VALIDATION OF THE WALDVOGEL TECHNIQUE FOR THE PROGNOSIS OF HAIL OCCURRENCE IN THE COUNTRYSIDE OF SÃO PAULO

VALIDAÇÃO DA TÉCNICA DE WALDVOGEL PARA PROGNÓSTICO DE OCORRÊNCIA DE GRANIZO NO INTERIOR PAULISTA

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Introduction

The occurrence of hail causes numerous economic and social losses to society in general, for example, in the United States of America, it generates annual losses of 1 billion dollars (ALLEN et al., 2015). Thus, several studies have been carried out in different parts of the world in an attempt to improve the prognosis of this phenomenon (TUOVINEN et al., 2009; MEZHER et al., 2012; SÁNCHES et al., 2013; NISI et al., 2016; FARNELL et al., 2017; LUKACH et al., 2017; JIN et al., 2017; STRŽINAR; SKOK, 2018).

In Brazil, according to the Ministry of Agriculture, Livestock and Supply (Mapa, 2018), hail is the second largest cause of payment of rural insurance claims, only behind cases of drought. In hail events, the payment of insurance policies reached the amount of R$ 1 billion and 63 million between years 2006 and 2017, which represents around 30% of the total amount paid in the rural insurance sector in the country. São Paulo is the third state with the highest amount of indemnities paid in the same period, with approximate amount of R$ 172 million, only behind states of Rio Grande do Sul and Santa Catarina.

It is important to analyze the behavior of hail in a given region, knowing its climatology, which facilitates the elaboration of alerts about the phenomenon in order to reduce damage caused to crops, agricultural facilities, buildings in general and vehicles. This type of information is vital for many economic activities such as agriculture and insurance companies (JIN et al., 2017; STRŽINAR; SKOK, 2018).

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For the monitoring of severe weather conditions, weather radar is used, which is the best tool for the identification and characterization of storms (SÁNCHES et al., 2013; RIGO; LLASAT, 2016). The advantages of using weather radar data are the approximately continuous coverage, almost real-time availability and good spatial resolution (STRŽINAR; SKOK, 2018).

Hail detection methods based on weather radar data are widely used in various parts of the world (MATHER et al., 1976; WALDVOGEL et al., 1979; LÓPEZ; SÁNCHEZ, 2009; SÁNCHEZ et al., 2013; RIGO; LLASAT, 2016); however, they need proof of reports on the surface to verify the effectiveness in predicting hail episodes (ALLEN et al., 2015; MARTINS et al., 2017). Several techniques have been used in an attempt to find thresholds for the identification of hail in a storm cell such as: Maximum reflectivity value (GEOTIS, 1963); Vertically integrated liquid water content (VIL) (AMBURN; WOLF, 1997); Difference between maximum reflectivity height of 45 dBZ and freezing level height (WALDVOGEL et al., 1979); among other techniques.

To improve the knowledge about the hail behavior in the countryside of the state of São Paulo and to reduce the degree of uncertainty of calculations made for the occurrence of hail on the surface, it is necessary to verify the effectiveness of hail detection techniques for the climatic conditions in the region. Among the various techniques, the methodology proposed by Waldvogel et al. (1979) stands out, who developed a simplified method to detect hail in a storm cell in central Europe, which is expressed by the relationship between weather radar data and atmospheric sounding data. So far, no research has been carried out in Brazil with the purpose of validating the Waldvogel et al. (1979) methodology for the atmospheric conditions of the study region. There is a great difference between the climate of central Europe, the study area by Waldvogel et al. (1979), and the climate of the state of São Paulo, which impacts the dynamics of the atmosphere and the behavior of storms (FRISBY; SANSOM, 1967; PUNGE; KUNZ, 2016).

The great difficulty of this research is the verification of hail on the surface, which in many cases in Brazil, occurs through press reports and civil defense records, where the main focus is on damages generated by the phenomenon, without due attention to crucial issues such as hail diameter when it hits the surface. In addition, most of these records occur in the urban area of municipalities, where most of the population lives. As a consequence, there is little information in rural areas, the likely reasons being the low population density and the extensive territorial area (TUOVINEN et al., 2009; CECIL; BLANKENSHIP, 2012). In order to solve part of this problem, the Meteorology Center of Bauru (IPMET), linked to the “Júlio de Mesquita Filho” State University of São Paulo (UNESP), created on its website, from 2008, the “Voluntary Observer” area with the purpose of collecting reports from the population referring to hail cases that reached the surface in the coverage areas of the institution's weather radars, including information on hail diameter.

Thus, the aim of this study was to validate the Waldvogel et al. (1979) technique, finding the predictive threshold for the occurrence of hail in the state of São Paulo during the rainy seasons from 2008 to 2018 using data from the Doppler weather radar scans of Bauru / SP and analyzed by the very short-term weather forecast system, TITAN (Thunderstorm Identification, Tracking, Analysis and Nowcasting). The purpose is to improve the existing predictive system at IPMET / UNESP, which provides forecasting with hail occurrence alerts for the entire community in the area covered by the weather radar.

Material and methods

The study period included 10 rainy seasons in the state of São Paulo, that is, it corresponds to the months from October to March between years 2008 and 2018. The hail events analyzed come from the "Voluntary Observer" channel, where since 2008, users of the IPMET / UNESP website fill out a form with information on hail cases that reached the ground in the area covered by the weather radar of Bauru / SP. The form is filled with information of each event such as: - Location of the hail observation; - Date of occurrence; - Hail duration; - Hail size when reaching the ground. In the topic related to hail size, 7 options are available for information about hail diameter when reaching the surface: 0.3 cm; 0.6 cm; 1.5 cm; 2.5 cm; 3.5 cm; 5.0 cm and greater than 5.0 cm.

Information for each reported hail event is compared with data collected from the Doppler weather radar of Bauru / SP, band S (λ = 10.7 cm), which belongs to the Meteorology Center of Bauru (IPMET / UNESP), installed at coordinates 22.35ºS, 49.03ºW and 624 meters. To compare information obtained in the database (Voluntary Observer) with weather radar data, the following criterion was adopted: - analysis of radar scans within one hour interval before and one hour after each reported hail event in order to compensate for the accuracy of the hail report, as it is considered that the voluntary who witnessed the event does not pay as much attention to the accuracy of the time of each hail event. Then, for each event reported in the database, an investigation is carried out using images from the weather radar to verify whether the event actually existed (within the specified time interval). If so, the case is analyzed by the very short-term weather forecast system (TITAN).

Thunderstorm Identification, Tracking, Analysis and Nowcasting (TITAN) is a set of algorithms that identify, track and predict storm displacements (Dixon & Wiener, 1993). The database used by the system comes from data obtained from weather radar scans, which in this case will be data from the weather radar of Bauru (IPMET /

UNESP). A storm is defined as a contiguous region that exceeds reflectivity and size limits. Storms defined in this way are identified at discrete time intervals (in the case of this work every 7.5 minutes). The method used in the identification and displacement of storms is the centroid, which uses algorithms based on the following criteria: it uses value of 40 dBZ as the minimum reflectivity threshold, minimum volume of 16 km^3, and minimum height of 2 km and maximum of 30 km as parameters for identifying a storm. In this study, information from the top of storms (km) will be used, which is defined as the maximum reflectivity height of 40 dBZ.

To calculate the probability of hail on the surface, used by TITAN, the Waldvogel et al. (1979) methodology was used during a weather modification experiment in Central Europe using X-band radar ($\lambda = 3$ cm) by sowing clouds to suppress hail. The aim of this study was to find a simplified way to identify which storm cell would be capable of generating hail. The calculation is based on the difference between maximum reflectivity height of 45 dBZ (H_{45}) obtained from the weather radar and the freezing level height (H_0) of the atmospheric sounding, both measured in kilometers (km). In this work, the difference between H_{45} and H_0 was called ΔH, according to Equation 1. The result obtained in the experiment showed that the probability of the occurrence of hail increases dramatically with the increase in ΔH.

$$\Delta H = H_{45} - H_0 \qquad \text{(Equation 1)}$$

Information on the maximum reflectivity height of 45 dBZ (H_{45}) for each case under study comes from scans of the weather radar of Bauru. For the freezing level height (H_0), soundings from the “Campo de Marte” aerodrome (SBMT - 83779), in the municipality of São Paulo, belonging to the Ministry of Aeronautics, are used. This aerodrome is the closest to the study region, which operationally launches two daily radiosondesper day (12 UTC and 00 UTC) (http://weather.uwyo.edu/upperair/sounding.html). It is important to highlight that for events reported until 3 pm (local time), 12 UTC was used and for episodes reported after 3 pm (local time), 00 UTC was used to represent the height of the zero-degree isotherm in the region of the event in order to represent the real conditions of the atmosphere at that time of day.

Knowing the maximum reflectivity height of 45 dBZ (H_{45}) and the freezing level height (H_0) of each case, the ΔH values for each hail event are obtained. The purpose of this analysis is to determine the ΔH value from which the hail event is predicted in storm cells detected by the weather radar of Bauru.

Results and discussion

The spatial distribution of 175 hail events reported in the “Voluntary Observer” database of IPMET / UNESP, within the coverage area of the weather radar of Bauru in the rainy seasons under study (2008-2018) is shown in Figure 1, where the black circle represents the coverage radius of the quantitative task (CAPPI) of the isotherm radar of Bauru / SP. Featuredmunicipalities: AR (Araçatuba), B (Bauru), BB (Bebedouro), BT (Botucatu), C (Campinas), JB (Jaboticabal), M (Marília), O (Ourinhos), P (Piracicaba), RB (Ribeirão Preto), RP (São José do Rio Preto), SC (São Carlos) and SR (Sorocaba).

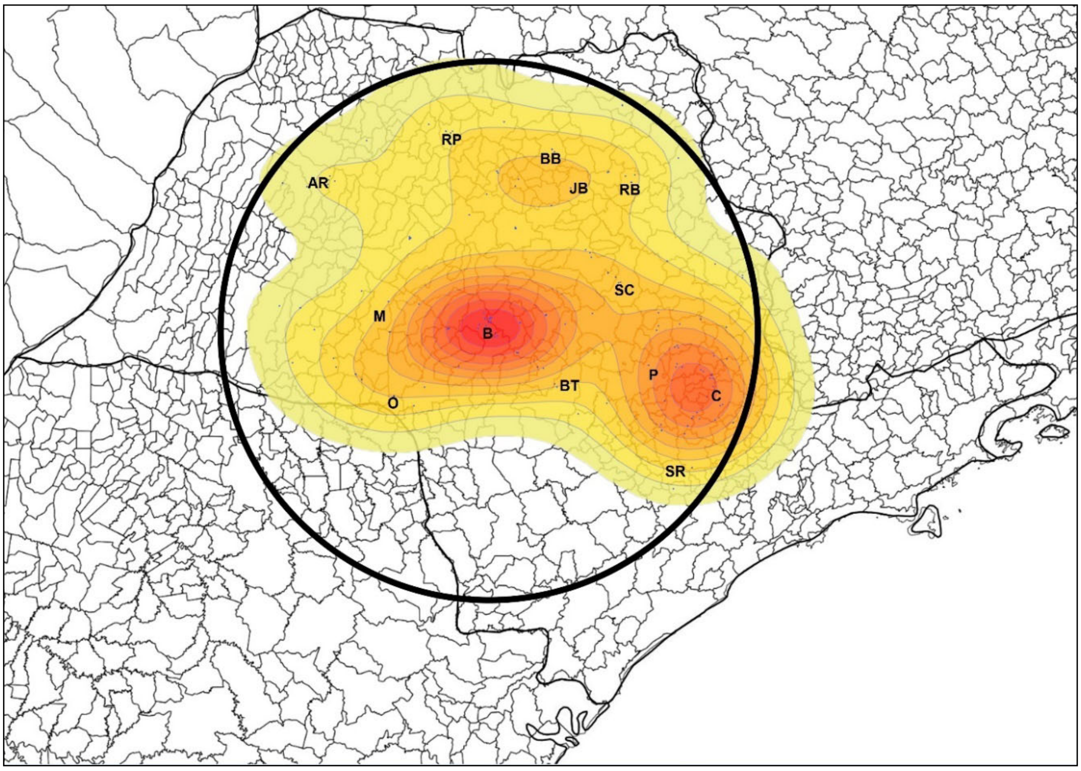

Figure 1. Spatial distribution of hail events reported in the rainy seasons form 2008 to 2018, in the coverage área of the weather radar of Bauru.

The region with the highest incidence is the region of Bauru, in the central region of São Paulo, where about 35% of cases were reported (within approximate radius of 100 km from Bauru). One of the causes is the performance of meteorological systems present in the state of São Paulo during the rainy season, increasing the instability conditions in the region, acting as convection trigger. This enables humid air to rise from near the surface to higher levels of the troposphere, favoring the condensation of water vapor, with release of latent heat, which further intensifies convection (a process known as positive feedback), to the point of reaching and exceeding the freezing level, thus producing hail (JOHNS; DOSWELL III, 1992).

This is one of the evidences of the formation of a severe storm. Other signs of the conception of severe storm are associated with the occurrence of rains, strong winds and tornados (FIGUEIREDO, 2005; SILVA DIAS, 2011).

Another factor in the analysis that may also explain the high incidence of hail in the region of Bauru is the presence of the IPMET / UNESP in the municipality of Bauru. The institution has a 45-year history of using the weather radar and plays a fundamental role in providing services to communities in the countryside of São Paulo, warning the population when severe events occur. Therefore, the broad knowledge of services provided by IPMET / UNESP and its wide dissemination by the press, especially in this region enables greater participation of users, reflecting the large number of reports of hail on the surface within a radius of about 100 km from Bauru.

The second region with the highest incidence is the region of Campinas (with approximately 25% of reported cases), where relief plays a major role in the development of storms in this sector of the state. It appears that at east of Campinas, there are regions with altitudes above 900 meters, indicating the presence of mountains, which favors convective instability and formation and development of storms, working as convection trigger. In the sector to the west of Campinas, there is a large region with altitudes around 600 meters, indicating the existence of a valley region. This configuration allows convection to be stimulated by the combination of factors such as upward movement over a frontal band (cold front), by daytime heating (REBOITA et al., 2010) and also by a physical obstacle in the relief, indicated by the presence of mountains (JOHNS; DOSWELL, 1992; POCAKAL, 2011; DE LA TORRE et al. 2015). Previous studies have shown that this region of the state has the highest incidence of storms in the area covered by the weather radar of Bauru (FIGUEIREDO, 2005; HELD; ESCOBEDO, 2010). Nacaratto et al. (2003) conducted a study on the climatology of the spatial distribution of atmospheric electrical discharges in the state of São Paulo. The work concluded that the region of Campinas is the region with the highest incidence of electrical discharges in the state of São Paulo.

Figure 1 also shows that in the southern and most western regions of the Bauru radar coverage area, few events are found in the database. However, this does not mean that these regions are less susceptible to hail. One of the assumptions is the little knowledge about the service provided by IPMET / UNESP, and the existence of a form that can be filled out on the institution's website, reporting hail events. What can be done to correct this problem, not only in these regions of the state, is to complement the database with other sources of information, such as data from surface weather stations in operation in the state of São Paulo. The aim is to increase the database for the hail study and thereby improve the knowledge on the frequency of the phenomenon in the area covered by the weather radar of Bauru.

The rainy season in the state of São Paulo, covers the months from October to March (COELHO et al., 2016), where approximately 74% of hail events were reported in the "Voluntary Observer" database between October 2008 and March 2018, that is, 175 cases occurred in the wet period and 61 occurrences in the dry period (April to September). Therefore, there is a peak of convective activity in this period of the year (October to March), reflecting the high number of severe storms, indicated by the occurrence of hail.

The months of November, January and October had the highest number of hail records, with 42, 36 and 34 episodes respectively. It was then observed that in the early spring and early summer, the period of greatest hail activity is found in the state of São Paulo, the same result identified by Frisby and Sanson (1967) in the Brazilian tropical region. In other parts of the world, the peak of hail occurrence is observed between late spring and early summer (TUOVINEN et al., 2009; PARASCHIVESCU et al., 2011; KALKHOVEN et al., 2017; LUKACH et al., 2017; Stržinar&Skok, 2018). In the southern region of Brazil; however, the peak of hail occurrence is observed between the end of winter and beginning of spring (MARTINS et al., 2017). On the other hand, the months of March, with 15 episodes, and December with 21 records, had the lowest number of cases.

The hourly distribution of hail events is shown in Figure 2, where it can be seen that 87.5% of cases occur between 2 pm and 9 pm (local time) indicating a decisive influence of solar heating, as shown by studies in other regions of the world (TUOVINEN et al., 2009; BAL et al., 2014; RIGO; LLASAT, 2016; LUKACH et al., 2017) and in Brazil (MARTINS et al., 2017). It is clear that in the afternoon, there is higher incidence of solar radiation, and consequently the highest temperature values (PORFÍRIO et al., 2012). This factor causes an increase in the saturation deficit, increasing the air evaporative demand, increasing evapotranspiration rates, thus contributing to the highest instability rates in this period of the day, which results in high moisture content at low levels of the troposphere, which is one of the triggering factors for the occurrence of storms (NASCIMENTO, 2005; MEZHER et al., 2012). The presence of hot and humid air at low levels of the troposphere establishes the supply of essential moisture for convection (JOHNS; DOSWELL III, 1992), favoring the rising of air close to the surface, carrying humid air to higher levels of the troposphere. This generates the condensation of water vapor and consequent cloud formation.

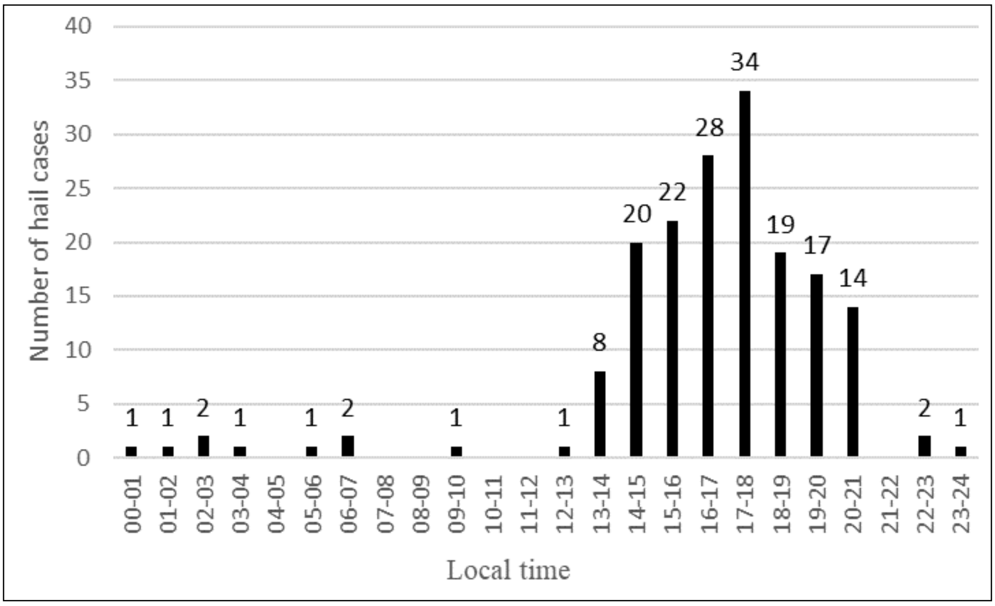

Figure 2. Hourly distribution of reported hail events, which hit the ground, in the rainy seasons from 2008 to 2018, in the coverage area of the weather radar of Bauru.

There is also a maximum peak occurrence between 5 pm and 6 pm (local time), with 34 episodes, which represents approximately 19% of total reported events. In other statesin the southeastern region of Brazil, most cases occur between 4 pm and 8 pm (MARTINS et al., 2017). There is a clear connection with the daytime thermal convection cycle. It was also observed that few hail events (about 7%) were reported in the early morning and morning, as well as at the end of the night.

The monthly distribution of events as a function of the hail diameter when reaching the surface is described in Figure 3. Hail events were classified as: - hail with diameters below 1.9 cm (D <1.9 cm) and equal to or greater than 1.9 cm (D ≥ 1.9 cm). It was observed that in 85.1% of cases, hail diameter was less than 1.9 cm, with 53.7% of events that occurred in the spring and 46.3% in the summer. For events with D ≥ 1.9 cm, which represents 14.9% of the total, spring is the season with the highest occurrence of cases, with 65.4%, while summer presents 34.6% of episodes. The explanation for spring presenting greater number of hail cases is based on the fact that it is a transition season between a dry period (winter) and a wet period (summer). Thus, storms develop in an environment of greater contrast of temperature and humidity, generating favorable conditions for the formation of storms with greater severity degree (ANSELMO, 2015), as evidenced by the reported hail events.

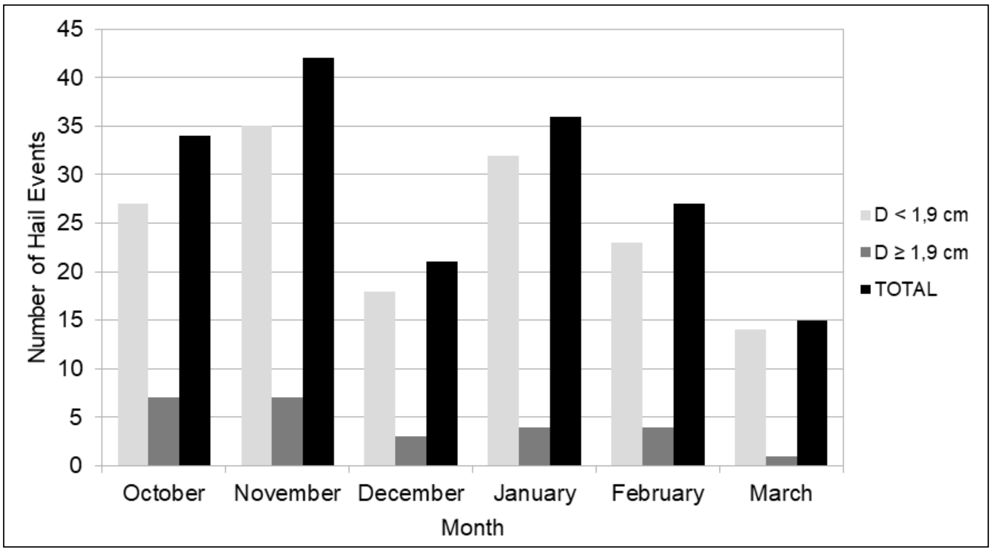

Figure 3. Monthly frequency of non-severe (D < 1.9 cm) and severe (D ≥ 1.9 cm) hail events in the coverage area of the weather radar of Bauru.

In relation to the total number of events, spring months presented 55.4% of cases and 44.6% occurred in the summer months. In Figure 3, it appears that the months of October and November show the highest number of severe hail events, according to threshold of D ≥ 1.9 cm, described by Johns & Doswell, (1992). One of the reasons pointed out for this fact is the lower freezing level height (T = 0ºC) at the beginning of the rainy season (LUKACH et al., 2017), as verified in the average values of Table 1. Taking into account that the average tops of storms reach higher values in these months, hail will have greater space to develop and gain size before precipitating, which is enhanced by the greater contrast between temperature and humidity observed in early spring, creating conditions favorable for the occurrence of severe storms.

Table 1. Average monthly values for the height of the freezing level (T = 0ºC) and for the tops of the storms, both with their respective standard deviations.

	Mean (Standard Deviation) of T=0ºC (km)	**Mean (Standard Deviation) of Tops (km)**
October	4.47 (0.27)	10.74 (1.58)
November	4.43 (0.26)	11.06 (1.98)
December	4,57 (0.27)	9.98 (1.45)
January	4.53 (0.32)	10.62 (1.42)
February	4.64 (0.25)	10.29 (1.52)
March	4.70 (0.26)	10.48 (2.20)

The variability of parameters H_{45}, H_0 and ∆H is shown in Figure 4, where the horizontal central line (red) inside the box represents the median p_{50} (50th percentile). The top edge of the box represents the p_{75} quartile (75th percentile) and the bottom edge of the box corresponds to the p_{25} quartile (25th percentile). The "wiskers" at the top of each box extend up to the highest height below p_{75} + 1.5 IQR, where IQR is the interquartile range given by p_{75} - p_{25}. The "wiskers" at the bottom of the box are values above p_{25} - 1.5IQR.

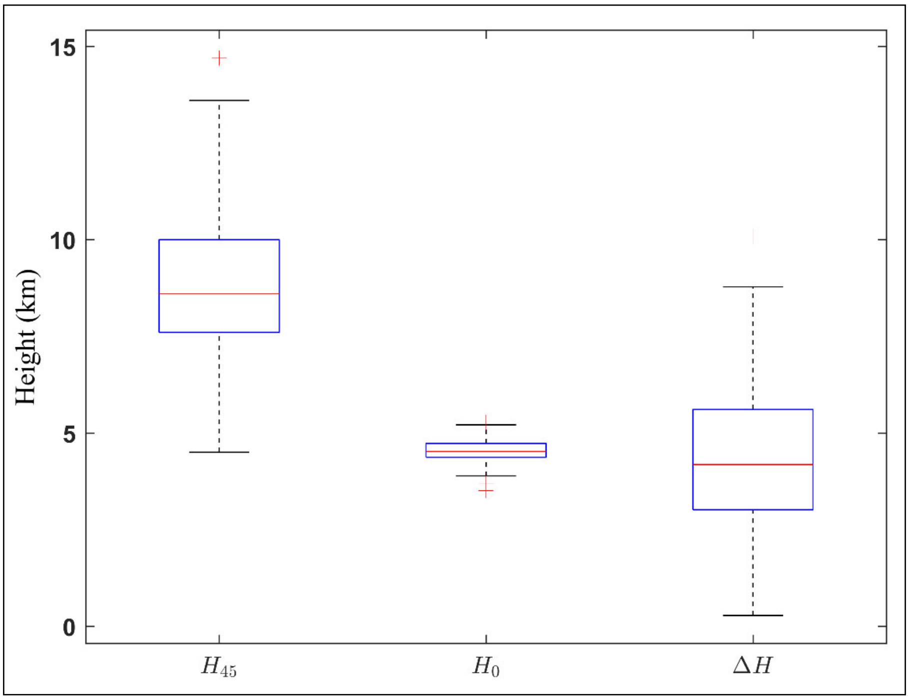

Figure 4. Box and whiskers plots (also known as boxplots) of H_{45}, H_0 e ∆H depending on height.

It was observed that H_0 has lower variability of values compared to H_{45}, with average height around 4.53 km (median of 4.52 km), with standard deviation of 0.28 km. around 8.76 km (median of 8.6 km), with standard deviation of 1.87 km. It was also observed that ∆H has great variability, with minimum value close to zero and maximum value close to 9.0 km, with average value of 4.23 km (median of 4.17 km) and standard deviation of 1.89 km. Then, it was observed that even for small ∆H values, there is occurrence of hail on the surface. The lowest ∆H value found was 0.28 km. In addition, 5 more cases with ∆H < 1 km were identified.

It is necessary to understand the behavior of the freezing level height (H_0) between regions of the state of São Paulo (at the limit of the tropical region) and the central region of Europe (middle latitudes). Parameter H_0 is included in the ∆H calculation and plays a fundamental role in understanding differences between the threshold found in central Europe and the threshold that was applied in the state of São Paulo.

Harris et al. (2000) showed that in the tropical band, the H_0 field is flat and approximately symmetrical in relation to the Equator, with average values of about 5.0 km. In regions with higher latitudes, the trend is for a decrease in H_0 values. In the range from 20º to 25º of latitude, in South America, average values are from 4.0 to 4.75 km. For latitude of 45º N (central Europe), H_0 values vary between 2.0 km (winter) and 3.0 km (summer).

To verify the result found by Harris et al. (2000), an analysis of the freezing level height climatology (H_0) was performed for the region of the state of São Paulo using the atmospheric soundings of the "Campo de Marte" aerodrome (SBMT - 83779), in the city of São Paulo. The study period comprises years from 2001 to 2018. Figure 5 shows the average monthly values in this period. It appears that the lowest values are between months of May and September, the driest time of the year and with milder temperatures. At the beginning of the rainy season, values of 4.51 km (October) and 4.52 km (November) are observed. These values are the lowest observed during the rainy season, from October to March. The annual H_0 average for the study region is 4.5 km, corroborating results found by Harris et al. (2000).

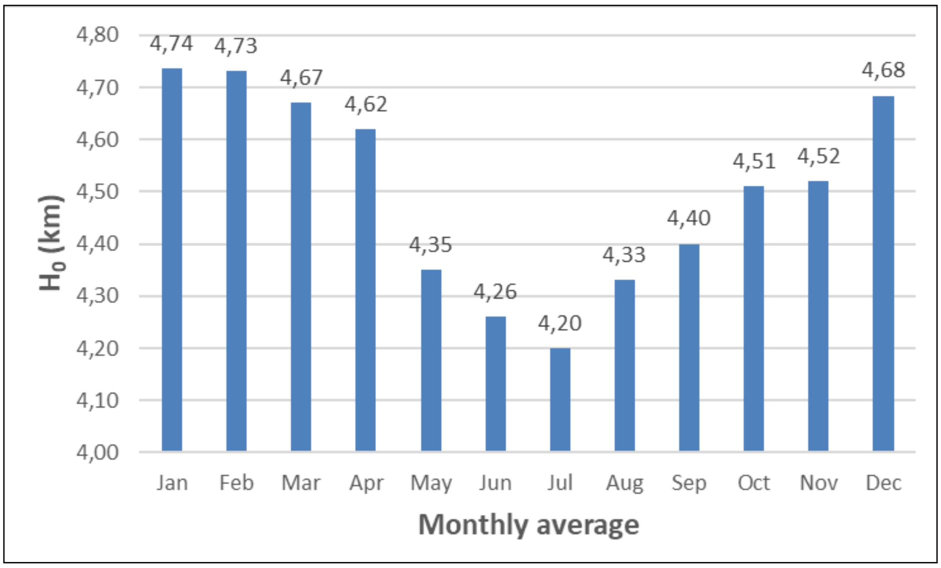

Figure 5. Average monthly values for the height of the freezing level (H_0) for the Campo de Marte aerodrome (SBMT - 83779), in the city of São Paulo.

To apply the threshold for H_{45} - H_0 (ΔH), it is necessary to know differences between the climate of central Europe, where the Waldvogel et al. (1979) methodology was developed, and the climate of the state of São Paulo, study region of this work. Therefore, some aspects of the climates of both regions were described in order to understand the differences between the threshold described for the central region of Europe and the threshold proposed for the state of São Paulo in this research.

The central region of Europe, more precisely the central region of Switzerland (in the city of Lucerne - 47° N latitude), where the X-band radar was installed during the experiment by Waldvogel et al. (1979), the climate has characteristics of humid fresh summer continental (Dfb - Koppen-Geiger classification), with no significant differences in the precipitated volume among seasons, with annual total around 1170 mm. Average temperature values fluctuate between 20ºC in the hottest months of the year (June and July) and close to 0ºC in the coldest months (December and January) (METEOSWISS, 2019). The region is located very close to the northern side of the Alps (with maximum altitude of 4810 m). The proximity of the Alpine Massif acts as a convection trigger, enhancing convective instability and favoring the formation of severe storms, reflecting the high incidence of hail in this region (PUNGE et al., 2014).

The climate in most of the area covered by the weather radar of Bauru, in the countryside of São Paulo, is characterized by being hot in summer and dry in winter (Aw - Koppen-Geiger classification), with annual precipitation between 1500 and 1900 mm. To exemplify the climate of a municipality in the study area, the climate of São Carlos is used to describe the climatic conditions found in the area covered by the weather radar of Bauru. The average annual rainfall is 1558 mm, with average values around 300 mm in January and 30 mm in July. Average temperatures vary between 22.7ºC in January and 22.9ºC in February and 17.1ºC in June and 17.2ºC in July (INMET, 2019).

In the experiment carried out by Waldvogel et al. (1979) in the central region of Europe, a (lower) threshold from which hail precipitation occurred in storms in this region of the planet was identified. Threshold for the occurrence of hail was identified when reflectivities of 45 dBZ (H_{45}) were verified at heights greater than or equal to 1.4 km above the freezing level (H_0), that is, in all storms that generated hail in central Europe, the ΔH value reached at least 1.4 km.

This value was considered as the lower threshold of his sample. The weather modification experiment, with the launch of rockets containing silver iodide, was intended to suppress hail in the storm identified by the radar, with potential for the occurrence of the phenomenon, according to threshold of $\Delta H \geq 1.4$ km. Using this information, it was possible to save 4.5% of rockets, which would be launched in storms with the aim of suppressing hail. These rockets would be wasted, since storm cells in these cases would not form hail, according to criterion used, which resulted in significant savings for the experiment operation.

Applying threshold of $\Delta H \geq 1.4$ km to the sample analyzed in this research, approximately 6.5% of proven hail cases that reached the surface would not be considered. Figure 6 shows the distribution of all events reported in the database as a function of ΔH during the 10 rainy seasons under study (2008 to 2018). Each point represents an ordered pair, with the abscissa axis characterizing the number of events and the ordinate axis indicating the ΔH value (km). As an example, the ordered pair (175; 0.74) is highlighted in red in the graph, with 175 being the number of hail cases and 0.74 the ΔH value for the event. The red line represents the 1.4 km threshold, and values below that line would be disregarded as hail events. Therefore, it is necessary to apply a value that fits the climatic conditions of the study region.

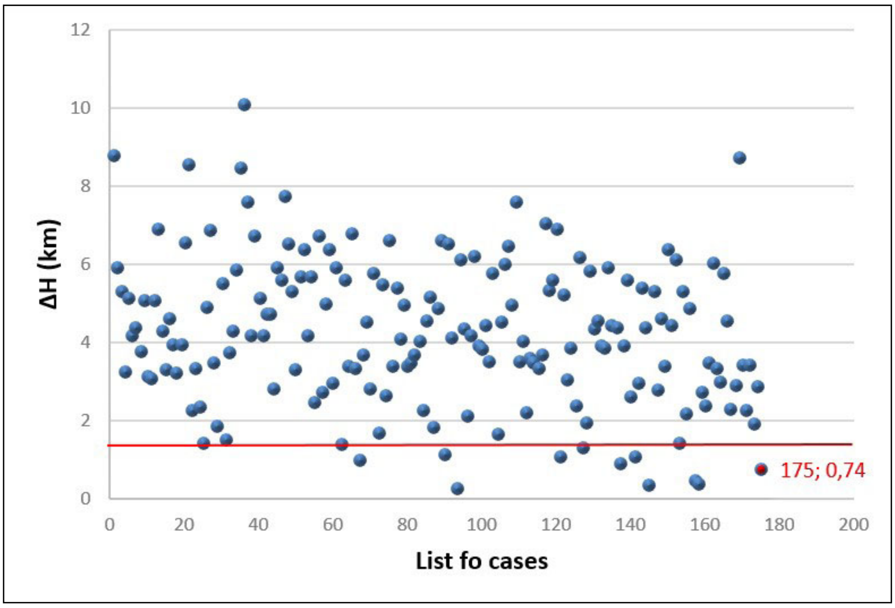

Figure 6. Distribution of hail cases as a function of ΔH. The red line represents the 1.4 km threshold.

Threshold of ΔH ≥ 1.4 km has been used in the very short-term IPMET / UNESP weather forecast system (TITAN) since December 2005. The application of the threshold proposed by Waldvogel et al. (1979), in the coverage area of the weather radar of Bauru does not take into account the climatic conditions of the study region. Thus, it is necessary to investigate the ΔH value adjusted to the local climate, from which hail is predicted in storms detected by the radar in the countryside regions of the state of São Paulo. The aim of this analysis is to improve the hail alert system generated by TITAN in the IPMET / UNESP weather forecasting and monitoring sector. Differences are striking between the climate of the Waldvogel study region and the climate of the state from São Paulo. The central region of Europe is located in a region of the terrestrial globe known as middle latitudes (between 30º N and 60º N latitude), with temperature and humidity gradients different from those found at the limit of the tropical region, where the state of São Paulo is located (between 20º S and 25º S latitude). This factor impacts the dynamics of storms in each region. Therefore, it is necessary to analyze in the "Voluntary Observer" database the ΔH values and determine the hail threshold in these storms (175 cases).

Analyzing all 175 hail events, which occurred in the countryside of São Paulo, threshold of $\Delta H \geq 0.28$ km is observed for the occurrence of hail, that is, in all cases, the ΔH value reached at least 0.28 km. This value is the one that best suits the climatic conditions of the study region in the rainy season analyzed, that is, from this value, hail occurrences are predicted in storms detected by the weather radar of Bauru / SP. Then, with the application of the threshold adjusted to the climatic conditions of the study region, it is possible to improve hail alerts generated by the IPMET / UNESP very short-term forecasting system (TITAN), made available to the entire population of the coverage area, especially to the agricultural community of São Paulo. This result will be implemented in the IPMET / UNESP very short-term forecasting system (TITAN), which will favor greater reliability of the alerts generated.

Conclusions

1. Applying threshold of $\Delta H \geq 1.4$ km to the sample analyzed in this research, approximately 6.5% of proven hail cases that reached the surface would not be considered.
2. Unlike data found by Waldvogel in central Europe, which report that from $\Delta H \geq 1.4$ km, there is occurrence of hailstorms, and results found in the countryside of the state of São Paulo, report that hailstorms occur from $\Delta H \geq 0.28$ km.

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