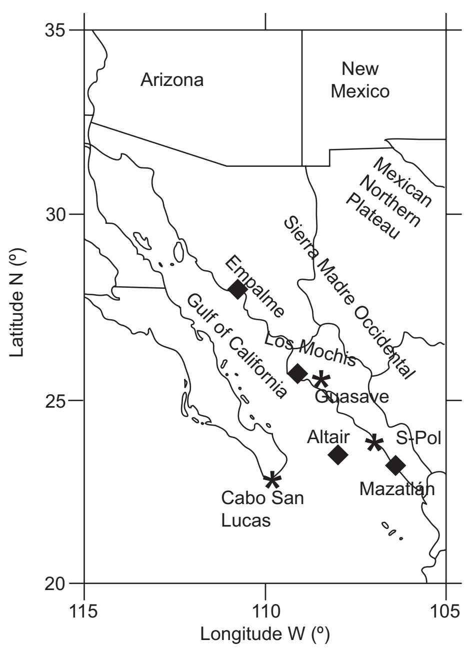

Fig. 1. NAME core region with deployed instrumentation used in this study, where * mark shows radars positions and ◆ mark shows soundings positions.

A cloud system was classified as a MCS only if it met five criteria (Table I), which were similar to those used by Bartels *et al*. (1984) and Hashem (1996). We used software called ASMEIS (Sosa-Chiñas and Valdés-Manzanilla, 1999) to find cloud systems that met these criteria.

For each cloud system, the ASMEIS software computed the greatest lineal length of area bounded by the –54 ºC (219 ºK) isotherm and determined its centroid. If a cloud system met the MCS criteria (Table I), then its centroid, was used to establish its track at different times.

Table I. Criteria to define if a cloud system is a MCS.

Parameter	Criteria
Length	Linear length of ≤ –54 ºC (219 ºK) contiguous enhanced area on satellite image is > 250 km
Duration	Minimum length scale is maintained for at least 3 hours
Initiation	The length scale criterion is first met
Termination	The length scale criterion is no longer met

To determine the meteorological conditions associated to MCS, we used the reanalysis data of NCEP global spectral model (Kalnay *et al.*, 1996) obtained from NOAA Climate Diagnostic Center (www.cdc.noaa.gov), that covered from 75º W longitude to 125º W and from 15º N latitude to 40º N. In addition, weather analysis and discussions, performed by the Forecast Operation Center based in Tucson, AZ during NAME field operations, were used to find meteorological systems influencing MCS formation (Pytlak *et al*., 2005).

The chosen definition of a MCS active period was when a daily MCS remains at least two consecutive days or two MCSs occurred in one day. On the other hand, an inactive period was when there were at least two days without the occurrence of any MCS, following Parker and Johnson (2000).

To determine the mesoscale organization of convection in the southern portion of the NAME core region, we used data from three radars: Los Cabos, Baja California Sur, and Guasave, SMN, both from Mexican Weather Service, and S-Pol (NCAR) located in La Cruz de Elota, SMN (Fig. 1). The Colorado State University radar meteorology group developed composite images of the data from the three radars (Lang *et al*., 2007).

Many studies have been done classifying MCS organization using radar images, like Bluestein and Jain (1985) and Houze *et al*. (1990). Our classification was similar to those of Johnson *et al*. (2005) and Lemone *et al*. (1998), based on the low-level and midlevel wind shear vector. To classify the organization of convection in relationship with wind shear, a couple of thresholds were defined: 4 m/s for low-level shear layer and 5 m/s for mid level shear layer, as in Lemone *et al*. (1998) and Johnson *et al*. (2005). Table III shows the criteria used to classify convective lines into eight categories in this study. In addition, Figure 11 shows schematics depiction, adapted from Lemone *et al*. (1998) and Johnson *et al*. (2005), of different categories of convective organization used in this work. We computed the convective line orientation and speed in the same way than Alexander and Young (1992), where line speed is normal to convective line orientation.

Sounding data were obtained from the NAME sounding network at Los Mochis, Sinaloa; Empalme, Sonora; Mazatlán, Sinaloa and on board of a Mexican navy research vessel *Altair*, located in the southern portion of the Gulf of California, to examine the kinematic and thermodynamic conditions associated in the MCSs formation. Selected soundings met the following criteria: its launching time was within four hours, at 200 km from the MCS and on its inflow side.

To analyze the thermodynamic conditions associated with MCS formation, we used sounding-derived values of convective available Potential Energy (CAPE), Convective Inhibition (CIN), lifted index and Precipitable Water (PW) from the Colorado State University Mesoscale Dynamic Group sounding data (http://tornado.atmos.colostate.edu/name/). This group computed CAPE assuming pseudo-adiabatic ascent (precipitation falls out immediately) of a parcel using thermodynamic conditions in the lowest 60 hPa, without temperature effects assumed (Ciesielski, personal communication). In addition**,** we computed wind shear using special software to analyze kinematic conditions associated with MCS formation.

3. Results and discussions

During NAME, 82 MCSs formed, 78 of them in the Mexican portion of the NAME core region, indicating a season lightly more active (+19%) than average 1997-99 (68.7 events) in the Mexican area (Valdés-Manzanilla, 2009) and implying more rainfall for this region, as was found by Lang *et al*. (2007). This active MCSs season was probably helped by a position of the 500 hPa subtropical ridge a little more to the south than normal (Fig. 2), as was also found by Johnson *et al*. (2007) and Douglas *et al*. (1986). This ridge enhanced the plateau monsoon of North America (Tang and Reiter, 1984), specifically in the Mexican Northern Plateau area, which was warmer and drier than normal (Figs. 3 and 4). However, this ridge did not change wind direction, specifically in the southern portion of the NAME core region, where easterly winds dominated (Fig. 5). Finch and Johnson (2010) also noted the importance of midlevel northeasterly winds, associated with inverted troughs, on the formation of MCSs on the lee side of the SMO.

Smith and Gall (1989) found similar conditions in their study of squall lines that occurred in the mountainous areas westward of the Continental Divide in Arizona and Northern Mexico, where midlevel easterly winds brought dry and warm air from the monsoon plateau of North America to the western foothills of SMO. They also found a vertical stratification where a moist layer was located beneath a dry one, which was conducive to convective instability. Nesbitt *et al*. (2008) suggested that the NAME MCS-generation mechanism is similar to that on the Front Range in the state of Colorado, proposed by Tripoli and Cotton (1989), but with opposite midlevel wind direction.

The MCSs active periods dominated during NAME and occurred from July until the first half of August of 2004, when the 500 hPa ridge was over the region (Table II), causing easterly winds on the lee side of the SMO. Inactive periods only occurred during the second half of August 2004 (Table II). Figure 6 shows 500 hPa anomalies between active and inactive periods, indicating that the 500 hPa ridge moved eastward, causing that southwesterly winds observed over northwestern Mexico.

Forty two MCSs formed in July 2004, 18% higher than the average for that month during 1997-99 (36.3 events) in the Mexican portion of NAME core region (Valdés-Manzanilla, 2009). MCSs formed mainly in the western foothills of the SMO, while a few formed in the coastal plain and the Gulf of California. MCSs moved mostly parallel to the SMO and northward (Fig. 7).

Thirty nine MCSs formed in August 2004, 21% higher than the average for that month in 1997-99 (32.3 events) in the Mexican portion of NAME core region (Valdés-Manzanilla, 2009). MCSs

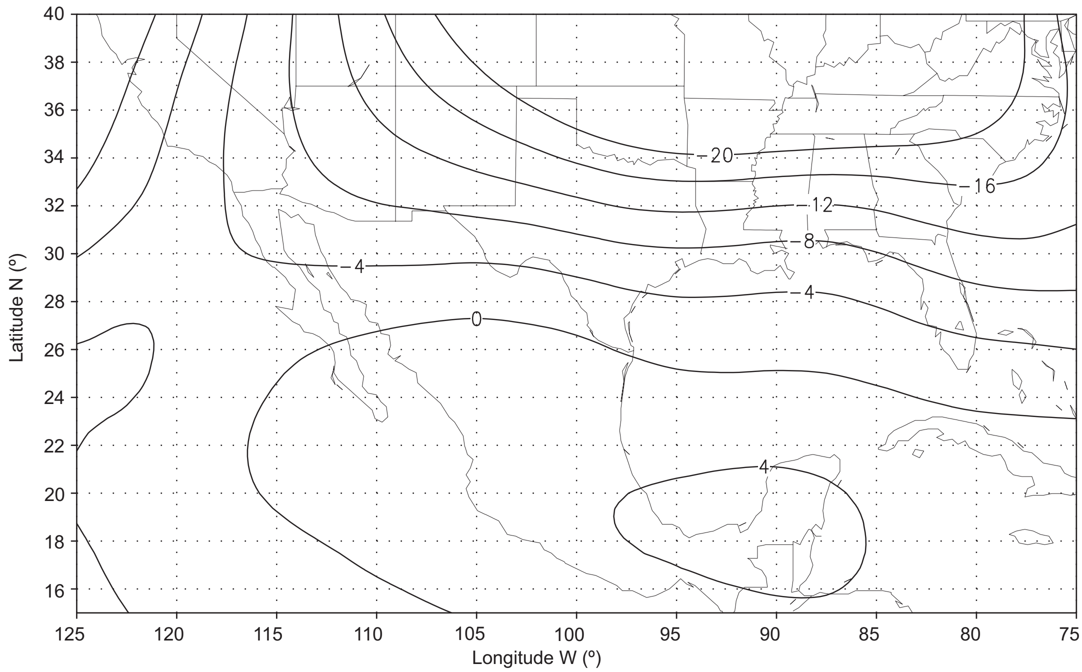

Fig. 2. 500 hPa heights (mgp) anomaly during July and August of 2004 from NOAA-NCEP Climate Diagnostic Center reanalysis data.

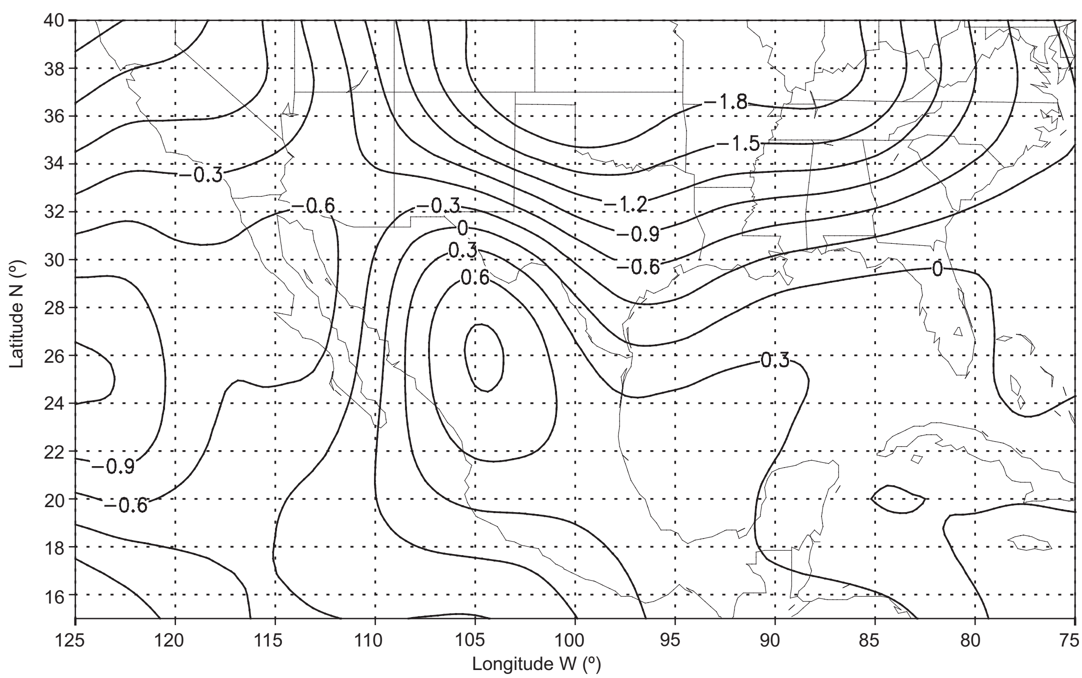

Fig. 3. 850 hPa temperature anomaly (°C) during July and August 2004 from NOAA-NCEP Climate Diagnostic Center reanalysis data.

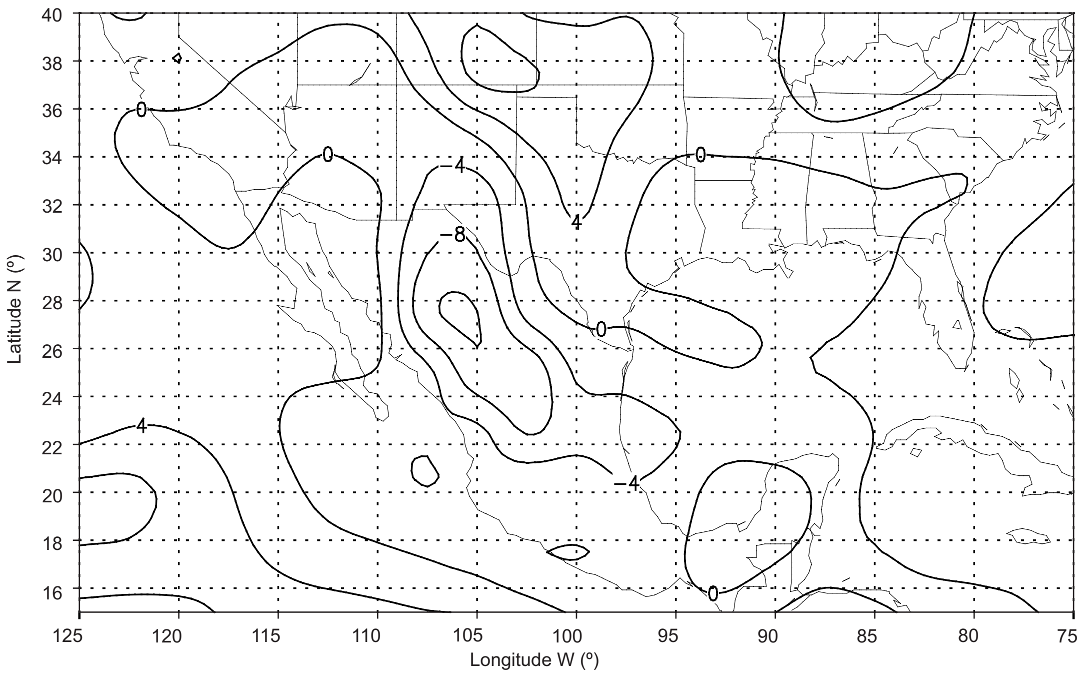

Fig. 4. 850 hPa relative humidity (%) anomaly during July and August 2004 from NOAA-NCEP Climate Diagnostic Center reanalysis data.

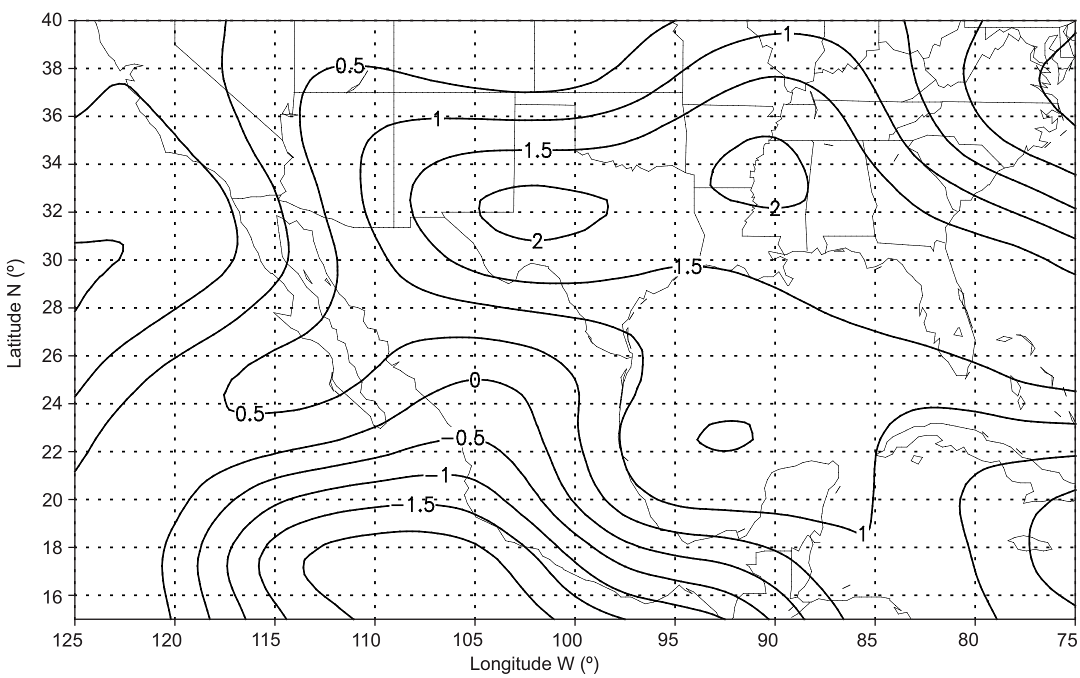

Fig. 5. 700 hPa zonal wind anomaly (m/s) during July and August 2004 from NOAA-NCEP Climate Diagnostic Center reanalysis data.

Table II. List of active and inactive periods of MCS occurrence during NAME.

Active periods	Inactive periods
2-11 July	15-16 August
13-18 July	21-26 August
20 July- 4 August	
6- 10 August	
12-14 August	
17-20 August	
27-31 August	

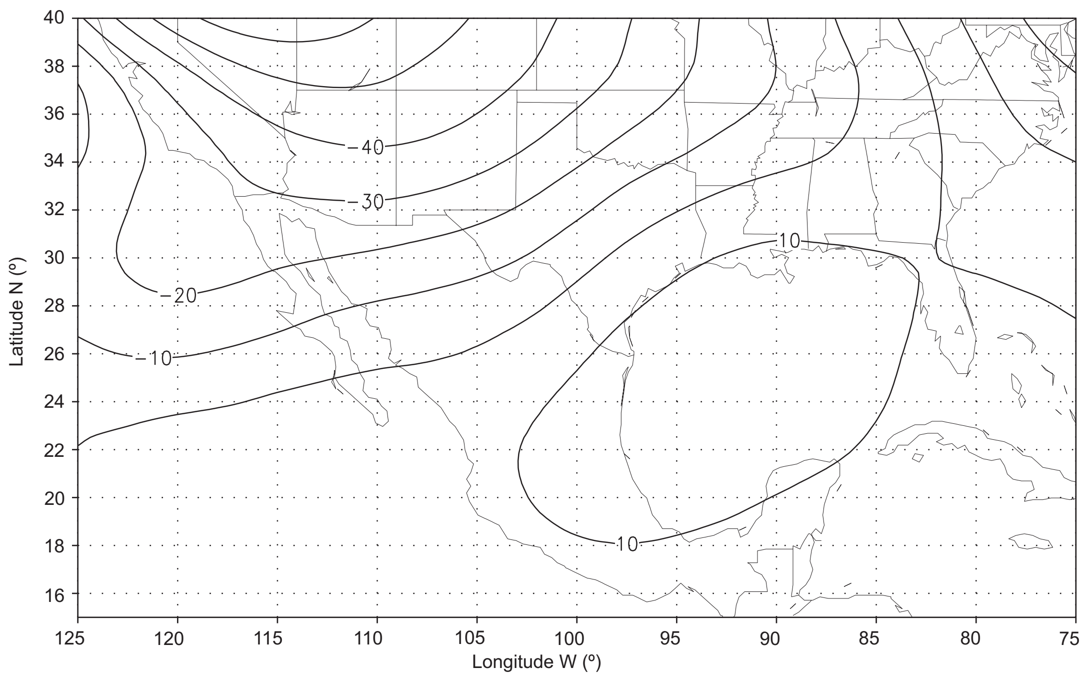

Fig. 6. 500 hPa heights (mgp) anomaly during MCS active and inactive periods in NAME from NOAA-NCEP reanalysis data.

formation occurred not only in the western foothills of the SMO but also in the Gulf of California (Fig. 8). MCSs motions were more variable this month than in July, dominated by two directions: parallel to the SMO and perpendicular to it. Parallel MCSs occurred mainly in the northern portion of SMO (Sonora and northern Sinaloa states), possibly related to the west coast meso-alpha systems found by Howard and Maddox (1988). Perpendicular MCSs moved toward the Gulf of California and occurred mainly in the southern portion of the SMO (southern Sinaloa and Nayarit states), possibly related to the lower west coast meso-alpha systems found by Howard and Maddox (1988).

The weather systems that influenced MCSs formation during NAME were ridges and high pressures (30.5%), inverted troughs (28.1%), tropical waves (14.6%), meso-cyclones (8.5%) and troughs (13.4%). In general, these systems produced easterly winds over Northwestern Mexico, which are favorable for MCSs formation in this region. Tropical cyclones produced only 4.8% of

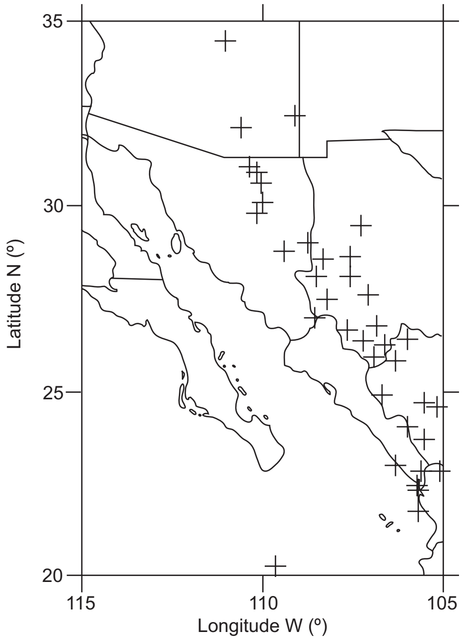

Fig. 7. MCSs positions during July 2004 over NAME core region. Plus sign shows MCS initial track positions.

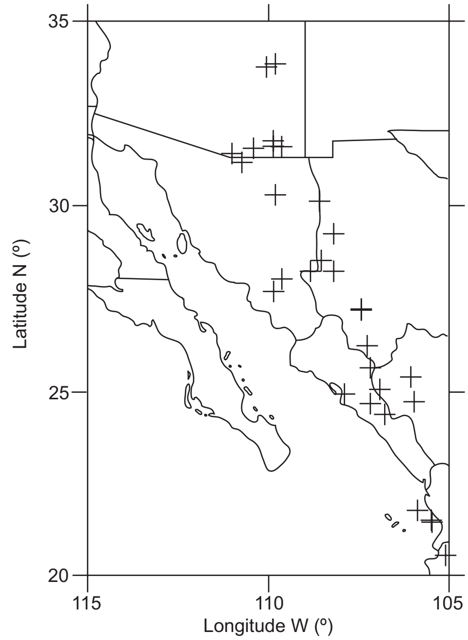

Fig. 8. MCSs positions during August 2004 over NAME core region. Plus sign shows MCS initial track positions.

MCSs, confirming results of Englehart and Douglas (2001) and Douglas and Englehart (2007), that these meteorological phenomena are not main rainfall producers in Northwestern Mexico.

MCSs initiation time was mostly (77%) between the afternoon and the evening (21:00-3:00 UTC, 15:00-21:00 Local Pacific Time), reflecting a strong influence of the diurnal cycle (Fig. 9) similar to Jirak *et al*. (2003). MCSs extinction time occurred mainly (57%) after midnight (3:00-9:00 UTC,

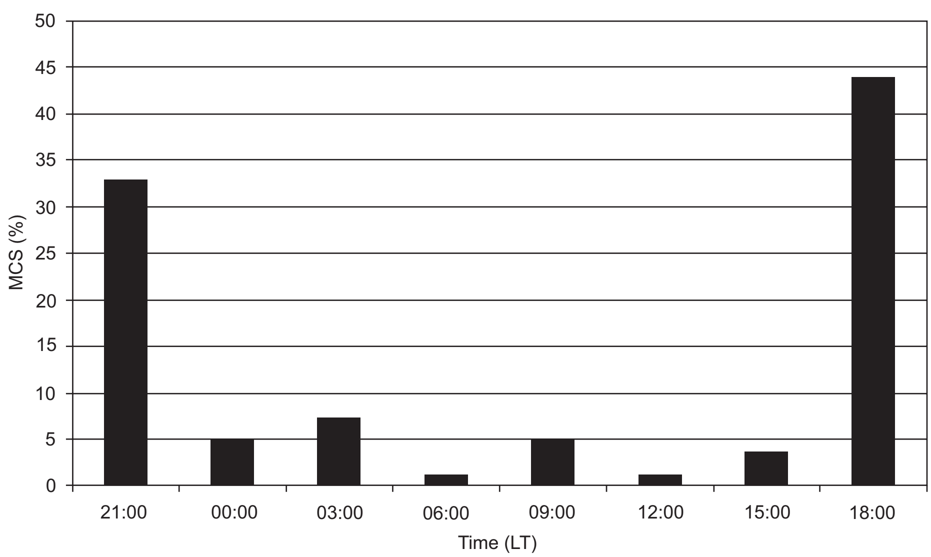

Fig. 9. Histogram of MCS initiation time at Local Time (UTC–6 hours).

21:00-3:00 Local Pacific Time) (Fig. 10). MCS mean duration was 7.46 hours, less than that found for Texas (18 hours) by Hashem (1996), indicating a weaker synoptic forcing. The maximum MCS duration was 23.0 hours, the minimum was 3.0 and the median was 6.98 hours.

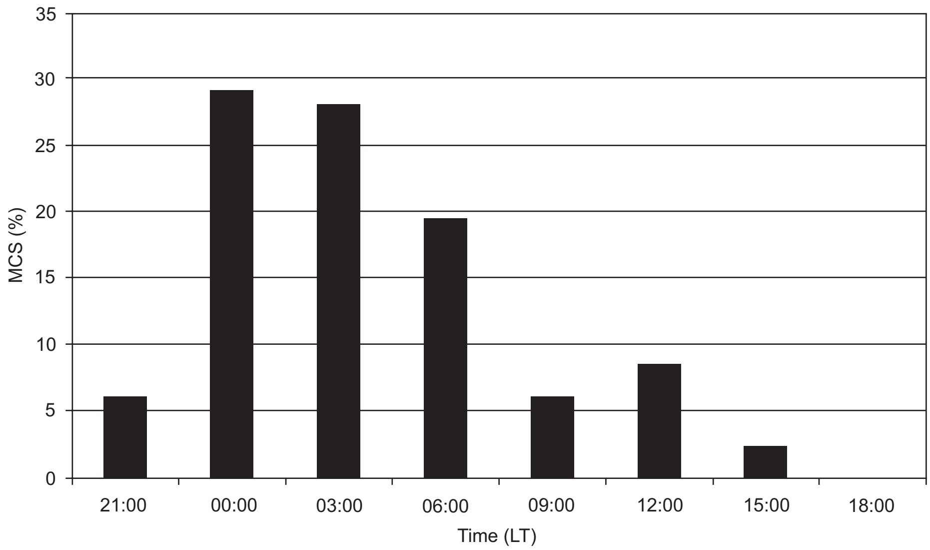

Fig. 10. Histogram of MCS extinction time at Local Time (UTC–6 hours).

The organization of convection was studied in only 20 of 82 MCSs that developed, corresponding to those that passed through the radars composite area and had available soundings at the right location and time. For the period of study, 70% (14) of the analyzed systems were classifiable in wind shear categories shown in Figure 11 and Table III. This is comparable to the 68% found by Johnson *et al*. (2005), during South China Sea Monsoon Experiment (SCSMEX), indicating relatively similar kinematics and thermodynamics characteristics between these regions. Figure 12 shows a radar image with a shear-parallel convective line.

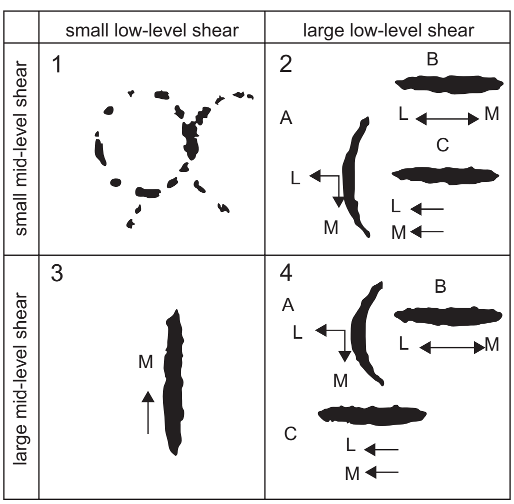

Fig. 11. Schematic depiction based in Lemone *et al*. (1988) and Johnson *et al*. (2005) of main categories of MCS convective organization for given vertical wind shear at low-level (0-2.5 km) and midlevel (2.5-6.0 km). Arrows marked L or M shows shear vectors for lower layer and middle one, respectively.

Table III. Types of mesoscale organization of convection using radar images.

Type	Description
1	Scattered convective cells with little intervening stratiform precipitation and no apparent spatial organization over a mesoscale region.
2A	A convective line (35 dBZ) with length >100 km for at least 1 hour, with its orientation perpendicular to the large low-level wind shear (>4 m/s) and parallel to the small mid-level wind shear (<5 m/s).
2B	A convective line (35 dBZ) with length >100 km for at least 1 hour, with its orientation parallel to the large low-level wind shear (>4 m/s) and antiparallel to the small mid-level wind shear (<5 m/s).
2C	A convective line (35 dBZ) with length >100 km for at least 1 hour, with its orientation parallel to the large low-level wind shear (>4 m/s) and parallel to the small mid-level wind shear (< 5 m/s).
3	A convective line (35 dBZ) with length >100 km for at least 1 hour, with its orientation parallel to the mid-level wind shear and large mid-level wind shear (>5 m/s) and small low-level wind shear (< 4 m/s).
4A	A convective line (35 dBZ) with length >100 km for at least 1 hour, with its orientation perpendicular to the large low-level wind shear (>4 m/s) and parallel to the small midlevel wind shear (>5 m/s).
4B	A convective line (35 dBZ) with length >100 km for at least 1 hour, with its orientation parallel to the large low-level wind shear (>4 m/s) and antiparallel to the large mid-level wind shear (>5 m/s).
4C	A convective line (35 dBZ) with length >100 km for at least 1 hour, with its orientation parallel to the large low-level wind shear (>4 m/s) and parallel to the large mid-level wind shear (>5 m/s).
U	Unclassifiable.

Line speed and difference between line speed and 700 hPa orthogonal wind were different between classifiable and unclassifiable MCSs, being statistical significant (t-Student test, probability = 0.05 and degrees of freedom = 18). Line speed was greater for classifiable than unclassifiable systems (Table IV). In addition, 38% of the classifiable convective lines were moving at speeds greater than 7 m/s,

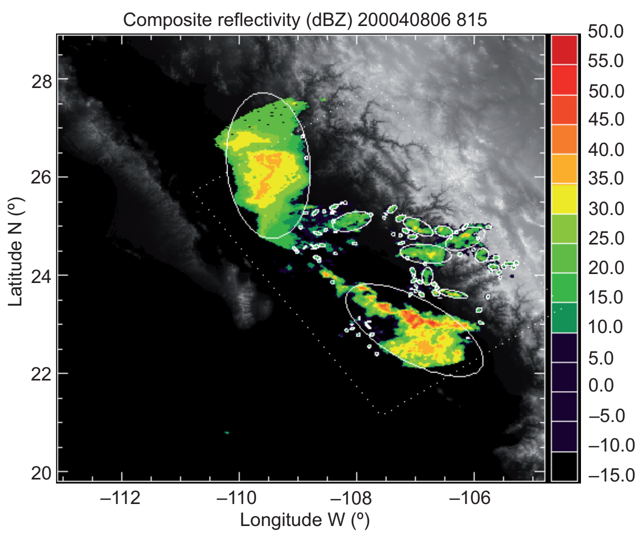

Fig. 12. Regional composite of radar reflectivity (dBZ) of the southern portion of NAME core region at 8:15 UTC August 6, 2004, which is showing a shear-parallel convective line, category 4C. Source: Colorado State University radar meteorology group.

Table IV. MCS kinematic and thermodynamic parameters.

Date of MCS	Type of organization	Wind shear 0-2.5 km (°/ms^{-1})	Wind shear 2.5-6 km (°/ms^{-1})	Line orientation (°)	Line motion (°/ms^{-1})	Normal wind at 700hpa (m/s)	Zonal wind 700hpa (m/s)	CAPE (J/kg)	CIN (J/kg)	Lifted index	Precipitable water (cm)	MCS duration (hours)
13/08/04	4ª	79.0/10.9	323.3/6.2	337.5	66.2/7.6	2.7	–4.1	1760	93	–4.4	5.03	15.0
06/08/04	4C	48.3/7.0	97.6/8.2	345	136.5/6.1	5.2	–4.2	578	252	–2.6	4.3	14.1
11/07/04	4C	88/10.7	5.7/6.9	120	327/4.6	–6.8	–5.6	342	642	–2.6	3.38	6.0
01/08/04	4B	31.3/10.5	168.2/9.5	337.5	102.4/2.9	1.6	1.4	1479	124	–3.1	5.72	7.0
21/07/04	4B	6.6/6.4	118.4/6.8	315	27.4/12.6	1.5	–4.6	1622	107	–6.4	5.7	13.0
17/07/04	4B	8.3/5.8	111.2/8.0	337	77.7/5.7	2.1	–3.7	1286	217	–5.6	4.6	4.0
12/07/04	4ª	88.3/9.7	335.1/12.4	325	74/7.2	5.2	–4.9	462	370	–3.3	4.2	6.0
03/08/04	2ª	112.5/9.5	31.1/2.3	45	140.1/8.0	7.5	–7.1	703	252	–5.2	5.1	23.0
06/08/04	2ª	44.8/5.4	135.0/3.5	305	57/5.2	3.3	–4.8	839	153	–3.3	5.19	12.0
09/08/04	2C	68.6/7.8	35/2.7	325	90/3.4	2.0	–2	807	272	–4.7	5.26	6.0
12/08/04	3	50.7/3.5	74.2/8.0	310	42/5.5	0.6	1	1363	37	–5.5	5.15	6.0
16/07/04	2B	91.3/9.3	324.8/2.7	292.5	90.0/2.7	0.8	–1	2807	107	–6.0	4.64	5.0
08/08/04	2C	87.5/5.4	123.7/2.1	300	90/8.3	5.0	–5	1016	246	–5	5.29	5.0
29/07/04	1	32.6/4.0	7.9/0.8	135	335/1.2	4.9	1	791	119	–2.9	4.1	8.0
10/07/04	U	100.0/7.8	84/1.9	0	151/4.2	6.2	–2.9	1995	335	–3.6	4.7	7.0
18/07/04	U	357.3/7.2	137.3/5.4	315	17.0/2.8	3.2	–4.9	1151	226	–5	4.55	4.0
27/07/04	U	121.3/2.3	109.5/8.0	315	115/1.8	4.3	–3.9	1079	188	–4.9	4.12	6.0
15/07/04	U	67.8/4.1	26.1/4.9	170	343/0.5	0.4	0.9	789	158	–3.4	5.29	7.0
02/08/04	U	133.8/10.1	101.3/3.9	330	126.7/2.0	5.5	–2.7	690	213	–1.9	4.41	5.0
13/07/04	U	80/5.4	39/6.6	315	85.1/2.8	5.1	–5.2	1518	227	–5.4	4.56	9.0

the threshold suggested by Barnes and Sieckman (1984) to consider convective lines as squall lines, and similar to the percentage of squall lines found by Lemone *et al*. (1998) in COARE. Only those that moved faster than the 700 hPa environmental normal wind speed were classifiable as Keenan and Carbone (1992) found in Australia. Other differences, but not statistically significant, were midlevel wind shear direction, MCSs duration and low-level wind shear magnitude, which were larger for the classifiable systems than the unclassifiable ones. In contrast, midlevel normal wind speed (700 hPa) was smaller for the classifiable systems than the unclassifiable ones.

For classifiable systems, line speed had good correlation (–0.64) with 700 hPa zonal wind, indicating that strong easterlies winds implied faster lines, as was also found by Farfán and Zehnder (1994) in this region. On the other hand, we did not find correlations between line speed and thermodynamics parameters, like CAPE or CIN, similar to Alexander and Young (1992) and Lemone *et al*. (1998), indicating the importance of kinematic parameters on line speed instead of thermodynamics ones. Nevertheless, there were good correlations between MCS direction of motion and precipitable water (–0.73) and line orientation (–0.71), indicating that southwestward moving MCS found more moisture and had their orientation parallel to the SMO. Therefore, these mountains have a huge influence on MCS genesis and development as was also suggested by Nesbitt *et al* (2008) and Smith and Gall (1989). Most of the classifiable MCSs moved in the same direction of the low-level wind shear vector, except category 4C that moved with the midlevel wind shear vector and category 4B that moved in a direction between these two wind shear vectors (Tables III and IV).

Most of analyzed MCSs were shear-parallel (69%), a slightly greater percentage than those found in SCSMEX (61%) by Johnson *et al*. (2005). That is probably due to the particular position of the midlevel shear with respect to the low-level shear in this region, which has great influence on line orientation according to Robe and Emmanuel (2001). In particular, when midlevel wind shear was large, the angle between midlevel and low-level shear was not favorable for the development of shear-perpendicular lines. Only when large wind shear was constrained to the lowest level, shear-perpendicular lines were possible, as was also noted by Smith and Gall (1989).

Most of shear-parallel lines, categories 2A and 4A (Tables III and IV), were like the squall lines called “fast movers” by Barnes and Sieckman (1984), because they had propagation speeds greater than 7 m/s, the longest lifetime, and moved in the same direction and speed of the low-level shear. In addition, their direction of motion was mainly from the northeast, indicating the great influence of the SMO in their genesis and development. Furthermore, the difference between line speed and 700 hPa environmental normal wind speed was slightly positive, indicating that they were in a critical or balanced state, as defined by Keenan and Carbone (1992), with an optimal wind shear balancing the buoyancy production of cold pool, consistent with the concepts of Rotunno *et al*. (1988).

Shear-parallel lines, categories 2B, 2C, 3, 4B and 4C (Tables III and IV), had shorter lifetime and smaller 700 hPa environmental normal wind speed than shear-perpendicular lines. Therefore, they were in an imbalanced-propagating state (Keenan and Carbone, 1992), with less than optimal wind shear to balance the buoyancy production of cool pool (Rotunno *et al*., 1988). In addition, we observed shear-parallel lines with secondary or multiple bands forming or rotating with time, when the midlevel shear direction was in the opposite direction of line orientation (category 4B Tables III and IV). Therefore, midlevel wind shear direction and magnitude were important in the formation and organization of convection of MCS in this region, as was also found by Finch and Johnson (2010).

4. Conclusions

During NAME in 2004, 82 MCSs formed in a lightly more active season than normal, due to a more southward than normal position of the 500 hPa ridge. Inactive periods were characterized by southwesterly midlevel winds in Northwestern Mexico, while active periods by easterly midlevel winds. MCS initiation time was mostly between afternoon and evening and their extinction time was after midnight, with mean MCS duration of 7.46 hours.

Ridges and inverted troughs greatly influenced MCSs formation in this region, while tropical cyclones had little influence. The Sierra Madre Occidental has a large influence in the MCSs genesis and development in Northwestern Mexico.

Most of analyzed convective lines in this region were classifiable (70%), with a large fraction of shear-parallel lines (69%). Not only the magnitude and direction of the midlevel and low-level wind shear vectors were important to MCSs morphology, as seen in weather radar images, but also the angle between these two wind shear vectors. Kinematic parameters were more important to MCS morphology than thermodynamic ones.

Acknowledgements

We would like to acknowledge to Richard E. Carbone from the National Center for Atmospheric Research (NCAR) for the invitation to participate in 2004 NAME field campaign. We also thanks the S-Pol radar team located in La Cruz de Elota, Sinaloa: David Ahijevych, Jonathan Lutz and Mitchell Randall, from NCAR, Steven Rutledge, Richard Johnson, P. E. Ciesielski, Robert Cifelli and Timothy Lang, from Colorado State University and Steve Nesbitt and Mathew Gilmore from University of Illinois at Urbana-Champaign. In addition, we would like to thank to the anonymous reviewers whose suggestions were very useful to improve this manuscript.

References

Alexander G. D. and G. S. Young, 1992. The relationship between EMEX mesoscale precipitation features properties and their environmental characteristics. *Mon. Wea. Rev*. **120**, 554-564.

Barnes G. M. and K. Seickman, 1984. The environment of fast and slow-moving tropical mesoscale convective cloud lines. *Mon. Wea. Rev*. **112**, 1782-1794.

Bartels D. L., J. M. Skrasdki and R. D. Menard, 1984. Mesoscale convective systems: A satellite climatology. NOAA Tech. Memo, ERL ESG 8, Department of Commerce, Boulder, CO, 63 pp.

Bluestein H. B. and M. H. Jain, 1985. Formation of mesoscale lines of precipitation: Severe squall lines in Oklahoma during the spring. *J. Atmos. Sci*. **42**, 1711-1732.

Douglas A. V., R. Blackmon and P. J. Englehart, 1986. Mesoscale convective complexes in extreme western Mexico: A regional response to broadscale drought. Proceedings Tenth Annual Climate Diagnostics Workshop, US Department of Commerce, NOAA, Boulder, USA, 129-140.

Douglas A. V. and P. J. Englehart, 2007. A climatological perspective of transient synoptic features during NAME 2004. *J. Climate* **20**, 1947-1954.

Englehart P. J. and A. Douglas, 2001. Eastern north Pacific tropical storms and the rainfall climatology of western Mexico. *Int. J. Climatol*. **24**, 350-362.

Farfán L. and J. Zehnder, 1994. Moving and stationary mesoscale convective systems over northwest Mexico during the Southwest Area Monsoon Project. *Weather Forecast.* **9**, 630-639.

Finch Z. O. and R. H. Johnson, 2010. Observational analysis of an upper-level inverted trough during the 2004 North American Monsoon Experiment. *Mon. Wea. Rev*. **138**, 3540-3555.

Hashem M. S., 1996. A climatology of springtime convective systems over the Northwest Gulf of Mexico and adjacent coasts. Master's degree thesis, Texas A&M University, College Station, TX.

Higgins W., A. Douglas, A. Hahmann, H. E. Berbery, D. Gutzler, J. Shuttleworth, D. Stensrud, J. Amador, R. Carbone, M. Cortez, M. Douglas, R. Lobato, J. Meitin, C. Ropelewski, J. Schemm, S. Schubert and C. Zhang, 2003. Progress in Panamerican CLIVAR Research: North American Monsoon System. *Atmósfera* **16**, 29-63.

Houze, R. A. Jr., B. F. Smull and P. Dodge, 1990. Mesoscale organization of springtime rainstorms in Oklahoma. *Mon. Wea. Rev*. **118**, 613-654.

Howard K. W. and R. A. Maddox, 1988. Mexican mesoscale convective systems- A satellite perspective. Proceedings of Third Int. American and Mexican Congress of Meteorology, Mexico City, Mexico, Mexican Meteorological Organization, 404-408**.**

Jirak I. L., W. R. Cotton and R. L. McAnelly, 2003. Satellite and radar survey of mesoscale convective system development. *Mon. Wea. Rev*. **131**, 2428-2449.

Johnson R. H., S. A. Aves, P. E. Ciesielski and T. D. Keenan, 2005. Organization of oceanic convection during the onset of the 1998 east Asian summer monsoon. *Mon. Wea. Rev*. **133**, 131-148.

Johnson R. H., P. E. Ciesielski, B. D. McNoldy, P. J. Rogers and R. K. Taft, 2007. Multiscale variability of the flow during the North American Monsoon Experiment. *J. Climate* **20**, 1628-1648.

Kalnay E., M. Kanamitsu, M. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne and D. Joseph, 1996. The NCEP/NCAR 40-year reanalysis project. *B. Am. Meteor. Soc.* **77**, 437-431.

Keenan T. D. and R. E. Carbone, 1992. A preliminary morphology of precipitation systems in tropical northern Australia. *Q. J. Roy. Meteor. Soc.* **118**, 283-326.

Lang T. J., D. A. Ahijevych, S. W. Nesbitt, R. H. Carbone, S. A. Rutledge and R. Cifelli, 2007. Radar-observed characteristics of precipitating systems during NAME 2004. *J. Climate* **20**, 1713-1733.

Lemone M. A., E. J. Zipser and S. B. Trier, 1998. The role of environmental shear and thermodynamic conditions in determining the structure and evolution of mesoscale convective systems during TOGA COARE*, J. Atmos. Sci*. **55**, 3493-3518.

Mohr K. and E. Zipser, 1996. Defining mesoscale convective systems by their 85 GHz Ice- Scattering Signatures. *B. Am. Meteor. Soc.* **77**, 1179-1189.

Nesbitt S. W., D. J. Gochis and T. J. Lang, 2008. The diurnal cycle of clouds and precipitation along the Sierra Madre Occidental during the North American Monsoon Experiment: Implications for precipitation estimation in complex terrain. *J. Hydromet*. **9**, 728-743.

Parker M. D. and R. H. Johnson, 2000. Organizational modes of midlatitude mesoscale convective systems. *Mon. Wea. Rev*. **128**, 3413-3436.

Pytlak E., M. Goering and A. Bennet, 2005. Upper tropospheric troughs and their interactions with the North American Monsoon. 19th Conference in Hidrology AMS, San Diego, USA, January 2005.

Robe F. R. and K. A. Emmanuel, 2001. The effect of vertical wind shear on radiative-convective equilibrium states. *J. Atmos. Sci.* **58**, 1427-1445.

Rotunno R., J. B. Klemp and M. L. Weisman, 1988. A theory for strong, long-lived squall lines. *J. Atmos. Sci.* **45**, 463-485.

Smith W. P. and R. L. Gall, 1989. Tropical squall lines of the Arizona monsoon. *Mon. Wea. Rev*. **117**, 1553-1569.

Sosa Chiñas M. A. and A. Valdés-Manzanilla, 1999. ASMEIS: herramienta para el análisis de sistemas convectivos de mesoescala. 9th National Congress on Meteorology OMMAC, Guadalajara, Jalisco, México, 246-249.

Tang M. and E. R. Reiter, 1984. Plateau monsoons of the Northern Hemisphere: a comparison between North America and Tibet. *Mon. Wea. Rev.* **112**, 617-637.

Tripoli G. J. and W. R. Cotton, 1989. Numerical study of an observed orogenic mesoscale convective system. Part I: Simulated genesis and comparison with observations. *Mon. Wea. Rev*. **117**, 273-304.

Valdés-Manzanilla A., 2009. Estudio de los fenómenos meteorológicos que producen las lluvias monzónicas en las laderas occidentales de la Sierra Madre Occidental. Doctoral dissertation, Universidad Nacional Autónoma de México, Mexico City, 100 pp.