The influence of active meteorological systems on the ionospheric *F*-region

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Abstract
Effects on the *F* region of two active meteorological systems will be analyzed. These systems are known as Mesoscale Convective Complexes (MCCs). Ionospheric data from a vertical sounder located in Tucumán will be used. By comparing the behaviour of the *F* region parameters on the days before and after the MCC storm day, we see outstanding differences. These differences occur during night and dawn hours in both cases. The two phenomena show influences on the *F* region. One case shows an increase in electronic concentration followed by a decrease and the other shows the opposite effect. Gravity wave propagation from the top of clouds could be connected to these MCCs effects. Other possible physical mechanisms are also discussed.

Key words *MCCs – F-region – virtual height – electronic concentration*

1. Introduction

The first results on a relationship between the lower and upper atmosphere were presented in the 1950's. Bauer (1958) associated perturbations in the *F* region with hurricane occurrence. The same author studied with ionospheric sounders how the *F* region was perturbed when a cold front was passing over the station. Pierce and Coronitti (1966) proposed a mechanism by which acoustic-gravity waves would propagate from the top of thunderstorms clouds to ionospheric heights. There are studies that relate the influence of severe storms to *F* region parameters (Baker and Davies, 1969).

With the discovery in the 1990's of new high altitude atmospheric flashes excited by lightning (Sentman and Wescott, 1996), it has been corroborated that the interactions between the lower atmosphere and the upper atmosphere and ionosphere are greater than previously thought. These optical emissions are known, according to their physical characteristics as sprites, jets or elves. They are originated in the lower atmosphere over active meteorological systems, especially over Mesoscale Convective Complexes (MCCs). Different theories have been put forward to explain the influence of these phenomena on the *D* and *E* regions (Inan *et al.*, 1995).

To understand the behaviour of the atmosphere we need to look for interrelations among its different regions.

All the above findings allow us to study the possible influence of active meteorological systems known as MCCs on the ionosphere. Manzano *et al.* (1998) analyzed the influence of MCCs passing near or over Tucumán in the ionosphere. All of the MCCs analyzed showed an anomalous behaviour in the *F* region on the day of the tropospheric storm.

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Following the first studies of the influence of MCCs on the ionosphere due to Manzano *et al.* (1998), we analyzed more MCCs crossing or passing near Tucumán, located at 26.9°S and 65.4°W.

2. The MCCs

An MCC is a subset of MCS (Mesoscale Convective Systems) readily observed using infrared satellite imagery. This particular type of display of satellite data provides contrasting shades of black, gray and white to indicate specific ranges of temperature.

Maddox (1980) defines an MCC as a complex of thunderstorms whose continuous cold-cloud shield (observed in enhanced infrared satellite imagery) achieves an areal extent of at least 10^5 km^2 at $T = -32\,°C$ (convective precipitation begins to accumulate when $T < -32\,°C$) and 50000 km^2 at $T = -52\,°C$ (to ensure that the system is convectively active and the precipitation is falling over a significant area) and exceeds these thresholds for at least 6 h. The 6 h minimum duration allows time for the Coriolis effect to act on mesoscale perturbations. An additional criterion requires that the ratio of the minor axis to the major axis of the cloud shield at maximum areal extent be not less than 0.7, the cold-cloud shield being quasi-circular. MCCs usually occur during spring and summer months in both hemispheres. The MCC typically forms in association with a weak mid-tropospheric short-wave trough and a weak surface front or outflow boundary. Known for their production of severe weather and copious rainfall, the population of MCCs has been documented in practically all regions of the world.

Velasco and Fritsch (1987) typified South American MCCs during 1981 to 1983. For every MCC the times of First Storms (FS), Initiation (I), Maximum Extension (ME) and End (E) are given. In the FS stage a number of individual thunderstorms develop within a region where conditions are favourable for convection. Latent heat release and compressional warming in the near environment may combine to produce a region of anomalous warming. In the initiation stage, the environment begins to respond to the presence of the anomalously warm region and a layer of mid-tropospheric inflow develops. Strong, low-level inflow of moist, unstable air continues and the system grows rapidly. In the ME stage the cold cloud shield reaches maximum size. The end of the MCC is marked by a rapid change in the character of the MCC, it loses its mesoscale organization and appears chaotic in the infrared imagery.

The north of Argentina, where Tucumán is located, is a region frequently affected by the development of MCCs.

3. Data analysis

Manzano *et al.* (1998) analyzed nocturnal MCCs with no geomagnetic activity. In this study we present two cases: April 24/25, 1982 (MCC 1) and December 20/21, 1981 (MCC 2). The last one is similar to those analyzed by Manzano and the other is fully developed during daylight, with moderate geomagnetic activity soon after the end of the MCC.

The tracks of the centroids of these two MCCs are drawn in fig. 1. The full circles indicate the location of the MCCs at their Maximum Extension (ME). Tucumán station is also located in this figure.

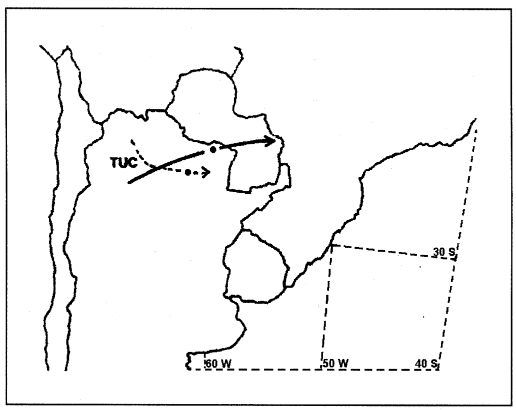

Fig. 1. Centroid tracks of the MCCs analyzed: MCC 1 (dashed line) and MCC 2 (solid line). Full circles indicate MCCs maximum extension.

In order to study the possible effects of MCCs on the ionosphere, we analyze ionospheric data from a vertical ionosonde located in Tucumán. *F* region critical frequency, f_0F_2, and ionogram virtual heights of reflection at fixed frequencies are used to study the behaviour of the ionosphere. Data were taken every 30 min for MCC 1 and every 15 min for MCC 2.

MCC 1 is a non typical one, since it occurs in a fall month and its development takes place during daylight. The FS appear at 09:00 LT and the MCC reaches its ME at 21:00 LT, ending at 00:00 LT. In general, the MCCs tend to reach their ME in the middle of the night, ending soon after dawn. The first storms develop directly above Tucumán. The centroid of the MCC at its ME is located at 26.5°S and 61.0°W. The area at its maximum extension reaches a value of 2.3×10^5 km^2. Due to its circular shape we can estimate the radius of the MCC at its ME, obtaining a value of approximately 300 km.

Analyzing the data we find that the ionospheric values are normal during the development of the MCC. But before it finishes we start to see some effects in the values of the storm day. So, in fig. 2a-c we show the behaviour of the ionosphere for night and dawn hours. The *x* axis represents LT. The development of the MCC occurs during April 24/25. Figure 2a shows data for the period April 23/24, the day before the development of the MCC. Figure 2b corresponds to the storm day and fig. 2c shows data the day after the storm. f_0F_2 is also drawn in a thick line.

We consider fig. 2a as representing a normal ionosphere with typical minimum critical frequency for April. The absence of data for virtual heights at 5, 6 and 7 MHz indicates a very low electronic concentration. After the storm day it seems that the virtual heights and f_0F_2 return to their normal values.

Storm day data show clearly that, compared to normal values, there is first a decrease in f_0F_2 values and an enhancement in virtual heights. Immediately after there is an increase in f_0F_2 and a decrease in virtual heights. This is more clearly seen superposing the three critical frequency curves. In a similar way we superpose the curves corresponding to the differences in virtual heights for 6 and 5 MHz. These curves are shown in fig. 3a,b.

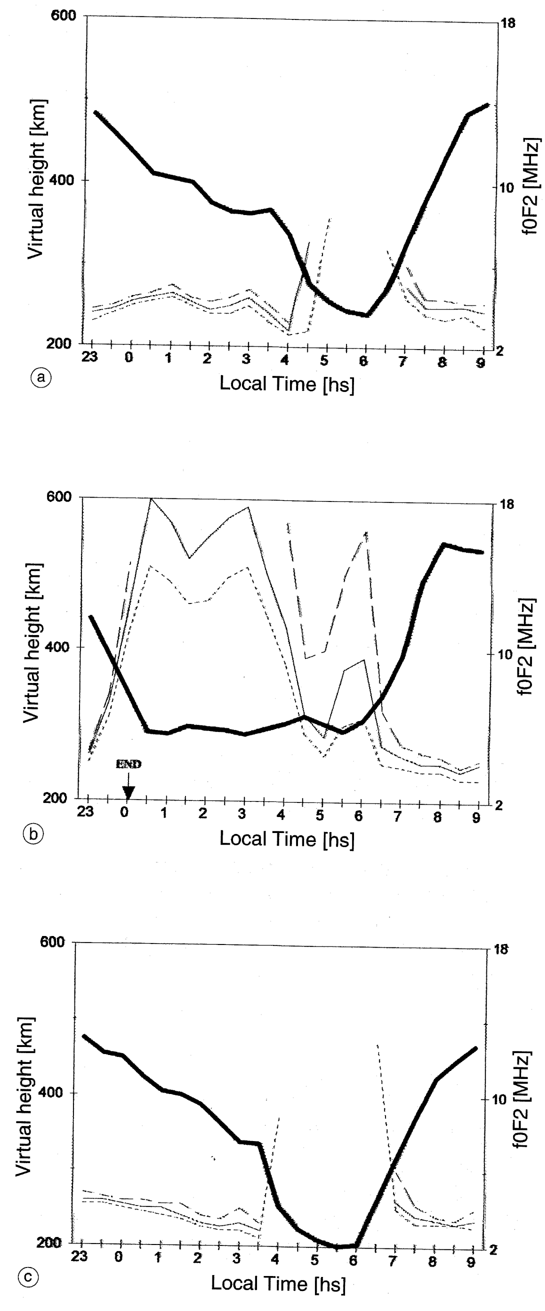

Fig. 2a-c. f_0F_2 (thick line), *h'F* at 5 MHz (dotted line), *h'F* at 6 MHz (solid line), and *h'F* at 7 MHz (dashed line) for the dates: a) April 23/24; b) April 24/25 (storm day); and c) April 25/26.

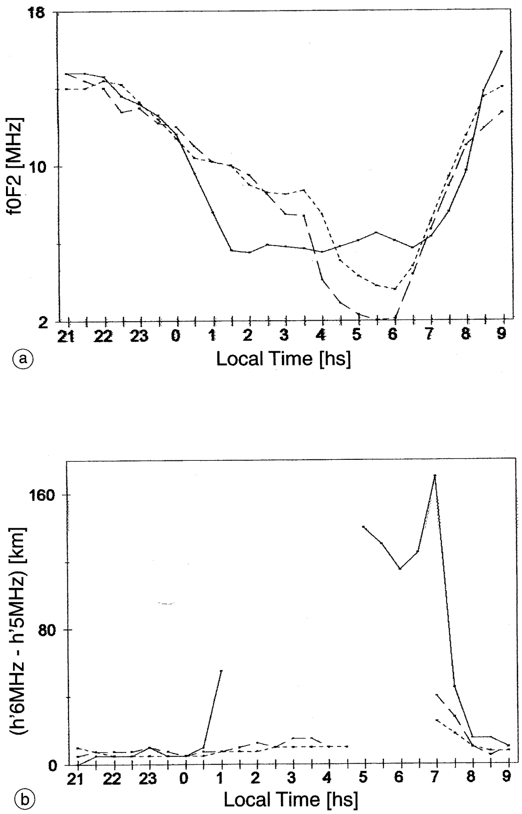

Fig. 3a,b. Dates: April 24/25, corresponding to the storm day (solid line), April 23/24 (dotted line), and April 25/26 (dashed line), for the parameters (a) f_0F_2 and (b) difference between $h'F$ at 6 MHz and $h'F$ at 5 MHz.

The decrease in f_0F_2, or the enhancement in differences of virtual heights, occurs during 23:30 LT - 04:00 LT approximately. Immediately, there is an enhancement of f_0F_2 comparatively with the other days. This occurs until 06:30 LT. After this hour, the behaviour is similar for the three curves. This would indicate that first there is a decrease in electronic concentration or ionospheric expansion and then an increase in electronic concentration or a compression of the ionosphere.

It should be noted that as soon as the MCC finishes, there is a moderate geomagnetic storm

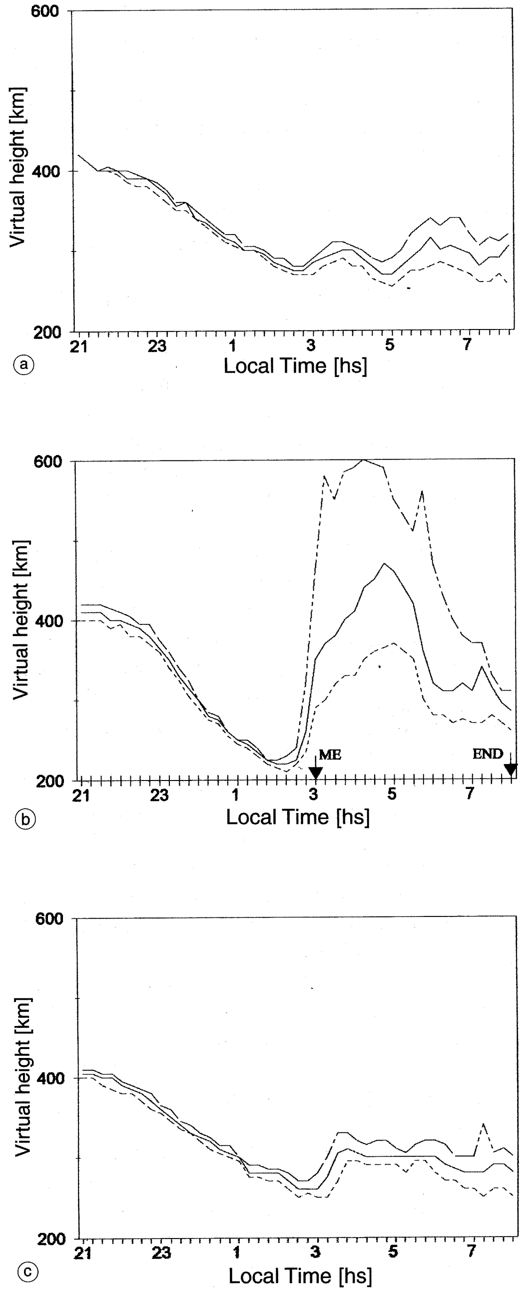

Fig. 4a-c. $h'F$ at frequencies 5 MHz (dotted line), 6 MHz (solid line), and 7 MHz (dashed line) for the dates: a) December 19/20; b) December 20/21; and c) December 21/22.

($D_{st} \approx -60/-70$ nT). The very low peak reached in f_0F_2 could be caused by this geomagnetic storm.

MCC 2 is a typical one, in the sense that its development takes place during the night, reaching its ME at 03:00 LT and ending at 08:00 LT. The location of the centroid of the MCC at its ME is 26.0°S and 60.0°W. With an area of 7.1×10^5 km^2, the radius of the MCC is approximately 500 km.

Data of f_0F_2 were not fully available. Fortunately they are available for the period in which we see the «abnormal behaviour».

Figure 4a-c shows virtual heights of reflection at fixed frequencies for the storm day. Since the curves are similar for the three periods during the first half of life time (17:00 LT - 08:00 LT) of the MCC, we show the data for the second half.

As in MCC 1, we see that during the storm day the ionosphere shows a different behaviour comparatively with the other days. Specifically we can see that there is an expansion of the F region because of the increase in virtual heights of reflection. This can be corroborated analyzing f_0F_2. In fig. 5 we see how f_0F_2 decreases during the storm day.

We can also see that the slope of the curves corresponding to the storm day in fig. 4a-c between 22:00 and 02:00 LT is steeper than that for the others days, reaching a minimum of approximately 200 km at 02:00 LT. f_0F_2 data for the compression time were not fully available.

The difference in virtual heights between the frequencies 5 and 6 MHz is shown in fig. 6, superposed on the three periods. This difference give us an idea of the thickness of the layer. It is clearly seen how this difference increases for the period in which f_0F_2 diminishes. The low virtual heights values reached in the storm day in the period 22:00 and 02:00 and the absence of changes in the differences for the same period could indicate that the F region has been compressed and reduced to a thin layer.

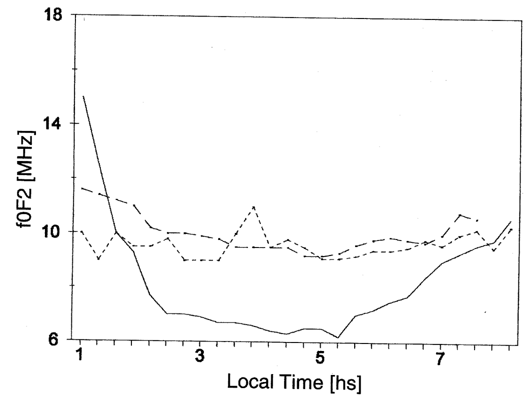

Fig. 5. f_0F_2 for the dates: April 23/24 (dotted line); April 24/25 (solid line); and April 25/26 (dashed line).

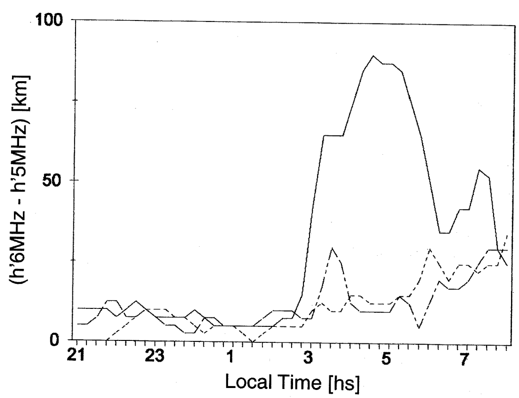

Fig. 6. Difference between $h'F$ at 6 MHz and $h'F$ at 5 MHz for the dates December 19/20 (dotted line); December 20/21 (solid line); and December 21/22 (dashed line).

4. Discussion

When we look for an explanation of these meteorological influences on the ionosphere, we have to take into account that there is more than one physical mechanism. It is known that lower regions of the atmosphere affect the ionosphere through electrodynamic interactions. These interactions involve:

1) Upward propagating waves: gravity waves may seed plasma instabilities that can be important in transferring energy and momentum, over a broad range of scale sizes, coupling large and small scale processes.

2) Dynamically induced composition changes: variations in the neutral dynamics in the lower atmosphere change the ionospheric electric potential, which maps into the *F* region along the highly-conducting magnetic field lines.

3) Upward lightning discharges known as «sprites» or «jets»: electrical discharges into the upper atmosphere are a mechanism for coupling the lower atmosphere with the ionosphere. The effects are observed mainly in *D* and *E* regions.

The mechanisms mentioned above are present when we talk about MCCs: 1) they are long-lived, lasting generally up to 13 h, and continuously produce new cells, being a permanent source of acoustic-gravity waves which propagate upwards; 2) such a huge system provokes motions of air masses, involving changes in the upper neutral air; and 3) sprites and jets are normal features above MCCs, but as was stated before their effects are limited to the lower ionosphere (*D* and *E* regions).

Manzano *et al.* (1998) proposed a mechanism based on the direction of propagation of the MCC. An MCC with meridional motion would expand the *F* region, while an MCC with zonal motion would compress the *F* region. This is explained stating that the movement of charged particles dragged by the neutral air depends on the geomagnetic field.

The two phenomena analyzed in this work have some influence on the ionospheric parameters. MCC 1 is an unusual MCC: it moves first from north to south (usually meridional MCCs move northward) and then eastward; its development takes place during daylight, and occurs in a fall month. Having a final west-east component we observe first an increase of electronic concentration and then a decrease.

MCC 2 has a north-east component, so the mechanism proposed by Manzano *et al.* (1998) could not fully apply. The results indicate that there is a decrease in electronic concentration followed by an increase.

Ionospheric ionization depends on atmospheric neutral density and on thermospheric temperature. Both of these parameters can be altered by gravity wave propagation into the lower ionosphere. Pasko *et al.* (1997) demonstrate that gravity waves launched by large area MCCs can lead to significant modulation of atmospheric density at mesospheric altitudes (tens of %). The wave energy dissipated is largely trapped at heights around 100 km, but some energy leaks upward to heights of 200-400 km.

Gravity waves can heat the neutral atmosphere through loss of the wave energy. This heating could lead to changes in electronic concentration. On a time scale of 10 h (mean life time of an MCC) the variation in the temperature of neutral air may be of the same order as the daily heating produced by solar radiation. In general we could say that when the neutral air temperature increases the electronic concentration decreases, possibly due to the increase in the recombination coefficients.

A deeper analysis regarding the propagation of acoustic-gravity waves is not possible due to the ionospheric data record frequency. We would need data every five or ten minutes in order to detect the presence of these waves in the *F* region.

MCC 1 shows in the storm day a first stage in which the slope of the f_0F_2 is steeper than the other days, indicating a huge loss of electrons. If we think that first the MCC has moved southward we could account for this behaviour with Manzano's explanation. The following compression could be explained by the final eastward movement of the MCC. An alternative explanation for the first effect observed would be a heating in the neutral atmosphere, due to gravity wave energy loss, that would cause a decrease of electronic concentration.

MCC 2 provokes first an ionospheric compression or increase in electronic concentration. In this case we could think that gravity waves could not propagate to ionospheric heights due to atmospheric conditions. At its ME a decrease in electronic concentration is observed that may be due to the direction of its motion or the heating of the neutral atmosphere.

5. Conclusions

1) The effects of MCC 1 are seen a few hours after the end of the storm, and MCC 2 effects are seen during its development, before it reaches its ME. The ionospheric parameter variations

occur during the night hours in both MCCs cases. This would indicate that the absence of a solar forcing would enhance MCCs influences.

2) The ionospheric effects caused by MCCs that do not have a pure meridional or pure zonal movement cannot be fully explained by the mechanism proposed by Manzano *et al.* (1998).

3) The influence in the ionosphere would depend on the end time of the MCC.

4) Effects due to changes in the neutral air composition would have to be added to Manzano's mechanism in order to explain the behaviour observed.

As we can see, the cause of the MCCs-ionosphere interaction is not fully or uniquely understood. We need to go deeper in order to establish the physical mechanism by which some tropospheric phenomena act on the ionosphere.

We also need to extend the study of the influence of MCCs in the ionosphere by analyzing lower ionosphere data, neutral density, tropospheric and stratospheric temperatures. More MCCs data all over the world would strengthen a statistical analysis.

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