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Migration monitoring of *Ascia monuste* (Lepidoptera) and *Schistocerca cancellata* (Orthoptera) in Argentina using RMA1 weather radar

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ABSTRACT

The meteorological polarimetric radar RMA1 located in the city of Córdoba was used for a nonconventional phenomenon detection. Massive migrations of both *Ascia monuste* during early summer of 2015 and *Schistocerca cancellata* during late winter of 2017 were characterized by means of polarimetric variables (correlation factor ρ_{hv} and reflectivity factor Z_H). The butterfly swarms show a pulsating behavior as a consequence of biological needs. The highest altitude detected was 2400 m msl. The correlation factor confirms the biological characteristic of the echo. The locust swarm migration shows a different pattern in several ways. First, it has a more uniform aspect regarding its displacement. Second, the locusts were observed to attain altitudes of 1700 m msl. Third, the correlation coefficient for the locust case showed regions with high values, which are different from the low value areas. It is concluded that radar observations of insect species may result in useful biological criteria for the government to asses areas that need to be protected for agricultural production.

1. Introduction

Weather radar echoes from insects have been used in migration studies; however, with recent radar polarimetric capabilities the reliability of the observations has increased (Irwin et al., 1988; Nieminen et al., 2000; Lang et al., 2004; Leskinen et al., 2011). Insects migrate in order to find suitable habitats for feeding, mating and producing the next generation (Wood, 2007). The migration of insects, which takes place in adult stage, is greatly facilitated by wind. It should be noticed that weather conditions have a strong effect on take-off, flight and landing. The migrant insects sometimes fly up to 2 or 3 km above the ground (Chapman et al., 2011). Pest insects, (locusts, armyworms, cutworms, bollworms), which are capable of long-range migrations are common, and may cause most of the losses in agricultural production (Leskinen et al., 2011). In southern South America, particularly Argentina, two insect species considered important pests, and also reported as migrant are the white butterfly *Ascia monuste* (Linnaeus, 1764) (Lepidoptera) and the South American swarming locust *Schistocerca cancellata* (Serville, 1838) (Orthoptera).

A. monuste is distributed from southern North America and Antilles to southern South America with at least seven subspecies and several forms. The adults have a medium size (length of wingspan = 63–86 mm), in laboratory conditions the life-cycle average is almost 32 days, and the adults longevity average is almost 19 days (Liu, 2005; Lauranzón-Meléndez et al., 2010). The caterpillars are one of the most important consumers of Brassicaceae and some subspecies are listed as pests of cruciferous vegetables. The adults frequently migrate from the breeding areas looking for food for their next generation (Barros-Bellanda and Zucoloto, 2003). Migrations have been reported before by Hayward (1953),Mather (1953) and Lauranzón-Meléndez et al. (2010) in different parts of South America. In Argentina, the subspecies *A. monuste automate* was reported several times to have migrant behavior. However, these reports are over 30 years old (Hayward, 1931a,b,c, 1953, 1955, 1964, 1969, 1972), except for a recent massive southward migration reported in northwestern Argentina in 2006 and 2008 (Navarro pers. com.). Another non-massive migration was observed in 2014 in the center of Argentina by the Beccacece and Drewniak (pers. comm) authors. In this case, the butterflies

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flew upper canopy with a fixed southwestward movement. All these reports were made just by field observations.

S. cancellata has been considered a dangerous pest in Argentina, especially in the past century where it produced significant economic damage (Gastón, 1969; Liebermann, 1948, 1972; Köhler et al., 1979; Hunter and Cosenzo, 1990; Sánchez et al., 1997; de Wysiecki, 2005). This locust has a wide geographic distribution which covers central and northern Argentina, Uruguay, Paraguay, southern Brazil, south-eastern Bolivia and central and northern Chile (de Wysiecki, 2005; Pelizza et al., 2012). Adults have a large size (length of male = 28–49 mm, female = 39–66 mm), and immature and mature stages are polyphagous, feeding on a variety of native plants and different crops (de Wysiecki, 2005).

In Argentina, *S. cancellata* presents two generations per year: an overwintering generation from May to September-October and a second generation from October to November (Barrientos-Lozano et al., 2013). The permanent breeding area is located in the northwestern provinces (southern Catamarca, southern and eastern La Rioja, northern Córdoba and southwestern Santiago del Estero). There is an annual cycle of migration and breeding within the invasion area that is strongly influenced by weather and seasonal variations (Waloff and Pedgley, 1986; Song, 2010).

The swarming locusts have been controlled under different pest management programs, and there were no reports of swarm locust migration except for some in 1961, 1989, 2010, and 2015 (Barrientos-Lozano et al., 2013). The latter locust swarming was reported to have an extent of 25 km^2 and the movement was from the breeding areas to North-central Argentina (Medina, 2016). This paper is organized as follows. First, migration processes of both species are reviewed. Second, an introduction to the radar RMA1 is presented. Third, previous weather radar migration observations are shown. Next, Section 5 describes the actual RMA1 measurements of both species and the results analyzed from both biological behavior and physical scattering process. Finally, a number of conclusions are presented.

2. Insect migration studies in South America, with emphasis in Argentina

Billions of insects of the same or different generations migrate within and between continents every year to find new breeding areas, seasonally optimal habitats, sources of food, mating or avoidance of predators (Shamoun-Baranes et al., 2014; Holland et al., 2006). Distances traveled are generally accomplished by flight and as mentioned before the weather has a strong effect on large-scale migratory movements (Leskinen et al., 2011; Chapman et al., 2011). The latter have serious implications for humans, such as losses in agricultural production by pests or ecosystem services such as crop pollination (Leskinen et al., 2011; Holland et al., 2006; Westbrook et al., 2016). Current studies of migratory insects are carried out in Europe, Africa, Asia, Australia, North America, and Central America (Chapman and Drake, 2010).

To these authors knowledge, in South America there are only a few outdated studies about migratory insects. Such as, the migration of the diurnal moth *Urania fulgens* (Walker, 1854). This species can fly thousands of kilometers from southeastern Mexico to Ecuador (Dudley and Srygley, 2008; Srygley and Dudley, 2008). The fall armyworm *Spodoptera frugiperda* (Smith, 1797) is noted for its long distance flight capabilities in the western hemisphere, and genetic studies showed that there are similarities of the haplotypes in both North and South America (Nagoshi et al., 2017). The moth *Agrotis ipsilon* (Hufnagel, 1766) has been recorded to migrate to the sub-Antarctic island South Georgia from throughout the South American mainland (Bonner and Honey, 1987). Some butterflies were reported in Brazil to be a common migratory species in the Amazonian region (Negret, 1988). Also, several migrant butterflies over the Colombian Caribbean Sea were observed by Srygley (2001). A particular study was focused on the desert locust *S. gregaria* (Forskal, 1775) present in Africa, which amazingly migrated to South America in October and November, 1988. Different swarming of desert locusts invaded the Caribbean region and northern South America after a sea crossing of some 5000 km (Rosenberg and Burt, 1999). The swarming locust of tropical South America *S. piceifrons* (Walker, 1870) is known for an important migration from Peru, or from another unknown breeding area, to Ecuador, Colombia, and Venezuela (Harvey, 1983).

Table 1
Technical data of RMA1.

RMA1 Specifications	
Type	C-band radar system
Location	Lat:-31.441, Lon:-64.191
Radar elevation (MSL)	475 m
Operation frequency	5625 MHz
Pulse duration	0.4 to 3 µs
Max resolution	60 m @ 0.4 µs
Peak transmitted power	350 kW
Maximum range	240 km
Cell resolution	0.48 km
Beam elevations	12 elevations from 0.51 to 15.1°
Recorded fields	Horizontal Reflectivity (Z_H), Radial Velocity (V_D), Spectral width (W), Differential Reflectivity (Z_{dr}), Differential Phase Shift (ϕ_{dp}), Specific Differential Phase (K_{dp}), Correlation Coefficient (ρ_{hv})

Historical records of insect migrations in Argentina include the following studies: Hayward from 1925 to 1972 (Lamas, 2013), focused on migratory butterflies. These studies consisted on notes of behavior of migrant speed and direction pattern (Hayward, 1929, 1972). The migration of butterflies such as *Junonia genoveva* (Cramer, [1780]), *Libytheana carinenta* (Cramer, [1777]) and *Vanessa carye* (Hübner, [1812]) of the family Nymphalidae, and *A. monuste*, *Tatochila autodice* (Hübner, [1818]) and *Colias lesbia* (Fabricius, 1775) of the family Pieridae were reported (Hayward, 1953; Hayward, 1931c; Dallas, 1932; Orfila, 1932; Hayward, 1940; Gibson, 1947; West, 1993). All species were observed flying in a massive pack of individuals with a fixed movement, frequently from northern to southern Argentina.

Recent studies about insect migration that occurred in Argentina belong to four orders of insects: Coleoptera (weevils), Odonata (dragonflies), Lepidoptera (butterflies and moths) and Orthoptera (locust). Some species are potential crop pests while others are recognized as dangerous crop pests. Stadler and Buteler (2007) studied that the migration of *Anthonomus grandis* (Boheman, 1843) (Coleoptera: Curculionidae) tends to disperse during late summer and early fall matching the end of the cotton season, a process favored by high wind speeds. However, this can be considered as a dispersive passive-movement rather than a migration. von Ellenrieder (2003) observed a mass migration of hundreds of teneral *Rhionaeschna bonariensis* (Rambur, 1842) and *R. confusa* (Rambur, 1842) (Odonata: Aeshnidae) perching on bushes and grasses near the shore of the Rio de La Plata in February 1998. Malcolm and Slager (2015) and Slager and Malcolm (2015) evidenced a partial migration of *Danaus erippus* (Cramer, 1775) (Lepidoptera: Nymphalidae). These authors commented that *D. erippus* migrates with southward flight from northwest Argentina during the fall, especially in April. Finally, the migratory locust *Schistocerca cancellata*, a historical pest in Argentina, is currently monitored by the Secretaría Nacional de Sanidad Animal (SENASA) to prevent the potential damage from high density swarms to different crops (Latchininsky, 2013).

3. RMA1 - Radar Meteorológico Argentino 1

A weather radar is an instrument used to detect and characterize storms and other meteorological phenomena. Most weather radars

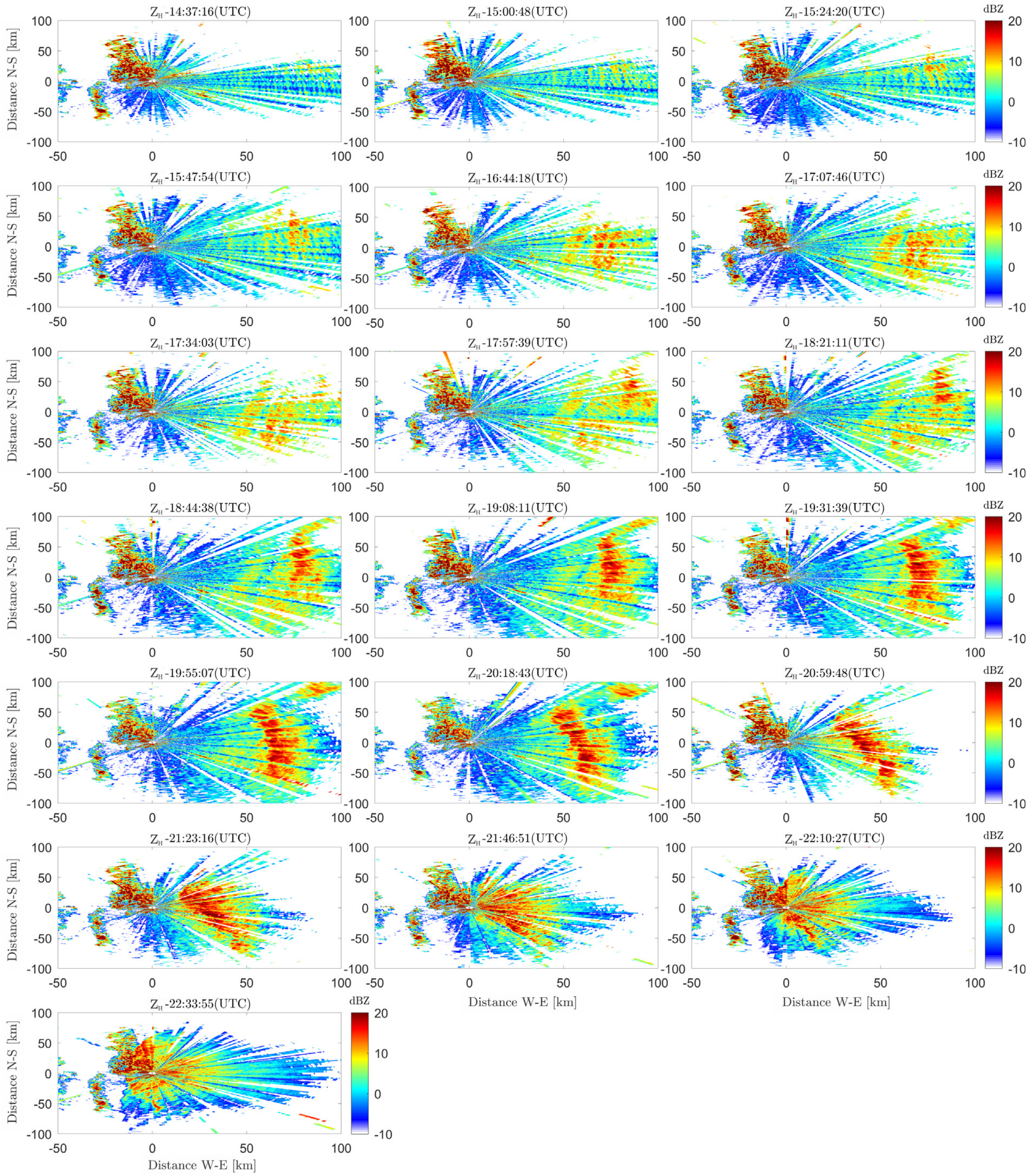

Fig. 1. Reflectivity factor sequence from RMA1 during 11/12/2015. The A. Monuste swarm shows an apparent westward movement towards the radar. Note that the wind direction was from the NNE sector according to National Meteorological Service.

transmit high power electromagnetic pulses dwelling about 1 µs and attaining power levels of the order of hundreds of KW's. The radar antenna emits these pulses to targets under observation which intercept and scatter part of the pulse energy, returning a small part of the order of some pW back to the radar. This received signal or echo is amplified, digitized and processed in the radar receiver, so it can be displayed and recorded. The time elapsed between the emission and the back-scattered signal reception is used to determine the target range since the pulse moves at the speed of light. The RMA1, is a C-band polarimetric Doppler radar located at the campus of the National University of Córdoba, Argentina (Lat:-31.441, Lon:-64.191). The RMA1 was manufactured by INVAP S.E., and it is capable of transmitting peak power pulses of 350 KW focused on an axisymmetric 3 dB beam of 1°. The radar emits both horizontal (H) and Vertical (V) polarizations simultaneously, allowing the calculation of 3D fields of several variables or parameters: horizontal and vertical reflectivity factors (Z_H and Z_V in $mm^6\ m^{-3}$), radial velocity V_D, spectral width W, differential reflectivity (Z_{dr}), phase difference (ϕ_{dp}), specific phase difference (K_{dp} in degrees per unit length) and correlation coefficient (ρ_{hv}). The coverage radius of successive volumes alternates between 480 km and 240 km. Table 1 exhibit a RMA1 characteristics.

Dual-polarization technology produces valuable information on the shape and nature of the detected target. The correlation coefficient (ρ_{hv} or RHOhv) provides a measure of the consistency of the shapes and

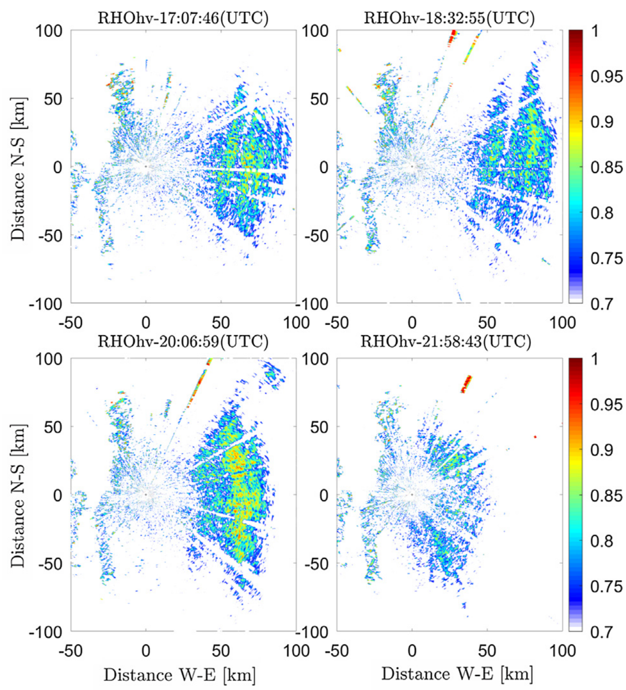

Fig. 2. Sequence of PPI1 scans of the correlation coefficient ρ_{hv}.

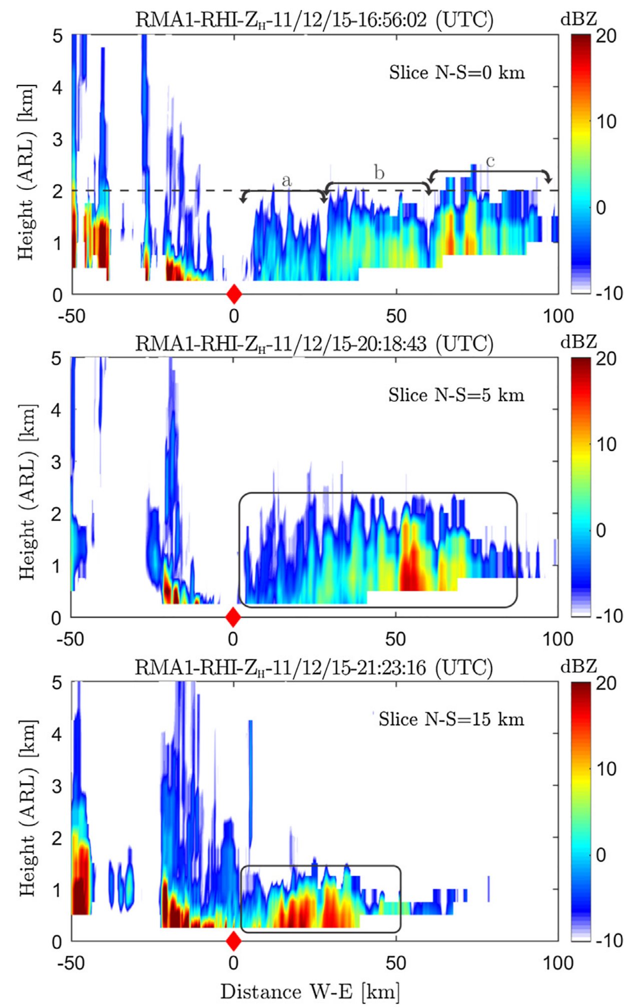

Fig. 3. Vertical slices of reflectivity factor at the indicated times. From top to bottom the intercept increases from 0 to 15 km. Note the presence of bands of butterflies (a), (b) and (c) in the top panel. These bands merge in the middle and bottom panels as indicated by the black rectangles.

sizes of targets within the radar beam. A higher value shows a higher consistency in the size and shape of radar targets while a lower value indicates greater variability in shapes and sizes. ρ_{hv} can be used to help to distinguish meteorological from non-meteorological targets, find the melting layer, identify giant hail, identify tornadic debris, and check the quality of other dual polarization variables.

Differential reflectivity (Z_{dr}) is the ratio of the horizontally polarized reflectivity to the vertically polarized reflectivity. Positive values of Z_{dr} indicate that dominant particles are larger in the horizontal dimension than in the vertical one and vice versa. Values near zero indicate that targets are similar in size in the vertical and horizontal dimensions.

Differential phase shift (ϕ_{dp}) is a measure of the difference in 2-way attenuation for the horizontal and vertical pulses in a radar volume. As vertical and horizontally polarized radar pulses pass through a particular set of targets, the both pulses become attenuated and slow down, which results in a change of each pulse's phase by different amounts. ϕ_{dp} manifest the difference in phase shift between the horizontal pulse and the vertical pulse. This provides information about the shape and concentration of radar targets. However, ϕ_{dp} values are cumulative along a particular radar radial, which makes it more difficult to interpret.

Specific differential phase (K_{dp}) is a derived product that shows the gradient along the beam of ϕ_{dp}. Positive K_{dp} values indicate greater phase shift in the horizontal polarization than in the vertical one. As a meteorological example, an increase in K_{dp} gives an indication of an increase in the size and concentration of rain drops and therefore, an increase in rain rate. This means that K_{dp} is useful for pinpointing areas where the heaviest rainfall is occurring.

4. Weather Radar insects observations

Since 1945 when Lack and Varley (1945) found some radar echoes in a clear day and named them "angels echoes", until Crawford (1949) found that birds were responsible for those echoes, many researchers have tried to identify biological backscatter using weather radars.

Zrnić and Ryzhkov (1998) used a polarimetric weather radar, with 10-cm wavelength, and alternating vertically and horizontally polarized waves in order to distinguish biological echoes using Z_{dr},ϕ_{dp}, and ρ_{hv}. Their observations revealed two types of echoes: one has a Z_{dr} up to 10 dB, and ϕ_{dp} has a value of less than 40°. The other echo type exhibits much lower Z_{dr}, between −1 and 3 dB and larger ϕ_{dp} over 100°. For both echo types, ρ_{hv} is between 0.3 and 0.5, which is significantly lower than for meteorological scatter. Zrnić and Ryzhkov (1998) concluded that the first type of echo is attributed to insects whereas the second one is likely caused by birds, although they did not validate these observations.

Bachmann and Zrnić (2007) reported Z_{dr} values from 10 to 27 dB for insects and 15 to 27 dB for birds, using a WSR-88D. Gauthreaux et al. (2008) used an ARMOR C band Doppler weather radar to measure birds and insects. Gauthreaux et al. (2008) observed Z_{dr} values from 0.2 dB to 45 dB, but they concluded that it is difficult to discriminate different types of biological reflectors in the atmosphere solely on the basis of reflectivity data.

Using a polarimetric weather radar located in Helsinki, Finland (Kumpula C-band), Leskinen et al. (2011) worked in an experimental setup to detect pest immigration. Their measurements had low Z_H values, between 0 and 5 dBZ, but high Z_{dr} values above +7 dB in most of the echoes. Leskinen et al. (2011) concluded that these values were due to the horizontal orientation of the elongated insect bodies. In 2013, the upgrade of the next-generation weather surveillance radars (NEXRAD) network in the United States to dual polarization was completed

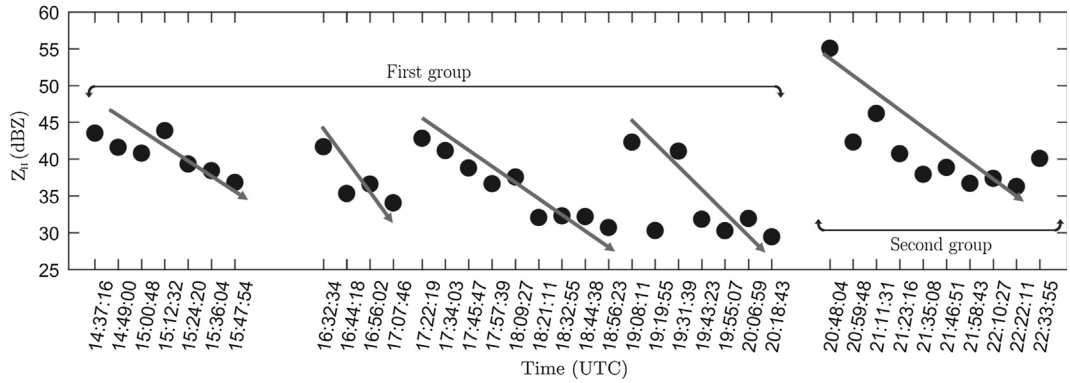

Fig. 4. Maximum reflectivity factor of the right half of each radar volume.

(Doviak et al., 2000), providing continental coverage of the airspace at ten-minute temporal resolution. This amount of quality controlled, archived, and freely-available data motivated biologists to study polarimetric radar products for biological interpretation. As an example, (Stepanian, 2015; Stepanian et al., 2016) worked with two datasets from the KHTX radar, both at an elevation angle of 0.5°. These authors observed two bird migrations, the first on May 3, 2015 at 05:05 Universal Coordinated Time (UTC) and the second on August 11, 2015 at 11:15 UTC when they detected purple martins (*Progne subis* (Linnaeus, 1758)), insects and weather.

It was concluded that automatic detection and classification of biological organisms will require the continued cooperation of biologists, meteorologists, computer scientists and radar engineers.

5. RMA1 observations

Radar observations of butterflies (*A. monuste*) were made on December 11, 2015 using a volume with 12 elevation angles: 0.5, 0.9, 1.3, 1.9, 2.3, 3.0, 3.5, 5.0, 6.9, 9.1, 11.8 and 15.1°. Gate resolution was 500 m, and maximum range was 240 km.

A different strategy was used for the observations of locust (*S. cancellata*) on August 21, 2017 this time with 15 elevation angles: 0.5, 0.7, 0.9, 1.3, 1.8, 2.3, 3.1, 4.0, 5.1, 6.4, 8.0, 10.0, 12.5, 15.6 and 20°, a gate resolution of 300 m and maximum range of 238 km. Each elevation angle is associated with a PPI scan numbered from PPI1 to PPI12 in the first strategy and from PPI1 to PPI15 in the second.

5.1. Ascia monuste observation

The swarm of *A. monuste* arrived at the city of Córdoba on December 11, 2015, which was a clear day as confirmed by both weather satellite and RMA1 radar. Fig. 1 describe to horizontal reflectivity factor (Z_H in dBZ) echo in a sequence during the day while the swarm approached the city of Córdoba from east to west. Each panel represents the PPI1 (lowest elevation angle) of the radar separated by approximately 24 min each. Initially, the swarm is not a uniform mass, but instead it is divided in different bands from 14:37 to 17:34 UTC (color ranging from orange to red with a medium concentration). Afterwards, the bands gather and concentrate into a single unit near the city from 17:57 to 21:23 UTC (red color with a high concentration). Gradually, the swarm starts to disappear from the radar image in the afternoon (from 21:46 to 22:33 UTC). According to (Kumjian, 2013) radar echoes that do not correspond to meteorological targets are characterized by a low correlation coefficient (ρ_{hv} < 0.80). This view is not held for biological targets by other researchers that using models of insects calculate ρ_{hv} > 0.90 according to their orientation with respect to the radar beam (Stepanian et al., 2016; Melnikov et al., 2015). This can be observed in Fig. 2 where four PPI1 scans of ρ_{hv} at different times are shown. In both figures, a fixed radar echo to the west of the RMA1 is observed associated with the mountain range called Sierras Chicas and Sierras Grandes oriented North - South with the nearest point at about 25 km. Fig. 3 presents a vertical slices at different times of the radar volume in west-east direction. The top panel shows a plane passing through the radar detection volume. The center panel exhibit a plane passing 5 km North of the radar while the bottom panel shows a plane 15 km North. This figure present a radar bands that suggest three well defined groups denoted by a, b and c, later joining in a single mass. The figure also evince a strong clutter to the west caused by the terrain. One important aspect seen in Fig. 3 is the altitude the swarm can reach. Top and middle panel suggest that butterflies can reach up to 2000 m Above Radar Level (ARL). Later on in the afternoon, the height of the swarming butterflies starts to diminish as seen in lower panel of the figure. Chapman and Drake (2010) suggested that butterflies migrations are in low-altitude. However, previous studies of migratory butterfly *Vanessa atalanta* (Linnaeus, 1758) indicate that flights may occur as high as 1000–3000 m (Mikkola, 2003). In agreement with the present results, Hayward (1953) reported a massive swarming of *A. monuste* in Argentina flying at about 1500 m or even higher. It may well be the case, therefore, that the paucity of records of butterflies at high altitude in windborne migrations is simply a consequence of the lack of appropriate methods for detecting this phenomenon (Stefanescu et al., 2007), which shows the importance of radar observations. Another important observation is the apparent pulsating intensity of the radar echo. The maximum of radar reflectivity factor values along the day determine a sort of sawtooth behavior with five different periods from 14:30 to 22:30 UTC with a mean of 25 min as seen in Fig. 4. The western half of the volumes where there is orographic clutter is ignored. The particular detection of the fluctuating weather radar echoes has a possible biological explanation. Some butterflies of the first group may have descended to feed from plants, to look for mates, and to find host-plants to oviposit while others continued their flight. The second group of butterflies may have joined the delayed butterflies of the first group which started to fly again at higher altitude after feeding. In the afternoon, the butterflies came down to seek shelter from the night in urban woodland.

This behavior was observed in the field the following days. In contrast to some specimens that came down to look for ornamental and native flowering herbaceous plants to feed, others continued their flight at high altitude. Also, butterflies had an oviposition behavior on different species of native Brassicaceae as well as crops of the same family such as arugula, broccoli, and cauliflower. In the afternoon, or before a storm, most butterflies stopped their flight and used exotic and native trees to shelter. This interesting behavior was also reported by Hayward (1953, 1955).

A comment on Fig. 4 is important at this stage. There are only two ways to lower the maximum echo of successive radar volumes: a spread of the swarm leading to a lower density of insects or a descent as described in the above paragraphs. From Fig. 1 it is clear that there is not

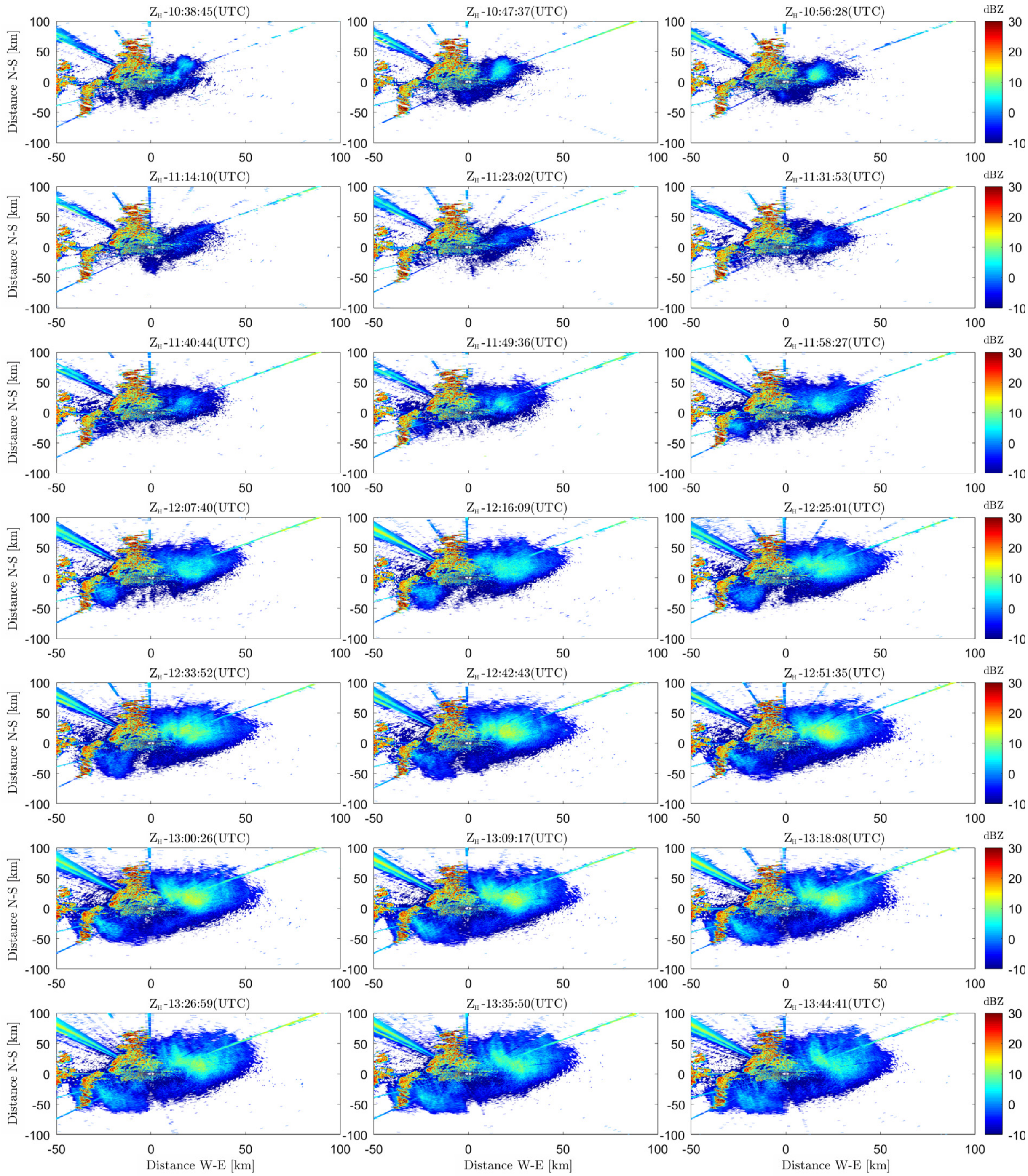

Fig. 5. Reflectivity factor sequence from RMA1 during 21/08/2017.

an important spread of the swarm. Therefore the only explanation for the sawtooth behavior of the radar echo in Fig. 4 is the second option.

5.2. *Schistocerca cancellata*observation

The swarming of *S. cancellata* arrived to Córdoba city on August 21, 2017. Similar to the migration of *A. monuste*, *S. cancellata* could also be observed by the weather radar as seen in Figs. 5–7. Fig. 5 shows reflectivity factor of the swarm approaching the city of Córdoba from the North as observed in the field. Each panel represents the PPI1 of the radar for different instants of time from 10:38 to 13:44 UTC. The swarming has a uniform oval shape with the larger reflectivity factor at the center (green to yellow color). The swarming starts to expand over time when crossing the latitude of the city of Córdoba. A second smaller swarming can be observed close to the city (from 11:58 UTC). Local reports and the present work field observations indicate that the swarming locusts appeared from the NW-NNW of Argentina. The sudden appearance of the locust swarm may be due to both the close mountain range that divides the swarm into two groups, and the relatively low altitude at which these insects fly. In fact the radar scans in a cone and only when the swarm enters it the locusts are observed. At low altitude the maximum concentration crosses the latitude of the radar at about 13:00 UTC. At higher altitudes the maximum crosses at a different time as seen in Fig. 8. In each case the reflectivity reaches a maximum and then decreases. The fact that the surface wind prevailed from the NNE sector at speeds over 20 km h^{-1} along the whole event

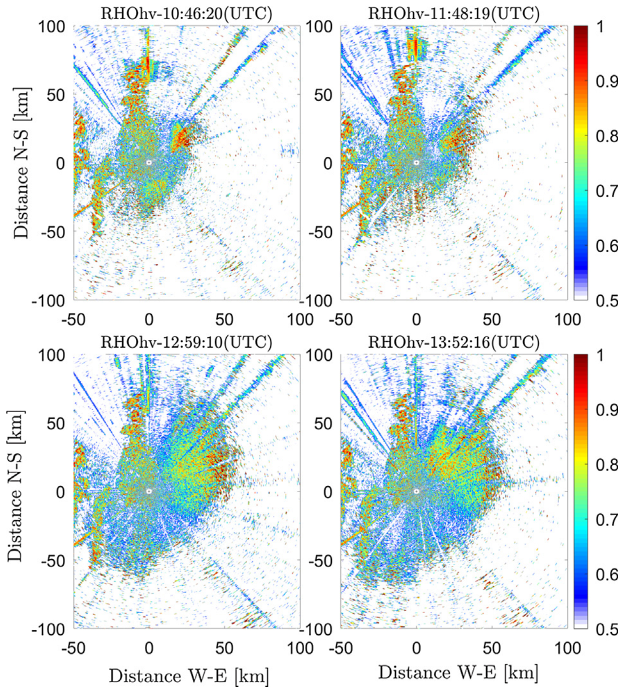

Fig. 6. Sequence of PPI1 scans of the correlation coefficient ρ_{hv} for the *S. cancellata*.

supports the above interpretation.

In the same way as in the case of butterflies, the correlation coefficient of locust ρ_{hv} is shown in Fig. 6. This figure present values referring to biological echoes ($\rho_{hv} < 0.8$). It should be noted that there are regions within the four panels where the ρ_{hv} takes high values $\rho_{hv} \approx 0.9$. It is considered to relate these high values to field observations that manifest the locust individuals moving in uniform coordinated formation. On the left hand, Fig. 7 presents a set of vertical slices in a similar fashion to Fig. 3 although this time the intercepts are −20, 10 and 20 km from the origin. The highlighted ovals indicate the locust radar echo. The right panels are shown for reference as they correspond to clutter before the arrival of the swarm. The top left panel of Fig. 7 confirm that the swarm is a single and uniformly-concentrated group to the east of the city. Later, more individuals arrive and form an expanded group (central left panel), and a second swarm is detected close to the west of the city (from 13:09 UTC). This figure also shows how the swarming locusts are detected at different altitudes reaching almost 1500 m ARL with a major concentration below 1000 m ARL. The first group decreases its height and starts to disappear from the radar image. However, the swarming continues moving at lower height. This fact could be corroborated by field observations.

The height of *S. cancellata* swarms observed by radar coincides with the migratory locust pests *Chortoicetes terminifera* (Walker, 1780) in Australia. Individuals involved can reach a height of 1300 m despite the fact that the highest density is always below 1000 m (Drake and Farrow, 1983). Another study observed a swarm of *S. gregaria* flying at heights up to 2000 m (Cressman, 0000). The highest radar reflectivity echo registered the day of migration in Córdoba was mostly constant between 44 and 46 dBZ, except for peaks at 12:07, 12:25, 12:33, and

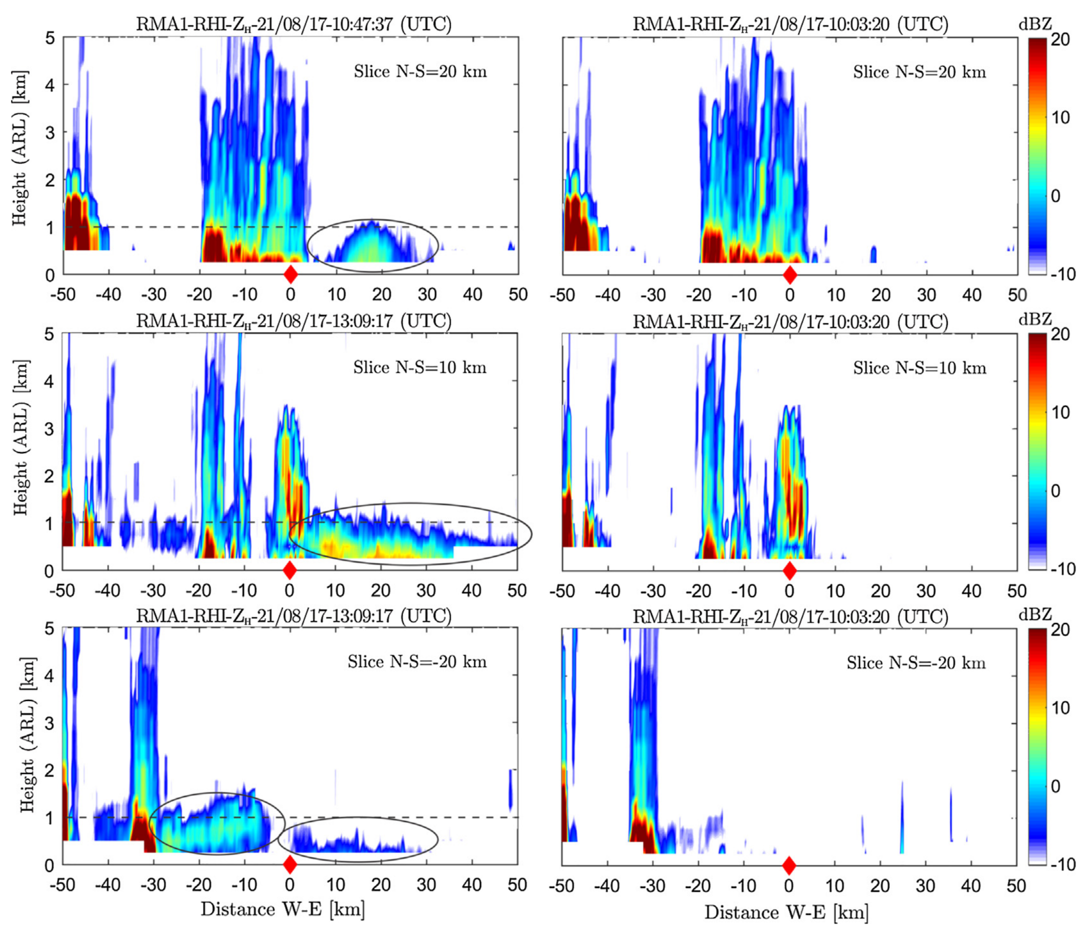

Fig. 7. Vertical slices of reflectivity factor at the indicated times. From top to bottom the intercept decreases from 20 to −20 km. Right panels are only for reference to appreciate the presence of locust in the left panels highlighted with black ovals.

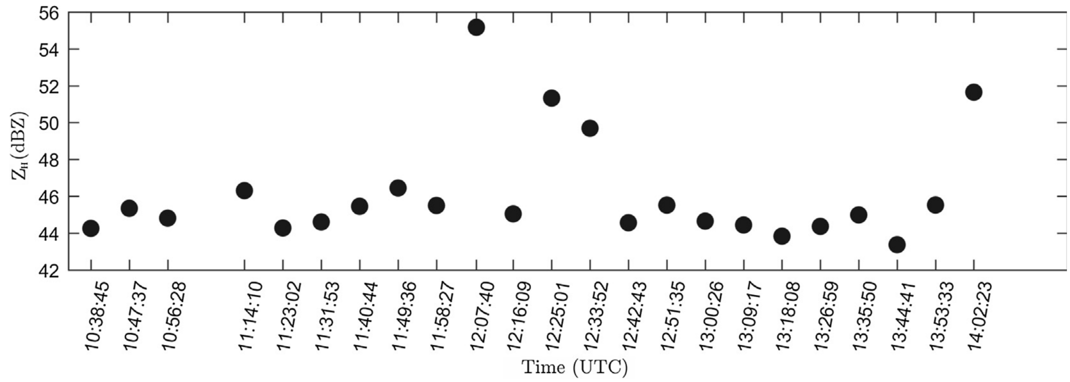

Fig. 8. Maximum reflectivity factor as a function of time of the right half of each radar volume. Note the short scale range of reflectivity factors indicating approximately constant locust concentration.

14:02 UTC as seen in Fig. 8. This is different from the radar reflectivity measurements of *A. monuste*, and could be a consequence of the continuous way the locust moved. This shows that the movement of the locusts was more uniform than that of the butterflies. In other words, the population of locusts fluctuate very little in numbers. On the contrary, butterflies manifest population pulses so that the values of reflectivity change with time.

6. Conclusions

A number of interesting observations were made with respect to these species. Butterflies reach higher altitudes and register larger echoes than locusts. Clearly, the former are lighter and can be carried up more easily by the wind than the latter. On the other hand, the intensity of the echo depends on the radar cross section as well as on the quantity (concentration) of insects. The study of the cross section in the laboratory is already in progress.

The radar results have demonstrated that the swarming of *A. monuste* was divided in several bands that started to join towards the end of the day. The individuals flew to more than 2000 m ARL, but most of the concentration was below this height and near surface, while the swarming locusts *S. cancellata* was uniform with a major concentration of specimens in the center. The individuals reached 1500 m ARL in their flight, but most of the concentration was between 1000 m ARL and the surface.

It was confirmed that both migrant species take off from mid-morning onwards, as atmospheric convection develops, and generally descend in the late afternoon. However, both species had different strategic migration, height and direction of movement pattern. These differences could be due to weather conditions on the day of migration, and intrinsic characteristics and biological attributes of each species, such as weight and flight capacity.

Research on the migration of insects is far from being settled, particularly in South America where most studies are outdated. To the best of the authors knowledge, this is the first report of migratory insects detected by weather radar echoes in South America. A polarimetric Doppler radar, such as the RMA1, is a reliable tool for insect migration detection which helps to discriminate insects from other causes of echoes. Radar allows earlier detection; for example, the arrival of *A. monuste* to the city of Córdoba was first detected by weather radar, and almost one day later by surface observation. However, it is necessary to use both kinds of information to improve the understanding of the phenomenon of migratory insects. The RMA1 is highly effective at determining migration parameters, and provide better information about the identity of the targets such as height, shape of the swarms, and also to forecast the direction of movement.

This study explored new observations of insect migrations particularly for two species that have economic importance in South America. This is the reason why it is vital to gain a good understanding of insect migration pests since the better that pest migrations are predicted and detected, the more efficient the control measures in agriculture will be. In the future, radar detection of such mass migrations or invasions may be used to develop a system of early warnings that could form part of SENASA plans related to pests management. On the other hand, the RMA1 can also be used to study massive migrations of beneficial insects such as pollinators.

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