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VARIABILITY AND RISK ASSESSMENT OF HAIL IN THE REPUBLIC OF MOLDOVA

M. Daradur[1] T. Leah[2], R. P. Pandey[3], V. Cazac[4]

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Abstract. Overall goal of the current research is to improve hail monitoring and risk assessment as an essential component of hail risk management and planning. The research investigates geographical and temporal variability of hail incidence based on conventional stations reports on hail days from 1891 to 2015. Using the advances in extreme value modeling the study provides the first regional assessment of hail risk based on the return level and waiting time concept within a univariate framework that provides critical information for designing resilience to cope with this climate hazard at high resolution. The proposed in the study the systems of hail risk assessment aimed at ensuring more effective use of the hail data in terms of aligning with management design information, which is essential for preparedness planning and proactive response measures.

Introduction

The hail is considered to be one of the most devastating and high impact weather phenomena in the mid-latitude regions. In these regions surface air temperatures, moisture contents and stratification of the atmosphere particularly promote the instability associated with hail formation processes (Mohr and Kunz, 2013, Van Der Linden et al., 2015). However, hail hazard risk assessment is a great challenge due to small spatial extent of hail which may not be captured accurately by observation systems (Baldi et al, 2014).

To obtain comprehensive spatial information about the hailstorms, different datasets (observational, synoptic, and supplemented with insurance and media reports) are combined. The constraints inherent in hail related data sets are assumed to be compensated, enabling high-resolution detection of hail streaks and assessment of the hail hazard (Kunz and Puskeiler, 2009). Recent approaches are

[1] Research and Project Centre, Republic of Moldova, m.i.daradur@gmail.com
[2] "Nicolae Dimo" Institute of Soil Science, Agrochemistry and Soil Protection, Republic of Moldova, tamaraleah09@gmail.com
[3] National Institute of Hydrology Roorkee, 247667, Uttarakhand, India, rppanndey@gmail.com
[4] State Hydrometeorological Service, Republic of Moldova, valeriucazac@hotmail.com

based on using remote sensing satellite or radar proxy hail data sets (Cintineo et al., 2012; Cecil and Blankenship, 2012; Punge et al., 2014).

An another approach is to relate the environments that promote to hail formation, combining different meteorological, geographical and atmospheric variables relevant to hail generation by using a univariate or multivariate statistic models (Brooks, 2009; Mohr et al., 2015; Allen et al, 2015). A limited studies have investigated the terrain impacts on hail occurrence, though the complex topography gives a specific climate response to hail variability by modifying the heat transport and triggering forced convection that result in considerably changes in natural environment (Suwała and Bednorz, 2013; Daradur et al., 2016).

Early hailstorm studies in many countries reviewed hail information at various time and space scales, and pointed out the principal areas under hail risk. Hail has been well studied in Europe and particularly in USA where there are large societal impacts of hazardous high impact weather (tornadoes, hail, and damaging wind) and there exist long observational records (Tippett at al., 2015; Allen et al., 2015). The U.S. National Climatic Data Center's storm data observational hail record is the most comprehensive publicly available data set (Allen et al., 2015). European hail frequency research has been carried out using data from weather stations and hail pads (Sioutes et al. 2009; Pocakal et al, 2009; Berhet et al., 2013) or radar reflectivity (Puskeiler, 2013). Proxies for hail events derived from insurance (Nicolaides et al., 2009) and satellite temperature imagery (Punge at al., 2014) has been also used for hail risk assessment. Trends in hail observations are made by using damage as a proxy (e.g., Kunz et al., 2009), number of hail events (Berthet et al., 2011; Hermida et al, 2013), convective parameters (Mohr and Kunz, 2013) etc. A study of convective parameters for the 30 year period 1978-2009 in Germany and Europe identified increasing Convective Available Potential Energy (CAPE) attributed to increased moisture at low levels, in turn due to rising temperatures and increased evaporation (Mohr and Kunz, 2014). It was demonstrated that the atmosphere has become more unstable over the last two to three decades over Central Europe, consistent with the observed increase in higher convective potential. Berthet et al. (2011) found no changes in the number of hail events, but identified an increase in hail size related to increasing temperatures for hail-prone Pyrenean and Mediterranean regions of France. At the same time a significant decreasing trend in the frequency of hailstorm days was detected in most regions of China for the period 1959 - 2014 (Shi et al., 2014). The decrease in surface hailstorms is attributed primarily due to the increase in the height of the environmental melting level resulting from climate warming (Mahoney et al., 2012). However the estimation of the hail evolution in a changing climate is challenging due to the large inter annual variability of conditions promoting occurrences of severe events (Van Der Linden et al., 2015). Limited hailstorm projections also show the difficulties to deal with the high impact weather phenomena on a small horizontal scale. In particular, an increase indicated in the convective conditions that lead to hail formation and to an increase in damage days are not always consistent and demonstrate changes which are not very large and lack statistical significance (Van Der Linden et al., 2015).

Owing to the high level physical exposure, as well as insufficient capacity to manage hail risks, the Republic of Moldova is highly vulnerable to this hazardous phenomenon. In spite of considerable societal impacts, in the last decades scant attention has been paid to hail hazard in the country. Up to now information on the regional characteristics of hail occurrences can be found in a few empirical studies. The early studies (Lasse, 1975; Atlas of Moldavian SSR, 1978) were undertaken to document of the mean annual and seasonal variations of hailstorms in Moldova by using the data that covered 10 years (1964-1973) and limited meteorological stations (5 meteorological stations). They were based on a regime-reference approach describing a number of statistical characteristics (average, min, max etc.) of the frequency and spatial distribution of hail. In the issued Scientific and Applied Reference Book on Climate (1990) and Hazardous Meteorological Phenomena in Ukraine and Moldova (1991), the set of hail statistics was recalculated over time to reflect the new realities due to climate variability and change. Later they were updated for the period 1961-2005 by Putuntica (2008).

However, the indicated regime-reference approach failed to illustrate the true complexity and fine details of surface hail occurrences. Nevertheless, they do indicate some important general trends in hail distribution patterns in space and time. An attempted to incorporate local topographic factors to develop models relating to high-resolution estimates of hail incidence was undertaken by Daradur at al. (2016). In particular, the combination of statistical and spatial interpolation has been used to be effective in modeling high-resolution detection of the hail hazard in the complex terrain of the country. This study is a further generalization and development of previous research of authors. *Overall goal of the current research is to improve hail events monitoring and risk assessment.* It was undertaken in an effort to upgrade the existing tools for hail early warning systems that can be used for more effective policy interventions to reduce hail impacts. The study examines spatial and temporal distribution of hail incidence that occurred between 1891-2015 yrs. and uses the traditional univariate framework to quantify the hail risk based on return level and return time concepts, which provides critical information for decision making. **The investigation has also ensured more effective use of the actual and modeled hail data in terms of aligning with management design information and decision support tools.** This information is an innovative task and is required by a variety of models and decision support tools that are essential for designing resilience for coping with this climate hazard at community level. In this context the issues of climate change impact on the hail intensity and frequency, which are discussed in this paper, seem to be highly relevant.

2. Materials and methods

2.1. Data

The observed hail data from SHS since 1891 in Moldova have been used in the study. However not all stations cover the entire period from 1891 to 2015. The data quality and continuity became much more continuous after 1950. Climatologically hail records, as provided by conventional stations of the State Hydro-meteorological Service of Moldova (SHS), are referred to days of hail observed on the ground. In the research, a *hail day* is defined as a day during which hail is observed and recorded at each meteorological station. An analysis assessed the temporal fluctuations of hail frequency in a century scale for 125-year period (1891-2015) derived from carefully screened long term hail incidence records of Chisinau station. To ensure a relatively large and continuous data record to reveal observed trends in the hail dynamics, 8 stations have been chosen with complete observations from 1949 to 2015. The mean annual hail frequency at a station is defined as the mean number of hail days per year. The mean monthly hail frequency is defined as the average number of hail days in each month.

2.2. Variability analysis and risk assessment

In the climate variability and change context, the risk assessment aimed at identifying a range of climate-related risks and events induced by climate variability or exacerbated in a changing climate. It is a useful tool to address a range of negative weather and climate-related impacts (Daradur, 2001; Nogaj et al., 2006). Risk is considered here as a hazard (a potential threat), but it refers to the relationship between its frequency and as a measure of the degree of that potential threat, that is with an additional implication of the chance of a particular hazard actually occurring (Smith, 2001; Daradur, 2001; Dalezius et al., 2014). Hence, hail risk assessment is considered a part of the climate risks management process that identify hail risks and evaluate the magnitude of their consequences and the likelihood that they occur.

It has been assumed that the frequency of hail comes from a Poisson process of rate λ. This implies that the distribution of the times τ between hailstorm events is exponentially distributed with mean $1/\lambda$ (Rauner, 1976; Coles, 2001; Daradur, 2001, Nogaj et al., 2006). It is assumed also the hail events are independent and come from identical distribution. Analysis of mean annual hail days indicates that the Poisson distribution is generally adequate (significance at the 10% level, using x^2 test) in Republic of Moldova. Hence, if P is the probability of occurrence of a hail event, then the average return time estimate *F(τ) = 0.50* has been defined as the inverse of its probability 1*/P.*

Hail risk ratings focus on the traditional univariate framework using the return level and return time concept (Rosbjerg and Madsen, 1998; Daradur, 2001). The concept is a byproduct of the extreme value analysis and it is considered as a convenient tool for climate risk assessment (Nogaj et al., 2006; AghaKouchak et al., 2014). In a stationary case, the concept provides critical information for decision making and it is widely used for extreme weather and climate events risk assessment (Daradur, 2001; Tonini et al., 2012).

T**he return level with an average return period $\tau_{0.50}$ represents an event that has a 1/$\tau_{0.50}$** chance **of occurrence in any given year (Daradur, 2001;** Cooley et al., 2007; AghaKouchak et al., 2014)**. In the study** a confident **return time (**$\tau_{0.95}$) **was also estimated. It is a** practically ensured event with **the** probability of a-hail event which is characterized by the value of F(τ)=0.95 (Daradur et al., 2015). For operational purposes the value of $\tau_{0.95}$ has been calculated based on the average rate (λ=1 year^{-1}) of the Poisson distribution: $\tau_{0.95}$ = 3.0*λ^{-1} (Rauner, 1986; Daradur, 2001). These estimates, as well as the average return time period, is understandable, simple to handle and provide important information for designing hailstorm yearly warning systems and proactive preparedness planning.

The 5-tier risk rating scale is based on number hail days and the normalized annual hail probability for a particular location. The probability of experiencing a hail is expressed as an **-average return period** (**$\tau_{0.50}$**) which is the average time interval between two hail events. It is an average value taken over the period from 1963 - 2015. A particular area with an **average return period of hail** close to 1 year (at least one event each year) is used to define *a high sensitive* for hail planning purposes. The set of hail risk **estimates for the management design information** are provided as:

- ***an average return period*** *at least one day with a hail;*
- *a confident (practically ensured)* ***return time*** *at least one day with a hail, and;*
- ***an average return period of two and more days with a hail.***

The first two estimates represent the overall probability of hail and it - defines the overall sensitivity of a particular location to hail risk. The third one provides a surrogate information of the potential loss from hail hazard since the number of events is a key determinates of damaging hail. Overall hail sensitivity is categorized into 5 levels and hail risk assessment is based on the table.

2.3. Hail risk assessment in a changing climate

It is of particular interest to study the issue of hail and related extreme climate events dynamics in a changing climate. The study investigates of the hail sensitivity to climate variability and change using a time-depended aggregated function *F(τ)* based on the ratio of the increment function ($\Delta F/\Delta\tau$) with the time of hail observations. The value of *F(τ)* with the time of observations is none other than the rate (λ=1 year^{-1}) of the intensity of the Poisson distribution (Cox and Lewis, 1966). Hence, a selection of sufficiently small sub-time scale of $\Delta\tau$ enables us to analyze the differential value of the hail occurrence rate $\lambda_d(\tau)$ and its variation over time (Daradur et al., 2015).

Tab. - Categorization of the areas' overall hail sensitivity and the set of hail risk estimate (Republic of Moldova)

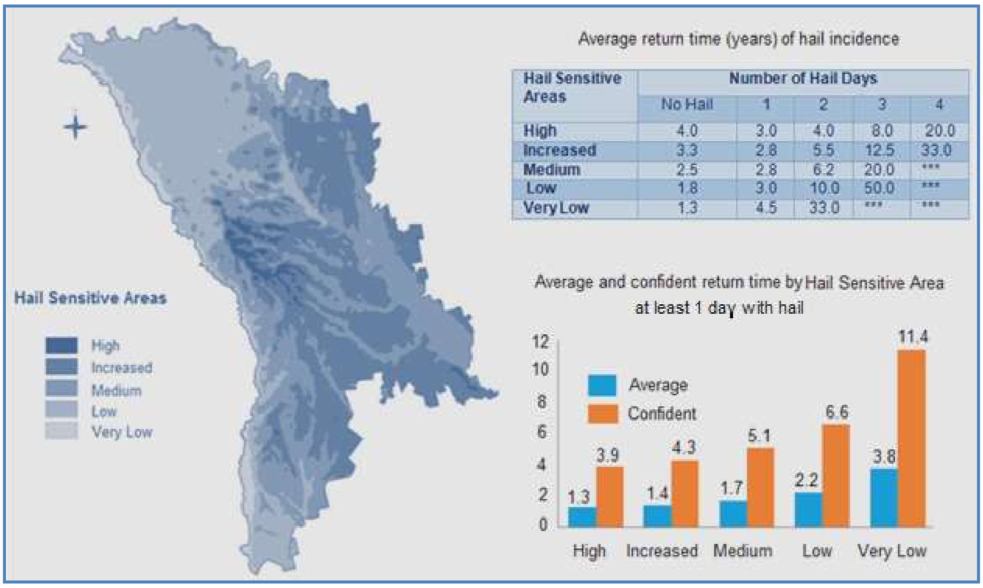
Hail sensitive area	Hail risk estimates and description			
	Average return period, years 1 day	Confident return period, years 1 day	Average return period, 2 and more days with hail	Description
High	<1.3	<4	<4	Very frequent hailstorms and damage
Increased	1.3-2	4-5	4-6	Frequent hailstorms and damage
Medium	2-2.5	5-7	6-10	Relatively frequent hailstorms and damaging hail
Low	2.5- 3	7-10	10-30	Rarely experience hailstorms and damaging hail
Very low	>3	>10	>30	Very rarely experience hailstorms and damaging hail

To reveal an active response hail formation to climate change we analyzed the dynamics the intervals of hail generation *F(τ)* for the period spanning from 1949 to 2015 as a whole and for two no overlap periods of observations 1949-1980 and 1981-2015. The t-test was used to determine a statistical difference of Poisson rate between these two periods ($\lambda_2 - \lambda_1$) of observations (Wilks, 1995). An analysis of the temporal fluctuations in hail frequency in a century scale (125-year period) derived from carefully screened records of Chisinau station which has long term hail incidence records. The observation on this phenomenon started in 1891 with missing records in some years that were replaced by multiannual values.

3. Results and discussion

General trends of spatial hail fall patterns over the territory of Moldova indicates several different prone areas (Fig. 1). Central (hilly) part is an area with average >1,5 day per year and the greatest sensitivity to hail (Daradur et al, 2016). Northern and Southern flat area has mostly minimum days with hail, and the values ranges from 0.3 to 0.9 days.

Length of the return period for a day with no hail at all is longer in the areas predisposed to hail incidence. For example, in the areas with a high sensitivity it consists about 4 years, whereas in the less prone areas it does not exceed 2 years that means, on an average, every four and two years with no hail days. Geographical distribution of the exact 1 day with hail is not clearly expressed and consists over the country 2 - 4.5 years. However, the spatial differences of the return time of hail increase to a considerable extent with the increase of the magnitude of the hail falling. For example, the return period with 2 hail days over the territory of Moldova consists from 4 to 33 years; with 3 days consists already from 8 to 50 years.



Hail Sensitive Areas	Number of Hail Days				
	No Hail	1	2	3	4
High	4.0	3.0	4.0	8.0	20.0
Increased	3.3	2.8	5.5	12.5	33.0
Medium	2.5	2.8	6.2	20.0	***
Low	1.8	3.0	10.0	50.0	***
Very Low	1.3	4.5	33.0	***	***

Fig. 1 - Hail sensitive areas and return periods of hail incidence in the Republic of Moldova [Note: ***Return time is more than 50 years in above table with figure]

Observational records as well as climate projections provide strong evidence of warming of Moldavian climate. Linear trend used for the analysis of time series of climatic parameters shows an increase in the mean air temperatures in the Republic of Moldova more than 1.0°C with an enhance in the past decades 1980-2015 (Fig. 2).

In general, the changes are accompanied by an increase of high impact weather and climate events (Sutton et al., 2013; Taranu, 2014). An analysis assessed the temporal fluctuations in hail-day and occurrences during past 125-year period, from 1891 to 2015, derived from carefully screened records of Chisinau station in an assessment showing no long-term change through this period – the

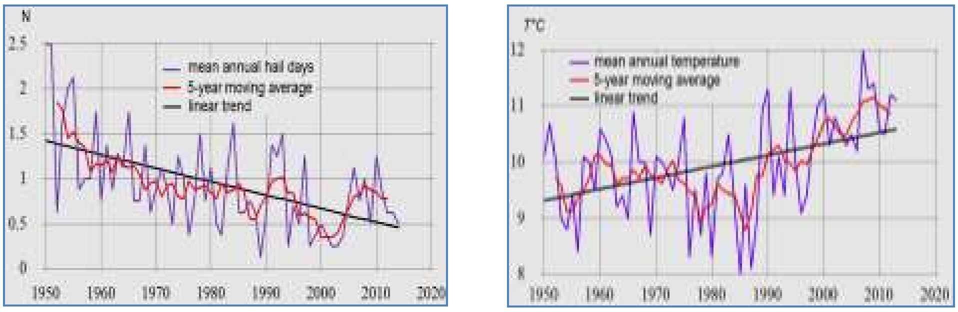


Fig. 2 - Long-term dynamics of the average number of days with hail incidence (N) and air temperature (T °C) for recent decades (1950-2015)

annual number of hail days remained almost unchanged in the mean. However, an analysis that included the data from set of stations covering the whole territory of Moldova results in a much different assessment showing long-term decrease since 1950-s. Herewith, reduction in the number of days with this phenomenon is observed in all months of the warm period (April to September). Significant decreasing trend of hail days can be attributed to warming the upper atmosphere due to climate change that leads to increasing the height of environmental melting and preventing hail formation (Mahoney et al., 2012, Shi et al. 2016).

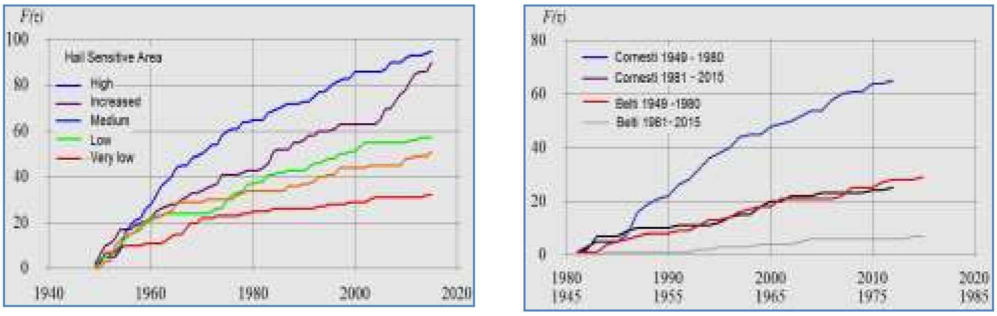


Fig. 3 - Time-depended aggregated function F(τ) of the intervals of hail events by sensitive areas (Republic of Moldova, 1949-2015) and comparison of the F(τ) for two non overlapping periods (1949-1980 and 1981-2015). Note: The comparison of two non overlapping periods (1949-1980 and 1981-2015) is shown here for specific stations with the high (Cornesti) and low (Beltsi) hail hazard risk

To reveal changes in intervals of hail generation in a changing climate we have used the time depended function *F(τ)* of hail incidence. The analysis (Fig. 3) indicates that the main particularity of the intervals of hail generation *F(τ)* is a stair-step character of its dynamics which points out on strengthening and weakening of the environments that contribute to the hail formation as a weather phenomenon. At the same time, gradation curve *F(τ)* is irregular, which indicates on a weak "organization" of the original function and the random nature of the atmospheric processes contributing to hail generation.

More detailed investigation reveals an important particularity which consists in the fact that in the recent decades (1981-2015), the differential values $\lambda_d(\tau)$ of the Poisson rate in the intervals of hail generation F(τ) is considerably lower. In the figure 6, it is clearly noticed by the slow increment of original function F(τ) over the recent decades (1981-2015). This indicates on weakening of "failures" of the atmospheric processes contributing to hail generation resulting in the statistically significant decrease of the Poisson rate for post 1980-s climate. For example, for high sensitive area) the value of Poisson rate for the first period (1949-1980) is λ_1 =2.03, where as for the current climate (1981-2015) it constituted $\lambda_2 = 0.86$. Based on the calculation under the null hypothesis H_0 ($\lambda_2 = \lambda_1$), the confidence intervals show the values of λ supported by data fall between 1.76 and 2.36 with the statistically significant level at least 95%.

Conclusion and recommendations

This study was undertaken to investigate and better understand the hail hazard aiming at facilitating decision making and developing proactive preparedness measures in the Republic of Moldova. Moldova is highly vulnerable to hail incidence owing to the high level physical exposure, as well as inadequate capacity to manage hail risks. Variability of the intervals of hail generation in time has an irregular stair-step character which points out on the random nature of the atmospheric processes contributing to the hail as a climate phenomenon. More detailed investigation of the intervals of hail generation reveals a considerable decrease of the Poisson rate in the current climate (1981-2015) that indicates on weakening of "failures" of the atmospheric processes promoting to hail generation due to climate change resulting in a long-term decrease of hail incidence over the Republic of Moldova.

Using the advances in extreme value modeling the study provides the first regional assessment of hail risk based on the return level and waiting time concept, which is a convenient approach to developing proactive management plans. The investigation has also ensured more effective use of the actual and modeled hail data in terms of aligning with management design information and decision support tools.

The findings promote extended and new services in improving accessibility of the management design information for decision making. In particular, the study has upgraded the existing tools for hail early warning systems that can be used for more effective policy interventions to reduce hail impacts. However, for the outputs leading to improving accessibility and increased awareness to be more sustained, the efforts need to form a partnership with the key stakeholders in developing new design products based on real-time based services combined with integrating guide information.

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