DOI: 10.5433/1679-0359.2018v39n6p2337

Minimum temperature differences between the meteorological screen and grass in radiative frost nights

Diferenças de temperatura mínima entre o abrigo meteorológico e a relva em noites com geadas

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Abstract

A phenomenon called thermal inversion, in which there is the accumulation of colder and denser air in the layers closer to the soil, occurs in radiative frost nights, resulting in a temperature gradient with differences between the meteorological screen and grass, which vary depending on cooling conditions. Knowing this temperature difference assists in taking preventive measures against radiative frosts, as well as in estimating the probability of their occurrences. In this context, this study aimed to verify the adjustment of different probability distributions to determine the differences between the minimum temperature measured in the meteorological screen and grass temperature below 0 °C for eight regions of the Paraná State, as well as the probability of occurring these differences and adjust estimation equations of grass temperature from minimum air temperature. Temperature differences between the screen and grass were calculated and probability distributions of their occurrences were adjusted in order to determine risks per intervals of temperature differences. Estimation equations of grass temperature were adjusted from minimum screen temperatures. Average gradients of minimum temperature were observed between the screen and grass ranging from 4.2 to 6.3 °C in the analyzed regions. The average temperature difference measured in the meteorological screen and grass for the Paraná State was 5 °C. The probabilistic model of normal distribution is the most suitable for determining the probability of occurring the differences between the screen and grass temperatures for the Paraná State. Regional relief and climate conditions influence the magnitude of the minimum temperature gradient measured in the meteorological screen and grass. Estimation equations can be useful to determine the grass temperature based on the minimum air temperature for periods in which there is no such data and thus provide a subsidy for studies of risk analysis of frosts. The results of this analysis are empirical and the equations should be used in regions in which they were adjusted aiming at a higher accuracy.
Key words: Thermal inversion. Temperature gradient. Frost risk. Grass temperature.

Resumo

Em noites de geada de radiação ocorre um fenômeno denominado de inversão térmica, em que há o acúmulo do ar mais frio e denso nas camadas de ar mais próximas ao solo. Isto resulta em um gradiente de temperatura, com diferenças entre o abrigo meteorológico e a relva que variam dependendo das

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Received: July 15, 2017 - Approved: Aug. 13, 2018

condições de resfriamento. Conhecer essa diferença de temperatura auxilia na tomada de medidas preventivas contra as geadas de radiação, assim como na estimativa da probabilidade de ocorrência. Neste contexto, o objetivo desse trabalho foi verificar o ajuste de diferentes distribuições de probabilidade para determinar a diferença entre a temperatura mínima medida no abrigo meteorológico e a temperatura de relva abaixo de 0°C para oito regiões do Estado do Paraná, bem como a probabilidade de ocorrência das diferenças e ajustar equações de estimativa da temperatura de relva a partir da temperatura mínima do ar. Foram calculadas as diferenças de temperatura entre o abrigo e a relva e posteriormente foram ajustadas distribuições de probabilidade de ocorrência das diferenças, com a finalidade de determinar os riscos por intervalos de diferenças de temperatura. E, por fim, foram ajustadas equações de estimativa da temperatura de relva a partir da temperatura mínima de abrigo. Foram constatados gradientes médios de temperatura mínima entre o abrigo e a relva variando de 4,2 a 6,3°C nas regiões analisadas. A diferença média de temperatura medida no abrigo meteorológico e a relva para o Estado do Paraná foi de 5°C. O modelo probabilístico de distribuição Normal é o mais indicado para a determinação da probabilidade de ocorrência das diferenças entre a temperatura de abrigo e de relva para o Estado do Paraná. As condições de relevo e clima regionais influenciam na magnitude do gradiente de temperatura mínima medida no abrigo meteorológico e na relva. As equações de estimativa podem ser úteis para determinar a temperatura de relva com base na temperatura mínima do ar, para períodos nos quais há a ausência desses dados e, assim, dar subsídio para estudos de análise de risco de geadas. Os resultados da análise são empíricos e as equações devem ser utilizadas nas regiões nas quais elas foram ajustadas, para maior precisão.

Palavras-chave: Inversão térmica. Gradiente de temperatura. Risco de geada. Temperatura de relva.

Introduction

Frost can be defined from the physical point of view as the phenomenon of deposition of ice on any surface exposed to the open air (SELUCHI, 2009; WMO, 2012). Agronomically, frost is defined by any temperature drop with the capacity to damage plant tissues of cultivated plants through intercellular freezing (FIORENTIN, 2016). In the Paraná State, frosts that occur most frequently are called radiative frost or white frost. They are formed after the passage of cold fronts in nights when there are no clouds and winds. Under these conditions, an intense heat loss occurs in the exposed surfaces through the irradiation process and the air layer closest to the soil, which is cooled by conduction (CARAMORI; MANETTI FILHO, 1993). Due to the low thermal conductivity of air and the higher density of the cooler air on frost nights, the colder air accumulates near the soil surface. Thus, a temperature gradient is formed with lower temperatures near the soil, causing a thermal inversion (VALLI, 1972).

Agriculture is considered as a hazardous activity, especially during the winter season, when low temperatures sometimes reach critical minimum values and cause frost (LUCENA et al., 2014), which are a major contributor to productivity breaks of different crops. The susceptibility to frost differs according to the species and phenological phase in which the plant is found (AUGSPURGER, 2013; HUFKENS et al., 2012). Damage to crops depends on the number of occurrence and intensity of frost. Thus, the higher the intensity and duration of frost are, the greater the losses in agricultural production, leading to scarcity and increase in food prices (CECCON; XIMENES, 2013; EUGÊNIO FILHO; OLIVEIRA, 2014).

The occurrence of frost in the Paraná State is conditioned by the displacement of polar air masses that alter the regional balance of energy, more frequently in the winter, resulting in damages to agricultural production. The number of frosts and their intensity vary according to the region, being directly related to the latitude and altitude of each locality (ANDRADE et al., 2012; WREGE et al., 2012). Thus, the agroclimatic zoning for several winter crops has been studied for the Paraná State (ANDRADE et al., 2012; RICCE et al., 2014a, b), as well as the assessment and selection of plant genotypes tolerant to cold (NEVES, 2002).

Therefore, studies related to frost prediction are also of great importance. Predicting the occurrence of this phenomenon allows the issuance of meteorological warnings, alerting society, mainly farmers, about the possible occurrence of frosts (SANTOS et al., 2013).

Knowing the temperature gradient that occurs between the screen and grass assists in taking preventive measures against the radiative frosts, as well as to estimate the probability of their occurrences. In addition, the adjustment to a probability distribution makes it possible to determine the risks of occurrence for different values of the difference between the screen and grass (SENTELHAS et al., 1995). Once the temperature gradients and their probability of occurrence are determined, it is possible to use the minimum screen temperature data, measured at all meteorological stations, to conduct rich frost studies for crops. In this context, this study aimed to verify the adjustment of different probability distributions to determine the differences between the minimum temperature measured in the meteorological screen and grass temperature below 0 °C for eight regions of the Paraná State, as well as the probability of occurring these differences and adjust estimation equations of grass temperature from minimum air temperature.

Material and Methods

This study was performed with daily minimum temperature data measured in the meteorological screen at 1.60 m height and in the grass at 0.05 m height in 19 meteorological stations of the Agronomic Institute of Paraná (IAPAR) (Table 1), characterizing eight regions of the Paraná State, grouped according to their climatic conditions, as shown in Figure 1. Only events with a minimum grass temperature lower than 0 °C were analyzed, being calculated the difference between the minimum temperatures measured in the screen and grass.

Table 1. Meteorological stations of the Agronomic Institute of Paraná, geographical coordinates, and historical series for the eight analyzed regions of the Paraná State.

Region	Meteorological station	Altitude (m)	Latitude (S)	Longitude (W)	Period
NORTH	Bela Vista do Paraíso	600	22°57′	51°12′	1986-2015
	Ibiporã	484	23°16′	51°01′	1986-2015
	Londrina	585	23°22′	51°10′	1986-2015
NORTHEAST	Cambara	450	23°00′	50°02′	1986-2012
	Bandeirantes	440	23°06′	50°21′	1986-2015
NORTHWEST	Paranavaí	480	23°05′	52°26′	1986-2015
	Cianorte	530	23°40′	52°35′	1986-2002
	Umuarama	480	23°44′	53°17′	1986-2015
WEST	Palotina	310	24°18′	53°55′	1986-2011
	São Miguel do Iguaçu	260	25°26′	54°22′	1986-1997
	Planalto	400	25°42′	53°47′	1986-2015
SOUTH-WEST	Pato Branco	700	26°07′	52°41′	1986-2015
SOUTHEAST	Lapa	910	25°47′	49°46′	1988-2015
SOUTH	Palmas	1100	26°29′	51°59′	1986-2015

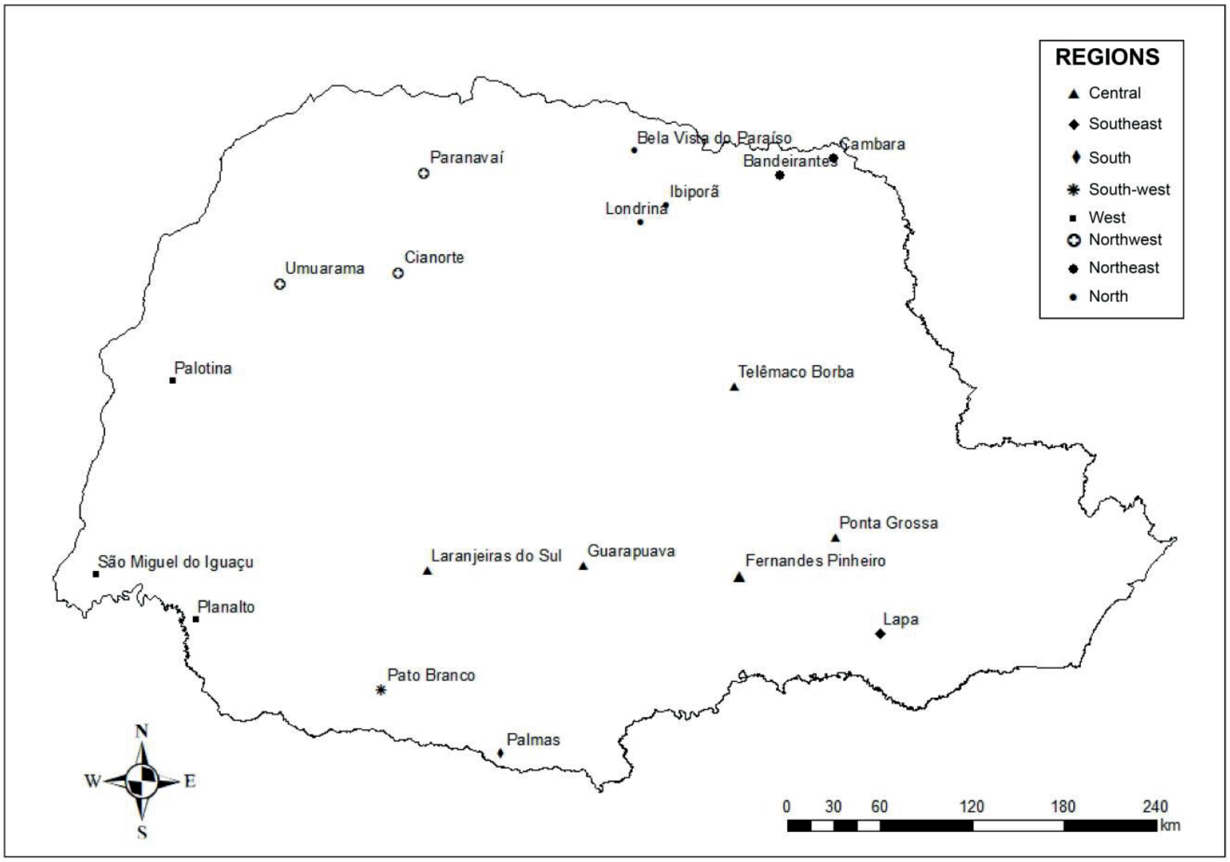
continue

continuation

CENTRAL	Telêmaco Borba	768	24°20′	50°37′	1986-2015
	Ponta Grossa	880	25°13′	50°01′	1986-2002
	Fernandes Pinheiro	893	25°27′	50°35′	1986-2015
	Guarapuava	1058	25°21′	51°30′	1986-2015
	Laranjeiras do Sul	880	25°25′	52°25′	1986-2008

The average values obtained by the difference between both temperatures were divided into class intervals (ASSIS et al., 1996). Subsequently, the adjustment of different probability distributions was verified, as described by Sentelhas et al. (1995) and Silva and Sentelhas (2001):

Figure 1. Representation of the defined regions and location of the Meteorological Stations of the Agronomic Institute of Paraná analyzed for the Paraná State.



Normal distribution

$$f(x) = \frac{1}{\sigma.\sqrt{2\pi}}.e^{-0,5(\frac{x-\mu}{\sigma})^2}$$

Where μ is the mean, σ is the standard deviation, and x is the calculated average temperature difference.

Log-normal distribution

$$f(x) = \frac{1}{\sigma x.\sqrt{2\pi}}.e^{-0,5(\frac{Ln(x)-\mu}{\sigma})^2}$$

Where μ is the mean, σ is the standard deviation, and x is the calculated average temperature difference.

Gamma distribution

$$f(x) = \frac{1}{\Gamma(\gamma)\beta^{\gamma}}.X^{\gamma-e-\frac{X}{\beta}}$$

Where $\Gamma(\gamma)$ is the gamma function of the parameter γ, whose value can be obtained by means of a table that takes into account the value of .

The parameters γ and β are calculated by the maximum likelihood method, as described below:

$$\gamma = \frac{1}{4A}.(1 + \sqrt{1 + 4\frac{A}{3}})$$

Where A is calculated by:

$$A = Ln\,\bar{X} - X_g$$

Where $\bar{X}$ is the arithmetic mean and X_g is the geometric mean.

$$\beta = \frac{\bar{X}}{\gamma}$$

The chi-square test (χ) at 5% probability level was used to determine which of the distribution functions best fit the studied dataset, as suggested by Assis et al. (1996):

In order to compare the distribution and the probability of occurrence of minimum temperature differences of the meteorological screen and grass for the eight regions, the data were classified into thirteen class intervals of 1.0 °C, starting at 0 °C up to 13 °C, making it possible to verify the gradient ranges with the highest probability of occurrence for the Paraná State.

To define equations that estimate the grass temperature based on the minimum temperature measured in the screen, linear regressions between the grass temperature and the minimum screen temperature were adjusted for each region. The significance of regression was assessed through the analysis of variance by applying the F-test at 5% probability level. The adjustment was assessed by the coefficient of determination (R^2). We compared the general adjustment of the pairs of data with events in which no cloudiness was observed in the night period, from data of nebulosity readings at 21:00 h on the day before the frost available by IAPAR, aiming at defining equations with a higher accuracy.

The equations adjusted for each region, as well as for the whole State, were tested from an independent database of a municipality for each region, being: Londrina, Bandeirantes, Paranavaí, Planalto, Pato Branco, Lapa, Palmas, and Guarapuava. The tests were performed using specific equations of the region for each municipality. The equation generated for the Paraná State was tested by the dataset formed by all those municipalities. We verified the correlation between the values of grass temperature estimated by equations and those observed, as well as the significance of correlations by means of the F-test at 5% probability level (FERREIRA et al., 2006).

Results and Discussion

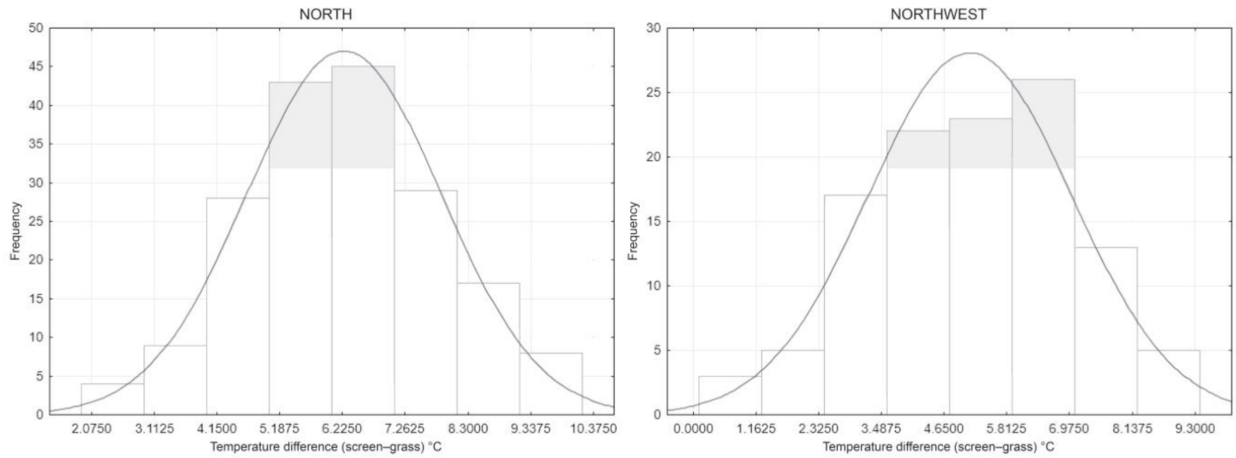
The values of temperature differences between the screen and grass were submitted to three probabilistic distribution models aiming at the best fit for each studied region (Table 2). The best fit was obtained by the Normal distribution for all regions, being the most suitable for determining the probability of occurrence of differences between the screen and grass temperatures for the Paraná State. Figure 2 shows the frequencies observed and estimated by the probabilistic model that presented the best fit for each region. Similar results were obtained by Silva and Sentelhas (2001) in a study on the difference between the screen and grass temperatures for the Santa Catarina State, in which five of the eight studied localities presented the best fit for the normal distribution.

Table 2. Adjustment of probabilistic models of normal, normal log, and gamma distributions of the minimum temperature difference between the screen and grass for eight regions of the Paraná State.

		Normal	**Log-Normal**	**Gamma**
REGION	x^2tab	x^2cal	x^2cal	x^2cal
NORTH	9.49	1.21^{ns}	6.52^{ns}	1.98^{ns}
NORTHEAST	9.49	6.35^{ns}	20.51^{*}	13.68^{*}
NORTHWEST	9.49	2.52^{ns}	32.45^{*}	13.08^{*}
WEST	11.07	4.17^{ns}	102.32^{*}	51.30^{*}
SOUTH-WEST	11.07	7.26^{ns}	75.10^{*}	39.24^{*}
SOUTHEAST	9.49	7.47^{ns}	62.18^{*}	28.29^{*}
SOUTH	15.50	10.51^{ns}	$185,29^{*}$	88.47^{*}
CENTRAL	12.59	6.82^{ns}	227.79^{*}	103.39^{*}

- Significant for α = 0.05; - Not significant.

Figure 2. Frequency observed and estimated by the normal probabilistic model of the minimum temperature difference between the screen and grass for eight regions of the Paraná State.



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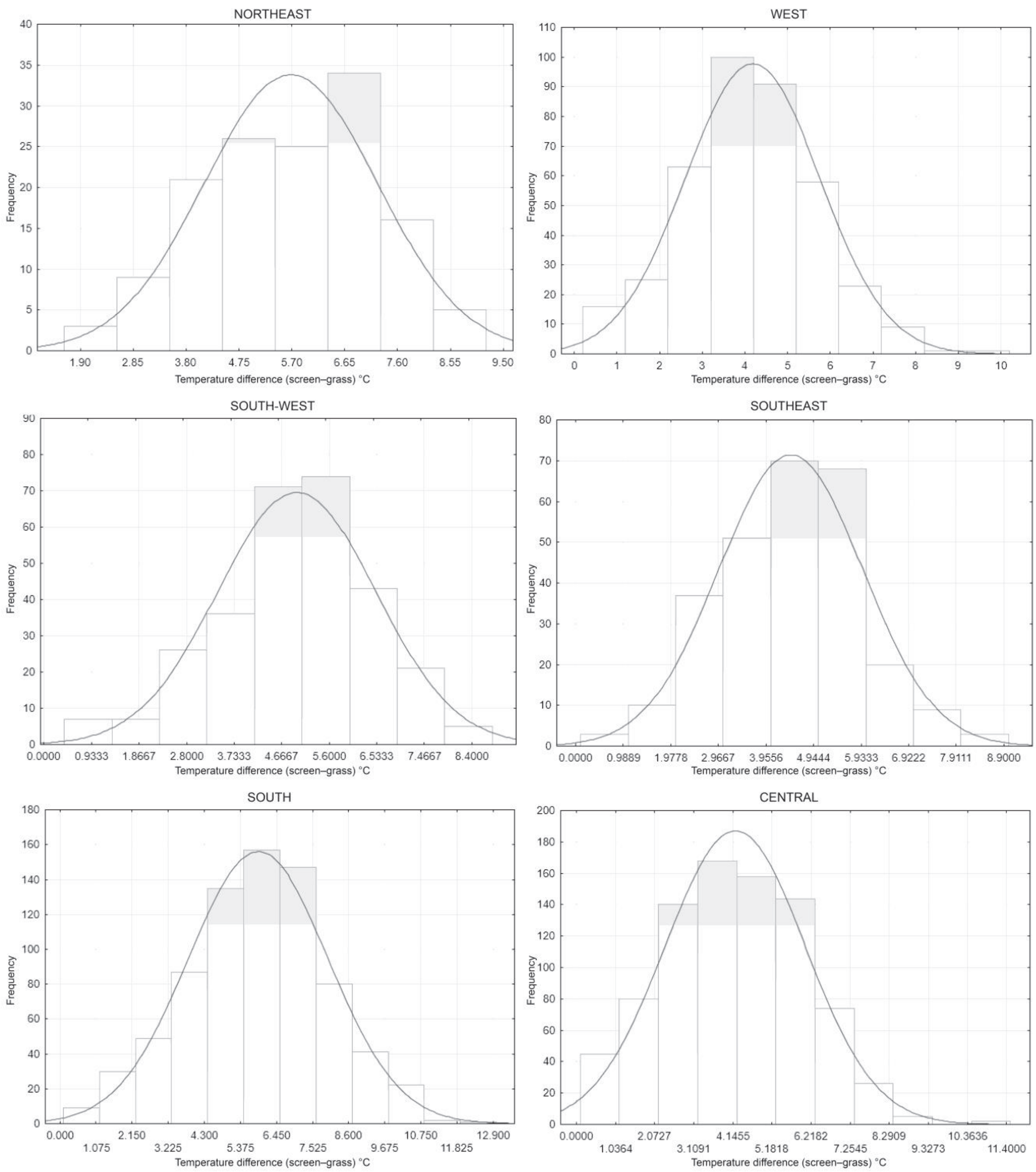

Table 3 shows that the lowest and highest average temperature differences between the screen and grass was found in the Central (4.2 °C) and North (6.3 °C) regions, respectively. Paraná is a state that is in a climate transition range due to its great variation of altitude and latitude. This conditions differences in the climate and in the occurrence of frosts between regions of the State. For instance, the South and Southwest regions have altitudes varying between 800 and 1300 m, with a milder climate and frequent occurrence of frost. On the other hand, the regions near the valleys of Paranapanema and Paraná have altitudes that vary between 200 and 350 m, conditioning higher temperatures (CARAMORI et al., 2001).

Table 3. Average difference between the minimum screen and grass temperatures for eight regions of the Paraná State.

REGION	Average difference (screen-grass) °C	Standard deviation
NORTH	6.3	1.61
NORTHEAST	5.7	1.56
NORTHWEST	5.1	1.88
WEST	4.2	1.58
SOUTH-WEST	5.0	1.55
SOUTHEAST	4.5	1.50
SOUTH	5.9	2.09
CENTRAL	4.2	1.86
PARANÁ	5.0	2.0

Therefore, despite the higher average gradient in the North region, it has higher values of minimum screen temperature, indicating the occurrence of low-intensity frosts. Another important aspect is that the northern regions of the State generally have lower altitude and hence lower wind speeds, where the occurrence of a lull in frosty nights is frequent, which may favor the formation of frosts and marked temperature gradients.

Regions with higher altitudes, generally located to the south of the state, have higher wind speeds and lull conditions are less common. This factor does not favor the formation of large temperature gradients but cooler regions with lower average minimum temperatures and a high-intensity frost. The southernmost regions are also more humid due to a higher precipitation volume and lower temperatures (CAVIGLIONE et al., 2000; WREGE et al., 2012). In addition, lower temperatures lead to higher values of relative air humidity and saturation with the foggy formation on cold winter nights, with the potential to reduce temperature differences between the screen and grass.

Regional conditions of relief may also influence the intensity of temperature gradient between screen and grass, and flat reliefs do not favor air drainage, maintaining the layers of colder air and near the soil stagnant, occasionally providing more accentuated gradients. More accentuated relief facilitates the drainage of cooler air to the lower parts, with a higher accumulation of cooler air in lowlands, where frost is more intense (CARAMORI et al., 2001).

The average temperature difference measured in the meteorological screen and grass for the Paraná State was 5 °C. Gradient values found are higher than those observed by Grodzki et al. (1996), who obtained differences between the screen and grass ranging from 2.8 to 3.8 °C, but with minimum temperatures below 10 °C for the period between April to September. Similar studies have been performed by other authors, such as Silva and Sentelhas (2001), who found differences in the average temperature between the screen and grass for eight localities in the Santa Catarina State ranging from 2.1 to 4.8 °C. Sentelhas et al. (1995) obtained average values of the temperature gradient between the screen and grass from 3.3 to 5.7 °C in a study carried out in ten localities in the São Paulo State. The variations found for these studies regarding the average values of the temperature gradient between the meteorological screen and grass can be explained by the difference in the size of the analyzed historical series, a criterion for including minimum temperatures of analyses, location, and the number of stations of each study.

The highest probability of occurrence of temperature differences in thirteen class intervals (Table 4) is within the range of 5.1 to 7.0 °C for the North, Northeast, and South regions, representing 48.1, 43.2, and 37.9% of the events, respectively. West and Central regions presented, respectively, 51.6 and 38.7% probability of occurrence within the range of 3.1 to 4.0 °C. In the Southwest and Southeast regions, the highest occurrences of studied differences are within the range of 3.1 to 4.0 °C, with 50 and 50.9%, respectively. On the other hand, the Northwest region presented 20.2% of its episodes within the range of 6.1 to 7.0 °C and 18.4% within the range of 4.1 to 5.0 °C, which are ranges of the highest probability of occurrence.

In the Paraná State, the occurrence of frosts is directly related to the displacement of polar air masses that alter the regional balance of energy, especially in the winter. The number and intensity of frosts vary according to the latitude and altitude of each locality (WREGE et al., 2012; ANDRADE et al., 2012), which reflect in variations in the minimum temperature difference in the meteorological screen and grass. In general, most of the studied episodes are within the gradient range between 4.1 and 7.0 °C, with regional variations in the range of the highest occurrence.

Table 4. Probability of occurrence of the minimum air temperature difference between the meteorological screen and grass in frost nights for eight regions of the Paraná State.

CLASS INTERVAL	NORTH	NORTH-EAST	NORTH-WEST	WEST	SOUTH-WEST	SOUTH-EAST	SOUTH	CENTRAL
0.0-1.0	0.0	0.0	0.9	3.6	2.1	1.1	1.2	5.0
1.1-2.0	1.1	1.4	4.4	4.9	1.7	3.7	3.2	9.3
2.1-3.0	2.7	1.4	8.8	14.0	9.0	13.7	5.5	13.7
3.1-4.0	3.8	15.8	15.8	25.8	13.4	18.8	7.6	18.2
4.1-5.0	14.8	18.0	18.4	25.8	24.5	25.8	15.7	20.5
5.1-6.0	23.5	18.7	15.8	14.0	25.5	25.1	21.1	17.9
6.1-7.0	24.6	24.5	20.2	8.0	17.2	7.4	16.8	9.9
7.1-8.0	15.3	15.8	9.6	3.4	5.5	3.3	13.8	4.2
8.1-9.0	9.8	3.6	5.3	0.3	1.0	1.1	8.0	1.0
9.1-10.0	3.8	0.7	0.9	0.0	0.0	0.0	5.4	0.2
10.1-11.0	0.5	0.0	0.0	0.3	0.0	0.0	1.4	0.0
11.1-12.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2
12.1-13.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0

Sentelhas et al. (1995) found the highest differences of minimum screen temperatures below 2 °C and minimum grass temperatures for the São Paulo State occurred in the range of 2.1 to 5 °C, with a 68% probability. In a study for the Santa Catarina State, Silva and Sentelhas (2001) found that 61% of the studied events at eight sites had probabilities of occurrence between the range of 1.1 to 4.0 °C. In our study, there was a greater dispersion in the differences between the screen and grass, with a probability of occurrence of differences between the range of 4.1 to 6.0 °C of 40.6%. The temperature differences between 3.1 to 4 °C and 6.1 to 7.0 °C also presented expressive values, with 14.9 and 16.1% probability of occurrence, respectively.

Grodzki et al. (1996) observed differences between the meteorological screen and grass of up to 7 °C for the Paraná State on nights of strong frosts and with a great atmospheric stability. These results are in accordance with those found in our study, in which even higher differences were observed for colder regions in the State. According to Bootsma (1980), cloudiness in the night period and wind speed can express a significant portion of variations between the minimum temperature measured in the screen and grass on frosty nights, so that the highest differences can be observed on nights of clear sky with a low wind speed.

Knowing the distribution that best fits the dataset allows the elaboration of equations that estimate the grass temperature from other meteorological variables. In this context, Table 5 shows the equations for estimating grass temperatures for each region as a function of the minimum temperature measured in the meteorological screen for the complete dataset and only for night events with a clear sky. Regressions and angular coefficients were significant in all cases at 5% probability level. In general, the adjustments for both conditions were equivalent, being little high on nights of clear skies in some regions. The coefficients of determination (R^2) presented acceptable values, except for the Northwest region, taking into account the great variability of meteorological events and the difficult determination of the correlation between them.

Table 5. Estimation equations of grass temperature (Tgrass) from the minimum screen temperature (Tmin) for the studied events and episodes without cloudiness for eight regions of the Paraná State.

	GENERAL		CLEAR SKY	
Region	**Equation**	**R²**	**Equation**	**R²**
NORTH	Tgrass = 0.6347 × Tmin − 4.7955	0.46	Tgrass = 0.6593 × Tmin − 4.8950	0.52
NORTHEAST	Tgrass = 0.6069 × Tmin − 4.4353	0.42	Tgrass = 0.6472 × Tmin − 4.7276	0.45
NORTHWEST	Tgrass = 0.3298 × Tmin − 2.7786	0.22	Tgrass = 0.3035 × Tmin − 2.6673	0.21
WEST	Tgrass = 0.5925 × Tmin − 3.4796	0.49	Tgrass = 0.5960 × Tmin − 3.5161	0.49
SOUTH-WEST	Tgrass = 0.6934 × Tmin − 4.1827	0.59	Tgrass = 0.6926 × Tmin − 4.2757	0.61
SOUTHEAST	Tgrass = 0.7352 × Tmin − 3.9641	0.58	Tgrass = 0.8439 × Tmin − 4.0988	0.63
SOUTH	Tgrass = 0.6414 × Tmin − 4.9756	0.54	Tgrass = 0.6380 × Tmin − 5.0465	0.54
CENTRAL	Tgrass = 0.5150 × Tmin − 3.2646	0.40	Tgrass = 0.5180 × Tmin − 3.3143	0.41
PARANÁ	Tgrass = 0.5688 × Tmin − 3.9370	0.44	Tgrass = 0.5553 × Tmin − 3.9547	0.44

Similar results were found by Sentelhas et al. (1995) when verifying the adjustment of stations of grass temperature estimation from minimum temperatures, temperature at the dew point, wind, and cloudiness, generating an equation for each meteorological variable and equations varying in combinations. Ferreira et al. (2006) studied the temperature gradient between the meteorological screen and grass for eight cities in the Rio Grande do Sul State, generating monthly equations to estimate the grass temperature from minimum temperatures. The R^2 values ranged from 0.49 to 0.96, with the best fit occurring in the coldest months, when the database division into smaller intervals may have been responsible for finding a higher correlation between the grass temperature and minimum temperature. Other authors (HELDWEIN et al., 1988; OLIVEIRA, 1997) determined estimation equations of grass temperature from minimum screen temperatures in the Rio Grande do Sul State and found R^2 values ranging from 0, 49 and 0.70, showing that even in a region colder than that of our study, in which there is a high occurrence of frost events, the coefficients of determination were close to those found for the Paraná State.

Estimation equations of grass temperature from the minimum temperature for each region and for the whole State were tested using an independent dataset in which the correlation of values of grass temperature estimated by equations and values of the observed grass temperature (Table 6) were observed for all the dataset and only for events without cloudiness. High and significant values of correlation coefficients (r) were found for all regions, except for the Northwest, where it is not recommended to use the equation created to estimate the grass temperature. In the other regions, the high correlation indicates that the adjustments of equations were acceptable and that their use can be employed, guaranteeing adequate results. These correlation coefficients were similar to those found by Ferreira et al. (2006) when assessing estimation equations of grass temperature from the minimum temperature for the Rio Grande do Sul State.

Estimation equations of grass temperature are easy to apply since they have as input variable only the minimum air temperature, allowing calculating the temperature gradient between the meteorological screen and grass in places where these data are not available. This information is important to support studies of risk of frosts and mechanisms of alert of occurrence of this phenomenon, allowing agricultural producers to take preventive measures to avoid or minimize possible damages caused by frost on crops (CARAMORI et al., 2008). In addition, the results can be used as a basis for future studies aiming at generating more precise equations by adding other meteorological elements that are related to the ideal conditions for the occurrence of frost, such as wind, cloudiness, and temperature in the dew point. However, this type of model may be restricted by the difficulty in obtaining these meteorological variables in certain regions.

Table 6. Correlation coefficients (r) between the values of grass temperature observed and estimated by equations for the studied events and episodes without cloudiness for eight regions of the Paraná State.

Region	GENERAL	CLEAR SKY
	r	r
LONDRINA	0.93	0.93
BANDEIRANTES	0.92	0.92
PARANAVAÍ	0.20	0.20
PLANALTO	0.81	0.81
PATO BRANCO	0.83	0.77
LAPA	0.78	0.83
PALMAS	0.90	0.90
GUARAPUAVA	0.72	0.72
PARANÁ	0.71	0.71

Conclusions

The probabilistic model of Normal distribution is the most indicated for determining the probability of occurrence of differences between the screen and grass temperatures for the Paraná State. Regional relief and climate conditions influence the magnitude of the minimum temperature gradient measured in the meteorological screen and grass.

Estimation equations can be useful to determine the grass temperature based on the minimum air temperature for periods without such data, thus supporting studies on risk analysis of frosts. The results of the analysis are empirical and the equations should be used in regions in which they have been adjusted aiming at a higher accuracy.

References

ANDRADE, G. A.; RICCE, W. S.; CARAMORI, P. H.; ZARO, G. C.; MEDINA, C. C. Zoneamento agroclimático de café robusta no Estado do Paraná e impactos das mudanças climáticas. *Semina: Ciências Agrárias*, Londrina, v. 33, n. 4, p. 1381-1390, 2012.

ASSIS, F. N.; ARRUDA, H. V.; PEREIRA, A. R. *Aplicações de estatística a climatologia:* teoria e prática. Pelotas: Editora Universitária/UFPel, 1996. 161 p.

AUGSPURGER, C. K. Reconstructing patterns of temperature, phenology, and frost damage over 124 years: spring damage risk is increasing. *Ecology,* Washington, v. 94, n. 1, p. 41-50, 2013.

BOOTSMA, A. *Frost risk survey of Prince Edward Island*. Ottawa: Department of Agriculture and Forestry, 1980. 35 p.

CARAMORI, P. H.; CAVIGLIONE, J. H.; WREGE, M. S.; GONÇALVES, S. L.; ANDROCIOLI FILHO, A.; SERA, T.; CHAVES, J. C. D.; KOGUISHI, M. S. Zoneamento de riscos climáticos para a cultura do café (*Coffea arabica* L.) no Paraná. *Revista Brasileira de Agrometeorologia*, Santa Maria, v. 9, n. 3, p. 486-494, 2001.

CARAMORI, P. H.; CAVIGLIONE, J. H.; WREGE, M. S.; HERTER, F. G.; HAUAGGE, R.; GONÇALVES, S. L.; CITADIN, I.; RICCE, W. da S. Zoneamento agroclimático para o pessegueiro e a nectarineira no Estado do Paraná. *Revista Brasileira de Fruticultura*, Cruz das Almas, v. 30, n. 4, p. 1040-1044, 2008.

CARAMORI, P. H.; MANETTI FILHO, J. *Proteção de cafeeiros contra geadas.* Londrina: IAPAR, 1993. 27 p. (Boletim Técnico).

CAVIGLIONE, J. H.; KIIHL, L. R. B.; CARAMORI, P. H.; OLIVEIRA, D. *Cartas climáticas do Paraná*, IAPAR. Londrina: IAPAR, 2000. CD-ROM.

CECCON, G.; XIMENES, A. C. A. Sistemas de produção de milho safrinha em Mato Grosso do Sul. *Seminário Nacional de Milho Safrinha*, Dourados, v. 10, n. 1, p. 25-31, 2013.

EUGÊNIO FILHO, E. C.; OLIVEIRA, D. C. Processo de Poisson aplicado à incidência de temperaturas extremas prejudiciais à cultura de café no município de Machado-MG. *Revista da Estatística da Universidade Federal de Ouro Preto*, Ouro Preto, v. 3, n. 3, p. 679-683, 2014.

FERREIRA, C. C.; FONTANA, D. C.; BERLATO, M. A. Relação entre a temperatura mínima do ar no abrigo meteorológico e na relva no Estado do Rio Grande do Sul. *Revista Brasileira de Agrometeorologia*, Santa Maria, v. 14, n. 1, p. 53-63, 2006.

FIORENTIN, A. M. X.; MIRANDA, R. B.; SCARPINELLA, G. D.; CAMELINI, J. H.; MAUAD, F. F. Estudo de susceptibilidade à geada para a cultura da cana-de-açúcar. *Revista Ciência, Tecnologia e Ambiente*, Araras, v. 3, n. 1, p. 43-50, 2016.

GRODZKI, L.; CARAMORI, P. H.; BOOTSMA, A.; OLIVEIRA, D.; GOMES, J. Riscos de ocorrência de geada no Estado do Paraná. *Revista Brasileira de Agrometeorologia*, Santa Maria, v. 4, n. 1, p. 93-99, 1996.

HELDWEIN, A. B.; ESTEFANEL, V.; MANFRON, P. A. Análise das temperaturas mínimas do ar registradas em Santa Maria, RS. I - Estimativa das temperaturas mínimas do ar a 5 cm do solo relvado e solo desnudo. *Ciência Rural,* Santa Maria, v. 18, n. 3, p. 3-14, 1988.

HUFKENS, K.; FRIEDL, M. A.; KEENAN, T. F.; SONNENTAG, O.; BAILEY, A.; O'KEEFE, J.; RICHARDSON, A. D. Ecological impacts of a widespread frost event following early spring leaf-out. *Global Change Biology*, Illinois, v. 18, n. 7, p. 2365-2377, 2012.

LUCENA, J. A.; SOUZA, B. I.; MOURA, M. O.; LIMA, J. O. Produção agropecuária e correlação com a dinâmica climática em Caicó-RN. *Revista Brasileira de Geografia Física*, Recife, v. 6, n. 6, p. 1617-1634, 2014.

NEVES, C. S. V. J. Recuperação de plantas de genótipos de aceroleira afetadas por geada no norte do Paraná. *Semina: Ciências Agrárias*, Londrina, v. 23, n. 2, p. 173-178, 2002.

OLIVEIRA, H. T. *Climatologia das temperaturas mínimas e probabilidade de ocorrência de geada no Estado do Rio Grande do Sul.* 1997. Dissertação (Mestrado em Fitotecnia) - Universidade Federal do Rio Grande do Sul, UFRGS, Porto Alegre.

RICCE, W. S.; CARVALHO, S. L. C.; CARAMORI, P. H.; AULER, P. A. M.; ROBERTO, S. R. Zoneamento agroclimático da cultura da videira no Estado do Paraná. *Semina: Ciências Agrárias,* Londrina, v. 35, n. 4, p. 2327-2336, 2014b.

______. Zoneamento agroclimático da cultura do abacaxizeiro no Estado do Paraná. *Semina: Ciências Agrárias,* Londrina, v. 35, n. 4, p. 2337-2346, 2014a.

SANTOS, A. P.; GONÇALVES, J. P.; FERREIRA, A. S.; SANTOS, S. R. Q. Previsão de geada para a Região Sul do Brasil: uma avaliação do Modelo ETA 15 km durante o Outono de 2012. *Revista Brasileira de Geografia Física*, Recife, v. 6, n. 1, p. 100-109, 2013.

SELUCHI, M. E. Geadas e friagens. In: CALVACANTI, I. F. A.; FERREIRA, N.; ASUNÇÃO, F. da S. D.; GERTRUDES, A.; SILVA, J. (Org.). *Tempo e clima no Brasil.* São Paulo: Oficina de Textos, p. 375-384, 2009. v. 1.

SENTELHAS, P. C.; ORTOLANI, A. A.; PEZZOPANE, J. R. M. Estimativa da temperatura mínima de relva e da diferença de temperatura entre o abrigo e a relva em noites de geada. *Bragantia*, Campinas, v. 54, n. 2, p. 437-445, 1995.

SILVA, J. G.; SENTELHAS, P. C. Diferença entre temperatura mínima do ar medida no abrigo e na relva e probabilidade de sua ocorrência em eventos de geadas no Estado de Santa Catarina. *Revista Brasileira de Agrometeorologia*, Santa Maria, v. 9, n. 1, p. 9-15, 2001.

VALLI, V. J. *Princípios básicos relativos à ocorrência de geadas e sua prevenção.* Rio de Janeiro*:* Ministério da Agricultura, Departamento Nacional de Meteorologia, 1972. 22 p.

WORLD METEOROLOGICAL ORGANIZATION - WMO. Guide to Agricultural Meteorological Practices. Geneva: Chair Publications Boards, n.134, 2012. 799 p.

WREGE, M. S.; STEINMETZ, S.; REISSER JÚNIOR, C.; ALMEIDA, I. R. (Ed.). *Atlas climático da região Sul do Brasil:* Estados do Paraná, Santa Catarina e Rio Grande do Sul. Pelotas: EMBRAPA Clima Temperado; Colombo: EMBRAPA Florestas, 2012. 333 p.