Nat. Hazards Earth Syst. Sci. Discuss., 2, 865–896, 2014
www.nat-hazards-earth-syst-sci-discuss.net/2/865/2014/
doi:10.5194/nhessd-2-865-2014

Natural Hazards and Earth System Sciences Discussions
Open Access

Agricultural losses related to frost events: use of the 850 hPa level temperature as an explanatory variable of the damage cost

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Received: 28 December 2013 – Accepted: 20 January 2014 – Published: 29 January 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The objective of this study is to analyze frost damaging events in agriculture, by examining the relationship between the daily minimum temperature at the lower atmosphere (at the pressure level of 850 hPa) and crop production losses. Furthermore, the study suggests a methodological approach for estimating agriculture risk due to frost events, with the aim to estimate the short-term probability and magnitude of frost-related financial losses for different levels of 850 hPa temperature. Compared with near surface temperature forecasts, temperature forecast at the level of 850 hPa is less influenced by varying weather conditions, as well as by local topographical features, thus it constitutes a more consistent indicator of the forthcoming weather conditions.

The analysis of the daily monetary compensations for insured crop losses caused by weather events in Greece, during the period 1999–2011, shows that frost is the major meteorological phenomenon with adverse effects on crop productivity in the largest part of the country. Two regions of different geographical latitude are further examined, to account for the differences in the temperature ranges developed within their ecological environment. Using a series of linear and logistic regressions, we found that minimum temperature (at 850 hPa level), grouped in three categories according to its magnitude, and seasonality are significant variables when trying to explain crop damage costs, as well as to predict and quantify the likelihood and magnitude of frost damaging events.

1 Introduction

According to a recent literature review (Gobin et al., 2013), scientific interest for weather-related risks in agriculture has increased to a great extent in the last two decades, following the concern on the relationship between climate change and extreme weather and climate events, the impact of such events and the strategies to manage the associated risks (IPCC, 2012). Weather is definitely the major risk in agriculture, causing important yield changes and production losses. Among the weather

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risks, frost is responsible for serious agriculture production losses. The Food and Agriculture Organization reports that more economic losses have been caused by freezing of crops in the USA than by any other weather hazard (Snyder and de Melo-Abreu, 2005), while the ultimate causes determining cold hardiness remain uncertain (Rodrigo, 2000).

A "frost" is the occurrence of an air temperature of 0 °C or lower, measured at a height of between 1.25 and 2.0 m a.s.l., inside an appropriate weather shelter (Snyder and de Melo-Abreu, 2005). The extent of crop damage depends on several factors, such as the local weather conditions, the duration of the frost event, as well as the growth stage of crop species exposed to low temperatures and consequently the season of the year. The probability and risk of damaging temperatures changes with the season of the year and, for some crops, sensitivity to damaging subzero temperatures also changes (Snyder et al., 2005). Also, greater temperature variance could increase the risk of frost damage as much as rising average temperatures decrease it. According to Rigby and Porporato (2008), spring frost risk to vegetation is as sensitive to increases in daily temperature variance (which increases frost risk) as to increases in the mean temperature (which decreases frost risk). Temperature is obviously one of the main indicators of frost risk and, thus, its relation to the observed agricultural losses can give valuable information when trying to estimate the probability of financial losses.

Quantification of agriculture risks is very important in understanding the extent of risk and planning for its effective mitigation (Gobin et al., 2013). Literature review on weather risk in agriculture showed that most of the studies are oriented towards the relation between climate change, climate and weather extremes (IPCC, 2012) and, in some cases, agriculture risks. Several studies investigate the effects of climate change on the frequency and severity of extreme weather events like hailstorms (Berthet et al., 2011; Changnon, 2009), flooding, drought and subsequent crop yield changes (Gobin, 2012) or economic losses due to crop damages (European Commission, 2009; Botzen et al., 2010; Moonen et al., 2002; Rosenzweig et al., 2002), while some work has been also done to link climate change with monetary compensations for crop losses. Botzen

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et al. (2010) examine the relation between normalized agricultural hailstorm damage and a range of indicators of temperature and precipitation for the Netherlands. The authors apply long-term climate change scenarios and discuss the response of hailstorm damages due to extreme events. In Saa Requejo et al. (2011), hail damages in Spain are correlated with summer minimum temperatures. In that context hail insurance data between 1981 and 2007 were considered to represent good estimates of hail damage intensity.

As it concerns Greece, most studies are about changes of climate elements due to the enhanced greenhouse effect. Tolika et al. (2008) assess statistical downscaling models in estimating future changes in the extreme temperature and precipitation conditions and Giannakopoulos et al. (2011) develop future climate scenarios and explore the implications, caused by changing climate, in urban and forest areas. Results show that agriculture may be strongly affected by changing future climate conditions and indicate important changes in the number of frost nights, as well as in the length of the growing season. Nannos et al. (2013) use insurance compensations to estimate the environmental change in Greece through the economic losses caused by the crop production damages. The authors go into a statistical trend analysis of annual damages announcements and compensation data provided by the Greek Agricultural Insurance Organization (GAIO) for the period 1986–2009 and show that in most of the cases (regions and meteorological risk types), there is a statistically significant trend.

The above literature review on the relation between weather-related variables and crop damages indicates a dearth of empirical work on the examination of the short-term frost risk as measured by the observed agricultural financial losses. Thorough examination of the relation between meteorological variables related to frost and the observed crop damages can provide valuable tools for the quantification of frost-related risk. That said, this paper explores the relation between the daily minimum temperature at the low levels of the atmosphere and more precisely at the pressure level of 850 hPa, and monetary compensations for crop damages attributed to frost. In this context, the paper suggests a methodological approach for estimating agriculture risk due

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to frost events with the aim to define damaging temperature thresholds and to estimate the short-term probability and magnitude of frost-related financial losses for different ranges of 850 hPa temperature. This study is actually part of the ongoing authors research on weather-related risks and subsequent societal impacts (Papagiannaki et al., 2013).

Risk, according to the United Nations International Strategy for Disaster Reduction terminology (UNISDR, 2009), is the combination of the probability of an event and its negative consequences. Risk assessment, apart from the analysis of potential hazards, further refers to the evaluation of the existing conditions of vulnerability, such as the physical, social, health, economic and environmental dimensions. However, the intention of the current study is to address only the economic risk from frost events in crop production, while the subsequent environmental or social problems are not discussed. According to monetary compensations for crop damages, frost is a major weather risk for most of the crop species cultivated in Greece. It is indicative that for many out of the 51 geographical prefectures of the country, frost insured losses accounted for more than 50 % of total losses due to weather-related phenomena.

The use of temperature at the pressure level of 850 hPa (T850, hereafter) as an explanatory variable of crop losses due to frost events has a number of advantages and limitations. Significant advantage is that 850 hPa is a standard level of model analysis fields and, thus, there is a high availability of gridded data time-series covering the entire period under examination. Also, T850 presents lower spatial variability compared to near-surface temperature. Furthermore, compared to the near-surface temperature forecast which is more influenced by conditions such as cloudiness and phenomena related with local topographical features, forecasted T850 constitutes a more consistent indicator of forthcoming weather conditions. On the other hand, crop damages are directly connected with ground local conditions, while the relation with temperature in highest altitudes is certainly weaker. However, near-surface air temperature is measured at a height of between 1.25 and 2.0 m a.s.l., thus representing the very local conditions and accounting for the very local agricultural damages. Furthermore, near

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surface temperatures present a high local scale variability, especially in complex terrain (Scheifinger et al., 2003). Consequently, only a very dense and long-time operating network of meteorological stations could provide consistent time-series observations. However the existing meteorological network in Greece is currently inadequate for such an analysis.

The remainder of this paper is structured as follows. Section 2 provides information about the data sources, methodological issues related to data processing and the spatial and temporal distribution of frost events that occurred in Greece during the period 1999–2011. Section 3 presents the methods developed and the results of the statistical analyses used to investigate the relationship between the daily minimum temperature at the level of 850hPa and the observed daily damage cost caused by frost events, as well as an estimation of the damage probability and its magnitude relatively to different temperature ranges. Section 4 discusses the results and their significance and Sect. 5 concludes the analysis. Finally, Appendix includes additional methodological and statistical information, complementary to Sect. 3.

2 Data and methodological issues

2.1 Sources of data

Data provided by GAIO consist of daily crop damage announcements and the respective monetary compensations by municipality and meteorological risk, namely hail, frost, windstorm, flood, excessive heat, excessive or out of season rainfall and snowfall, for the period 1999 to 2011. The daily announcement corresponds to the actual day the damaging event took place, while information on the duration of each event is not available. Therefore, in frost risk analysis, duration cannot be used as an explanatory variable of the magnitude of crop damage cost.

For the purposes of this study, the provided data have been further aggregated to account for each one of the 51 prefectures of the country, still at daily analysis.

In total, 116 957 announcements have been recorded, having an associated cost of EUR 2.8 billion in the entire examined period. Actual values have been changed to standardized values based on year 2011, so that the impact of inflation over time is taken off. According to Botzen et al. (2010), it is a common practice to normalize historical losses for socio-economic developments before climate conditions and change impacts are analyzed (Nannos et al., 2013; Barthel and Neumayer, 2012; Changnon, 2007). Specifically, standardized values of monetary compensations are calculated according to the annual GDP deflator, based on year 2005 = 100, as reported by the Hellenic Statistical Authority (www.statistics.gr). To further readjust the values of year-X costs in prices of year 2011, the following formula was used:

$$\text{Cost}\,(2011\,\text{price}) = \text{Cost}\,(\text{year} \times \text{price}) \times \text{GDPdefl}(2011\,\text{price}) \big/ \text{GDPdefl}(\text{year} \times \text{price})$$

GAIO is a public insurance company that covers in a compulsory way every Greek producer, while private insurance companies cover only a small part of the total agricultural risks. The organization operates on the basis of a number of regulations defining in detail the covered risks, the extent of the coverage, the loss evaluation and compensation method, the level of the (farmers) special insurance contribution, the various procedures, etc. (EC, 2006). With respect to compensations, GAIO covers only the direct losses of crop production and compensates for a specified percentage of total damage, which does not exceed the 75 %. Finally, the organization covers all crop species systematically cultivated in the country. A critical parameter concerning the consistency of data provided by the Greek insurance organization is that "insurance rule of the rural production" remained unchanged from the beginning of GAIO's operation until now (Nannos et al., 2013).

The T850 hPa data have been extracted from the ERA-Interim reanalysis database (Dee et al., 2011). ERA-Interim is the latest global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) with a spatial resolution of ∼ 80 km and a time-resolution of 6 h. From these gridded data, points rep-

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resentative for northern and southern Greece have been selected and the respective time-series for these points, for the selected period, are analysed.

2.2 Spatial and temporal distribution of frost related damages

Data concerning the amount of compensations for all Greek prefectures have been used to examine the spatial and temporal distribution of the cost of frost events in Greece for the period 1999–2011 and the percentage of frost in total crop losses caused by all insured meteorological risks. The distribution of damage cost by meteorological phenomenon shows that overall, during the period 1999–2011, frost is the most damaging one, accounting for 34 % of the total insured crop losses (Fig. 1), followed by hail (26 %) and heavy rainfall (22 %). The total cost of frost events is 970 million Euros. As illustrated in Fig. 2, insured crop losses due to frost vary widely between years, with damages being as low as 2 million Euros in 1999 and as high as 290 million Euros in 2003. The annual variability, however, cannot be statistically assessed, considering the short time period examined.

Statistical analyses will be further used to examine the effect of the daily minimum temperature at the pressure level of 850 hPa on the financial cost of crop production damages, for two different regions of the country, allocated in northern and southern Greece. Therefore, two regions of quite different latitudes and, consequently, temperature ranges and crop species cultivated within their ecological environment, have been examined. Furthermore, the two selected regions consist of some of the most affected prefectures, in which 70 % of total crop losses due to frost events occurred.

The spatial distribution of damage costs caused by frost events is depicted in Fig. 3, showing the overall damage cost that occurred to each prefecture. For presentation purposes the costs have been grouped in four ranges. As can be seen, the selected regions in north and south Greece, marked with a rectangle, include some of the most affected prefectures. Specifically, the northern region is located between central and western Macedonia and includes the prefectures of Pella and Imathia, which are the most affected areas of the country, as well as the prefectures of Florina, Kastoria, Kozani, Pieria and Grevena. The southern region includes the seven prefectures of Peloponnese (Corinth, Argolida, Arcadia, Messinia, Laconia, Achaia and Elia).

Monthly distribution of frost events is presented in Fig. 4, for the entire country, and the two examined regions. It is obvious that between June and September frost events do not occur in Greece. The northern region, where mostly deciduous trees are cultivated, suffers mostly from spring frost events, while in the southern part, where citrus trees and olives are very common, winter was the most catastrophic season during the period 1999–2011.

Regarding the crop species cultivated in the two regions, data on the areas cultivated (www.statistics.gr) and crop production (http://epp.eurostat.ec.europa.eu) indicate that there have not occurred any significant changes during the last decade. Specifically, in the north part of the country, peach and apple trees still account for the major part of the deciduous trees cultivated (approximately 65 % and 10 % respectively), while in Peloponnese orange trees dominate by approximately 65 %. Thus, overall the sensitivity of the examined regions to frost events, as measured by the sensitivity of the specific crop species to the occurrence of low temperatures, has not changed. In the following statistical analyses, the type of crop species damaged by the examined frost events has not been taken into account.

3 Methods

3.1 Measures

Table 1 presents descriptive statistics for minimum temperature (t_{min}) and damage cost (cost) data-series for each region ("North" for the northern region and "South" for the southern region examined). The number of observations (N) refers to the daily damage announcements recorded between 1999 and 2011. Frost events with damage cost below 1000 Euros have been excluded from subsequent analysis. These events, which represent the 17 % of total frost events that occurred in the two regions, are considered

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to be extremely localized and related mostly to special near-surface weather conditions. Consequently, it is very unlikely that T850 relates to the specific frost events.

In order to investigate the relationship between t_{min} and cost caused by frost events in each region, t_{min} data have been allocated in three groups of different temperature ranges, with the aim to identify possible temperature thresholds. Two groups represent the lowest and highest values, and specifically the lowest 25 % and the highest 25 % of the data-series, while the third group includes the medium (50 %) temperature range (complementary argumentation is given in the Appendix). Thus, we created a categorical variable, named "t_{min_c}", which consists of three temperature levels that are further assessed for their significance on explaining the crop damage severity. The three minimum temperature levels, t_{min_1}, t_{min_2} and t_{min_3}, correspond to the highest, medium and low temperature ranges respectively and specifically to the ranges presented in Table 2 for each region.

Another important parameter included in the statistical analyses is seasonality, which is considered indicative of the crop sensitivity in each region. Season 1, 2 and 3 correspond to winter, spring and autumn months (excluding September). Months between June and September were excluded as the number of frost damaging events attributed to these months is of minor importance (1.4 % for the northern region, 1.9 % for the southern region – see Fig. 4).

Consistent to the previous methodological approach, the estimation of the damage probability and its magnitude relatively to the temperature levels, required the grouping of the real damage costs in three categories that represent different damage severity (DS) levels. Specifically, DS1, DS2 and DS3 levels refer to the lower 50 %, the middle 40 % and the upper 10 % of the cost data-series respectively (complementary argumentation is given in the Appendix). The produced ranges of damage costs for the two regions are shown in Table 3.

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3.2 Analyses

To examine the relationship between t_{min_c} and cost, ordinary least squares (OLS) regression analysis was performed. Two models were assessed, one for each region. Prior to the analysis, we transformed the independent variable (cost) to its natural logarithm to normalize its distribution. Temperature levels were entered into the regression by means of two dummy variables, namely t_{min_2} and t_{min_3} (t_{min_1} was set as the baseline group). To evaluate the effects of seasonality, two additional dummy variables, namely season_2 and season_3 (season_1 was set as the baseline group) were also entered into the regression. To assess possible variation between the second and third categories for both t_{min_c} and season variables, regressions were re-run with different groups as baselines. In these repetitions, the F and R squared values as well as the significance of the variable coefficients remained unchanged. Table 4 shows the output of the regression analysis for each region.

F values for both models (North and South) are significant at 0.1 % level, indicating a very good fit of the data. The adjusted R square of the two models is 22 % and 16 % respectively, showing consistency of the explanatory power of the specified models across the two regions. To assess multicollinearity, we computed the variance inflation factor (VIF) scores. All values were well below the accepted cut-off of 10 (Hair et al., 2006), ranging from 1.12 to 2.06.

The coefficients of the dummy variable t_{min_c} inform us about how (direction) and how much (significance) the damage cost is expected to change when temperature changes from one level to the other. Accordingly, the two models, North and South, indicate significantly different effects on damage cost between low levels (t_{min_3}) and medium levels (t_{min_2}) as well as between low levels (t_{min_3}) and high levels (t_{min_1}) of temperature. Differences between medium and high levels of temperature are statistically significant only in the case of the south region. Concerning the season variable, the analyses show that overall, seasonality affects damage cost. Specifically, for both regions, two

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of the three pairs of groups produce different effects on cost at a statistically significant level.

We further propose a methodological approach of risk analysis, with the aim to predict (a) the likelihood that a frost event will occur at each temperature level, and (b) the probability that a certain level of cost damage will occur at each temperature level.

To produce the probability of a frost event to occur, we used a dichotomous variable DSi as the dependent variable. DSi takes values of 0 (no cost damage was recorded at a certain day) or 1 (any cost was recorded). The categorical t_{min_c} was used as the explanatory variable, based on the temperature thresholds that derived from the grouping of t_{min} when only days with damage cost were included (Table 2). Thus, t_{min_c} levels represent the same temperature ranges as the ones presented in Table 2, but different proportions. Specifically, when all days of all the examined seasons (winter, spring, autumn) are included, the t_{min_1}, t_{min_2} and t_{min_3} levels correspond to the lower 75 %, the medium 21 % and the upper 4 % of t_{min} data in the case of the north region and to the lower 67 %, the medium 28 % and the upper 5 % of t_{min} data in the case of the South region.

For the initial analysis, seasonality was controlled with the inclusion of the associated categorical variable. Due to the nature of the dependent variable, two logit regressions (one for each region) were performed. To further investigate variations between the different seasons, we run separate logit regression for each season and region (additional statistical information is given in Appendix, Table A1).

To obtain the predicted probabilities of a cost to occur at each level of temperature, we used a margin analysis after performing each logit regression. The outputs for these analyses are presented in Table 5.

After producing the probabilities of a damage cost to occur (i.e., presence of damage cost), the next set of analyses aim to predict the probability of a certain level of cost damage to occur (i.e., magnitude of cost damage) at each temperature level. Note that days with no damage cost occurrence were eliminated from the analysis. Thus, the produced probabilities are referring to the days with damage costs.

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For the specific analysis, DS was used as the dependent variable. Consistent to the previous analysis, we performed an overall analysis by controlling seasonality while also running separate analysis for each season. DS consists of three groups that indicate low, medium and high levels of cost damage. Due to the ordinal nature of the variable, a generalized ordered logit regression methodology (using maximum likelihood estimation) was employed. The advantage of this method is that it relaxes the proportional odds assumption underlying ordered logit regression, according to which the relationship between each pair of outcome groups is the same (additional statistical information is given in Appendix, Table A2).

To obtain the predicted probabilities of a certain level of damage cost to occur at each level of temperature, we used a margin analysis after performing each generalized ordered logit regression. The outputs for these analyses are presented in Table 6.

To illustrate how the output of Table 6 is interpreted, the first row of the table shows the probabilities of different levels of DS to occur at each temperature level. Therefore, for the north region, if a certain day the temperature falls into the first category (i.e., high temperature), then the probability of low DS (DS1) to occur is 58 %, the probability of medium DS (DS2) to occur is 32 % whereas the probability of high DS (DS3) to occur is 9 % (the sum of probabilities is 100 %).

4 Discussion

The first objective of the present study was to answer whether and how the level of the minimum temperature at the pressure level of 850 hPa relates to crop production damages. This is a critical issue before moving forward, because it defines the importance of all next steps of the analysis. According to the results of the regression analyses (Table 4), the level of t_{min} (minimum T850) explains a significant part of the produced damage cost, in both the north and south region under examination. Therefore, T850 is proved to be one of the main parameters that influence the development and magnitude of frost damaging events.

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Examining further this relationship, in combination with the effect of seasonality, we see that when moving from one t_{min} level to the other, the associated cost changes significantly. Especially when moving from the middle or high range of t_{min} (t_{min_2} and t_{min_1}) to the lower one (t_{min_3}), the associated cost is significantly higher in both regions examined (North and South).

The season effect is also significant in both regions and indicates increased damage cost when comparing spring time (season_2) with winter (season_1) and autumn (season_3). The outcomes imply that spring frost events may damage crops considerably, depending apparently on the growth stage of the plants at this time of the year. For example, according to the study of Food and Agriculture Organization, deciduous fruit trees, which are the most common plants cultivated in the north region, are more sensitive in spring and autumn (Snyder and de Melo-Abreu, 2005). Rodrigo (2000), also, reports that in temperate climates, losses due to frosts during bloom are more important than those due to low winter temperatures.

In what concerns the predicted probabilities of a cost to occur at each level of t_{min}, the analyses show that as t_{min} falls from higher to lower levels, the likelihood for crop damage to occur increases significantly. Depending on the season, high t_{min} (t_{min_1}) associates with a likelihood for damage cost to occur that lies mostly between 5 % and 10 %. When moving to medium t_{min} (t_{min_2}), the likelihood estimated is mostly between 20 % and 30 %, while the associated likelihood for low t_{min} (t_{min_3}) lies between 70 % and 90 % (Table 5).

Predicted probabilities for a damage cost to occur, taking seasonality into account, differentiate in many cases between north and south (Table 5). In the low t_{min} level, autumn involves the greatest risk in both regions compared to the other seasons. However, while in the north spring is expected to be the second more hazardous season, in the south winter ranks second, behind autumn. Specifically, during spring there is 83 % likelihood for damages to occur in the north when t_{min} falls in the low level (under $-6\,^{\circ}$C). In case of such an event, it is very likely (42 %) that the damage severity of this event will be very low, but, also, quite probable that the damage will be of medium

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or high severity (30 % and 28 % respectively, see Table 6). Quite lower is the probability for damages during spring in the South (50 %) when t_{min} falls in the low level (under −3.8 °C). However, if a damaging event occurs, it is very probable (32 %) that the damage will be of high cost.

On the other hand, significant damages are not expected in case of high t_{min}, with the exception of the respective probabilities predicted for spring time in the north. Indeed, the likelihood for serious damage costs during high t_{min} in the north is 39 %. These findings are complemented by the descriptive statistics for t_{min} and damage costs produced in each region. The minimum, mean and maximum values of temperature are quite different between north and south. As expected, in the north the respective values are much lower in the scale of temperature. However, both regions show very high maximum values, which implies that crop damages may occur even when T850 is high. Actually, the 25 % of frost events in the north relate to t_{min} values above 1.8 °C, 9 % of which correspond to events of high damage severity. Accordingly, in the South, the 25 % of frost events relate to t_{min} values above 4.7 °C, 1 % of which correspond to events of high damage severity. This implies that in the north, T850 is more often not representative of the near-surface weather conditions, where radiative cooling and, subsequently, temperature inversions (i.e. temperature increases with height) may occur.

5 Conclusions

In this study, analysis of the agricultural losses of the period 1999–2011 has been performed. It was found that frost is the most damaging weather-related phenomenon accounting for 34 % of the total insured crop losses in Greece. This finding motivated the investigation of the relationship between the daily minimum temperature at the 850 hPa level and the observed damage cost caused by frost events. Moreover, the statistical analysis aimed at providing estimates of the damage probability and its magnitude relatively to different temperature ranges.

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The analysis focused in two areas in Greece (north and south) that presented the highest amounts of frost-related damages. To summarize the most important findings, both studied regions relate to high risk of frost events. Highest is the risk in the north region particularly during autumn and spring, for which low T850 associate with very high probabilities of damages to occur. Moreover, in the north and for the lowest t_{min} level, it is very likely that damaging events will be of high severity only during spring which is partly related to the kind of crops cultivated. In the south, autumn and winter involve the greatest risk when T850 falls into the lower t_{min} level. Additionally, in the south and for the lowest t_{min} level, it is very likely that damaging events will be of high severity.

The outcomes of the statistical analyses provide valuable information regarding the qualitative and quantitative characteristics of frost-related risk in agriculture that may contribute to the research upon the agriculture risks assessment and management. To a large extent, the potential for frost damage depends on local conditions and, thus, it is difficult to be assessed due to the uncertainty included in weather forecasts. However, the significance of T850 as an explanatory variable of the damage cost allows us to rely on its forecast for providing predicted probabilities of damage costs. Practical application of this information may relate to farmer's warning for possible frost events and to the planning of frost protection measures. It is in the future plans of the authors to assess the outcomes of the present analysis, while frost events and agriculture damages will keep on being systematically observed as part of the authors' research on weather-related risks in Greece and subsequent socioeconomic impacts.

Appendix A

To enhance the robustness of our methodology and check for methodological consistency, statistical analyses were also performed for different groupings of t_{min}, setting in all cases equal percentages for defining the lower and upper t_{min_c} levels (from 20 % to 35 %). In all cases, the analyses produced consistent results.

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Accordingly, the analyses have been also performed for a different grouping of damage severity, where DS1, DS2 and DS3 levels correspond to the lower 50 %, the middle 30 % and the upper 20 % of the data-series. As expected, when the DS3 level included the upper 20 % instead of the 10 % of cost data, results of the analyses for both regions showed a consistent increase in DS3 probabilities, as well as a respective decrease in DS2 probabilities. The direction of these changes is in line with the main findings of the study and further supports their validity.

Logit regressions fit statistics are shown in Tables A1 and A2. Table A1 provides fit statistics for the logit regressions. The prob > chi2 for all models is significant at the 5 % level, indicating a perfect fit of the data. Table A2 provides fit statistics for the generalized ordered logistic models. In all model, except one, the prob > chi2 is significant at the 5 % level, indicating a perfect fit of the data.

Acknowledgements. The authors acknowledge the Greek Agricultural Insurance Organization (GAIO) and particularly the Director of Research and Application J. Ghizlis, as well as J. Chrysanthakis for the provision of the daily crop damage announcements and the respective monetary compensations for the period 1999–2011. The European Centre for Medium-Range Weather Forecasts is acknowledged for making available the ERA-Interim reanalyses fields.

References

European Commission: Regions 2020 – the Climate Change Challenge for European Regions, European Commission, Directorate General for Regional Policy, Brussels, 2009.

Barthel, F. and Neumayer, E.: A trend analysis of normalized insured damage from natural disasters, Climatic Change, 113, 215–237, 2012.

Berthet, C., Dessens, J., and Sanchez, J. L.: Regional and yearly variations of hail frequency and intensity in France, Atmos. Res., 100, 391–400, doi:10.1016/j.atmosres.2010.10.008, 2011.

Botzen, W. J. W., Bouwer, L. M., and van den Bergh, J. C. J. M.: Climate change and hailstorm damage: Empirical evidence and implications for agriculture and insurance, Resour. Energy Econ., 32, 341–362, doi10.1016/j.reseneeco.2009.10.004, 2010

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Changnon, S.: Increasing major hail losses in the US, Climatic Change, 96, 161–166, 2009.
Changnon, S.: Catastrophic winter storms: an escalating problem, Climatic Change, 84, 131–139, 2007.
Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J. J., Park, B. K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J. N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Q. J. Roy. Meteor. Soc., 137, 553–597, doi:10.1002/qj.828, 2011.
EC: Agricultural Insurance Schemes, European Comission, Joint Research Centre, modified 2008, 2006.
Giannakopoulos, C., Kostopoulou, E., Varotsos, K., Tziotziou, K., and Plitharas, A.: An integrated assessment of climate change impacts for Greece in the near future, Reg. Environ. Change, 11, 829–843, doi:10.1007/s10113-011-0219-8, 2011.
Gobin, A.: Impact of heat and drought stress on arable crop production in Belgium, Nat. Hazards Earth Syst. Sci., 12, 1911–1922, doi:10.5194/nhess-12-1911-2012, 2012.
Gobin, A., Tarquis, A. M., and Dalezios, N. R.: Preface "Weather-related hazards and risks in agriculture", Nat. Hazards Earth Syst. Sci., 13, 2599–2603, doi:10.5194/nhess-13-2599-2013, 2013.
Hair, J. F., Tatham, R., and Anderson, R. E.: Multivariate Data Analysis, Academic Internet Publ., 2006.
IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, edited by: Field, C. B., Barros, V., Stocker, T. F., Qin, D., Dokken, D. J., Ebi, K. L., Mastrandrea, M. D., Mach, K. J., Plattner, G.-K., Allen, S. K., Tignor, M., and Midgley, P. M., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp., 2012.
Moonen, A. C., Ercoli, L., Mariotti, M., and Masoni, A.: Climate change in Italy indicated by agrometeorological indices over 122 years, Agr. Forest Meteorol., 111, 13–27, doi:10.1016/S0168-1923(02)00012-6, 2002.

Nannos, N., Bersimis, S., and Georgakellos, D.: Evaluating climate change in Greece through the insurance compensations of the rural production damages, Global Planet. Change, 102, 51–66, doi:10.1016/j.gloplacha.2013.01.006, 2013.

Papagiannaki, K., Lagouvardos, K., and Kotroni, V.: A database of high-impact weather events in Greece: a descriptive impact analysis for the period 2001–2011, Nat. Hazards Earth Syst. Sci., 13, 727–736, doi:10.5194/nhess-13-727-2013, 2013.

Rigby, J. R. and Porporato, A.: Spring frost risk in a changing climate, Geophys. Res. Lett., 35, L12703, doi:10.1029/2008gl033955, 2008.

Rodrigo, J.: Spring frosts in deciduous fruit trees – morphological damage and flower hardiness, Sci. Hortic., 85, 155–173, 2000.

Rosenzweig, C., Tubiello, F. N., Goldberg, R., Mills, E., and Bloomfield, J.: Increased crop damage in the US from excess precipitation under climate change, Global Environ. Change, 12, 197–202, doi:10.1016/S0959-3780(02)00008-0, 2002.

Saa Requejo, A., García Moreno, R., Díaz Alvarez, M. C., Burgaz, F., and Tarquis, M.: Analysis of hail damages and temperature series for peninsular Spain, Nat. Hazards Earth Syst. Sci., 11, 3415–3422, doi:10.5194/nhess-11-3415-2011, 2011.

Scheifinger, H., Menzel, A., Koch, E., and Peter, C.: Trends of spring time frost events and phenological dates in Central Europe, Theor. Appl. Climatol., 74, 41–51, doi:10.1007/s00704-002-0704-6, 2003.

Snyder, R. L. and de Melo-Abreu, J. P.: "Frost Protection: fundamentals, practice and economics" Volume 1., Food and Agriculture Organization of the United Nations, FAO, 2005.

Snyder, R. L., de Melo-Abreu, J. P., and Matulich, S.: Frost Protection: fundamentals, practice and economics, Volume 2. Food and Agriculture Organization of the United Nations, FAO, 2005.

Tolika, K., Anagnostopoulou, C., Maheras, P., and Vafiadis, M.: Simulation of future changes in extreme rainfall and temperature conditions over the Greek area: A comparison of two statistical downscaling approaches, Global Planet. Change, 63, 132–151, doi:10.1016/j.gloplacha.2008.03.005, 2008.

UNISDR: Terminology on disaster risk reduction, United Nations, 2009.

Table 1. Descriptive statistics.

Variable	Region	*N*	min	max	mean	st.dev.
T_{min} (°C)	North	588	−18.16	14.14	−2.21	5.30
	South	613	−13.15	17.69	0.64	5.64
Cost (€)	North	588	1019	1.09×10^8	6.17×10^5	5.56×10^6
	South	613	1017	6.15×10^7	5.11×10^5	2.99×10^6

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Table 2. Levels of minimum temperature for the two regions (°C).

t_{min_c} levels	North	South
t_{min_1} (upper 25 %)	> (1.8)	> (4.7)
t_{min_2} (middle 50 %)	(−6.1)–(1.8)	(−3.8)–(4.7)
t_{min_3} (lower 25 %)	< (−6.1)	< (−3.8)

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Table 3. Levels of damage severity for the two regions (in 1000 Euros).

DS levels	North	South
DS1 (lower 50 %)	< 13	< 21
DS2 (middle 40 %)	13–245	21–657
DS3 (upper 10 %)	> 245	> 657

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Table 4. Linear regression analysis for each region.

Variable	North[a]	South[a]
intercept	9.03*** (0.18)	8.94*** (0.23)
t_{min_2}vs1	0.02 (0.19)	0.74** (0.22)
t_{min_3}vs2[b]	0.72*** (0.18)	1.96*** (0.21)
t_{min_3}vs1	0.74*** (0.22)	2.70*** (0.27)
season_2vs1	2.30*** (0.19)	0.63** (0.21)
season_3vs2[b]	−2.08*** (0.26)	−0.15 (0.26)
season_3vs1	0.22 (0.23)	0.47* (0.26)
Adj. R^2	0.22	0.16
F value	42.09***	30.72***

[a] Damage cost is the dependent variable. Values are unstandardized regression coefficients, with standard errors in parentheses, [b] the beta coefficients for these variables derive when repeating the analysis to include the omitted categories, $p < .10$, * $p < .05$, ** $p < .01$, *** $p < .001$.

Table 5. Probabilities of cost to occur for each level of temperature.

	Probability of cost damage to occur[a]	
	North	South
All seasons[b]		
t_{min_1}	0.08*** (0.01)	0.10*** (0.01)
t_{min_2}	0.28*** (0.02)	0.23*** (0.01)
t_{min_3}	0.69*** (0.04)	0.67*** (0.03)
Winter		
t_{min_1}	0.16*** (0.02)	0.10*** (0.02)
t_{min_2}	0.34*** (0.02)	0.23*** (0.02)
t_{min_3}	0.72*** (0.03)	0.70*** (0.03)
Spring		
t_{min_1}	0.06*** (0.01)	0.12*** (0.01)
t_{min_2}	0.26*** (0.03)	0.26*** (0.02)
t_{min_3}	0.83*** (0.08)	0.50*** (0.09)
Autumn		
t_{min_1}	0.06*** (0.01)	0.07*** (0.01)
t_{min_2}	0.28*** (0.04)	0.22*** (0.03)
t_{min_3}	0.89*** (0.10)	0.88*** (0.15)

[a] Damage severity level (dichotomous DSi) is the dependent categorical variable. Standard errors in parentheses. The probability of no cost to occur = 1-Probability of cost to occur, [b] autumn, winter and spring, * $p < .05$, ** $p < .01$, *** $p < .001$.

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Table 6. Probabilities of different damage severity (DS) levels to occur for each level of temperature.

North[a]	DS1	DS2	DS3
	All seasons[b]		
t_{min_1}	0.58***(0.04)	0.32***(0.04)	0.09***(0.02)
t_{min_2}	0.49***(0.02)	0.42***(0.02)	0.09***(0.01)
t_{min_3}	0.40***(0.04)	0.52***(0.04)	0.09***(0.02)
	winter		
t_{min_1}	0.77***(0.04)	0.22***(0.04)	0.02 (0.01)
t_{min_2}	0.61***(0.03)	0.37***(0.03)	0.02** (0.01)
t_{min_3}	0.42***(0.04)	0.55***(0.04)	0.03* (0.02)
	spring		
t_{min_1}	0.15***(0.04)	0.46***(0.06)	0.39***(0.06)
t_{min_2}	0.26***(0.04)	0.41***(0.04)	0.33***(0.04)
t_{min_3}	0.42***(0.10)	0.30***(0.09)	0.28***(0.08)
	autumn		
t_{min_1}	0.67***(0.07)	0.32***(0.07)	0.01 (0.01)
t_{min_2}	0.50***(0.07)	0.46***(0.07)	0.05 (0.03)
t_{min_3}	0.32** (0.12)	0.38***(0.16)	0.29 (0.12)

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Table 6. Continued.

South[a]	All seasons[b]		
t_{min_1}	0.71***(0.03)	0.28***(0.03)	0.01* (0.00)
t_{min_2}	0.50***(0.02)	0.44***(0.02)	0.06***(0.01)
t_{min_3}	0.29***(0.03)	0.41***(0.04)	0.31***(0.04)
	winter		
t_{min_1}	0.87***(0.04)	0.12***(0.04)	0.01 (0.01)
t_{min_2}	0.60***(0.03)	0.36***(0.03)	0.05** (0.02)
t_{min_3}	0.24***(0.04)	0.51***(0.04)	0.25***(0.04)
	spring		
t_{min_1}	0.57***(0.05)	0.42***(0.05)	0.01 (0.01)
t_{min_2}	0.49***(0.04)	0.44***(0.04)	0.08***(0.02)
t_{min_3}	0.41***(0.08)	0.27***(0.09)	0.32***(0.08)
	autumn		
t_{min_1}	0.70***(0.07)	0.29***(0.07)	0.01 (0.01)
t_{min_2}	0.49***(0.07)	0.42***(0.07)	0.10** (0.04)
t_{min_3}	0.28* (0.11)	0.21 (0.11)	0.51***(0.15)

[a] Damage severity level is the dependent categorical variable. Standard errors in parentheses, [b] autumn, winter and spring, * $p < .05$, ** $p < .01$, *** $p < .001$.

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Table A1. Fit statistics for logit regressions.

Models	N	LR chi-2	Prob > chi2	Pseudo R2
North				
All seasons[a]	2,983	576.25	< 0.00	0.20
Winter	1096	160.18	< 0.00	0.11
Spring	1,133	133.39	< 0.00	0.16
Autumn	754	75.84	< 0.00	0.16
South				
All seasons[a]	3021	381.35	< 0.00	0.13
Winter	1112	190.57	< 0.00	0.14
Spring	1132	51.21	< 0.00	0.05
Autumn	777	54.48	< 0.00	0.10

[a] Autumn, winter and spring.

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Table A2. Fit statistics for generalized ordered logit regressions.

Models	N	LR chi-2	Prob > chi2	Pseudo R2
North				
All seasons[a]	580	34.20	< 0.00	0.03
Winter	372	21.46	< 0.00	0.04
Spring	133	5.30	0.07	0.02
Autumn	75	9.07	0.01	0.07
South				
All seasons[a]	604	87.49	< 0.00	0.08
Winter	319	66.12	< 0.00	0.11
Spring	198	15.47	< 0.00	0.04
Autumn	87	17.47	< 0.00	0.11

[a] Autumn, winter and spring.

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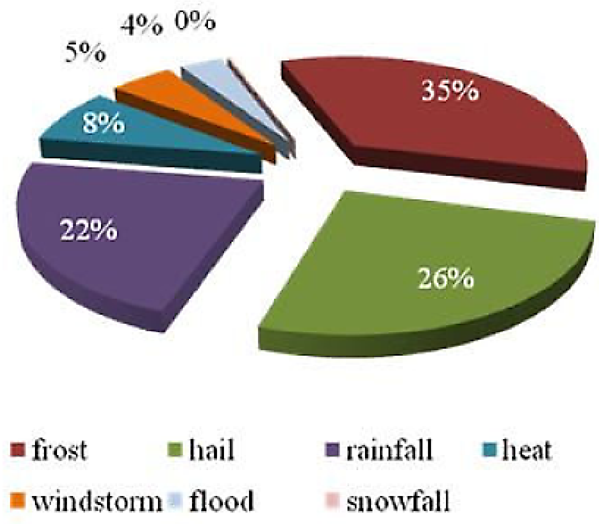

Fig. 1. Distribution of insured crop losses by meteorological phenomenon, 1999–2011.

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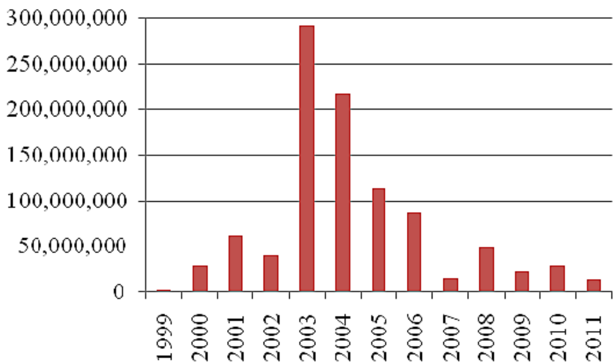

Fig. 2. Annual distribution of insured crop losses due to frost events (in Euros).

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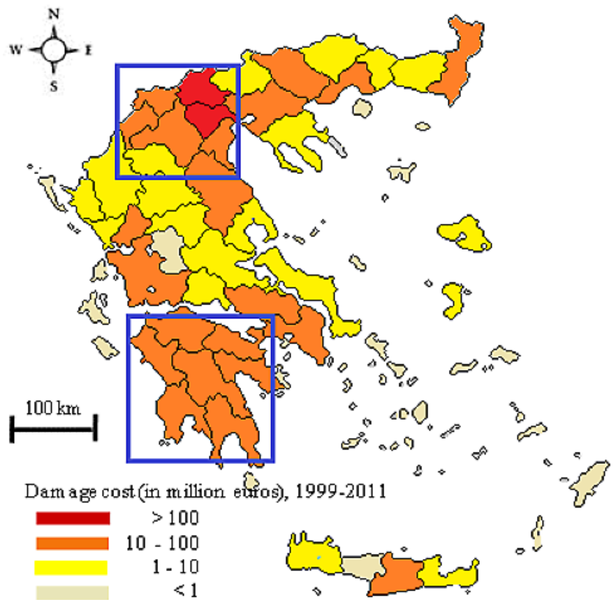

Fig. 3. Insured crop losses due to frost events by prefecture (1999–2011).

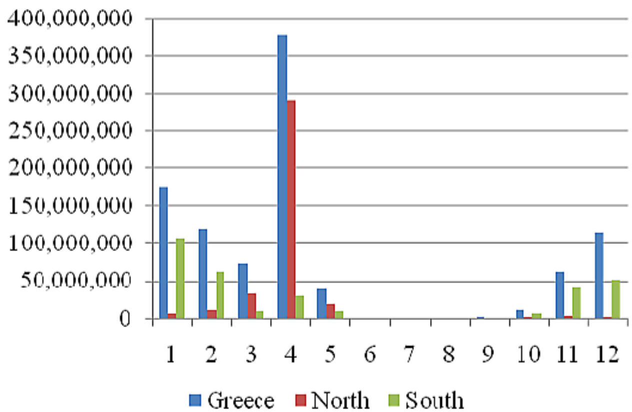

Fig. 4. Monthly distribution of insured crop losses due to frost events (in Euros).

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