We would like to thank the Reviewers for the positive comments and suggestions to improve the manuscript. The specific comments are addressed in detail below. Please note that the Reviewers' comments are shown in bold text and authors' replies are in plain text. Please find also the manuscript with the correction added as required by the reviewers.

Reviewer no 1.

Specific comments:

1. P 1496, L8-10: What other indicators were computed? How do they compare with Sc-PDSI?

The other indicators were added in the text. Comparison of Sc-PDSI with SPI (Standardized Precipitation Index) and SPEI (Standardized Precipitation-Evapotranspiration Index) was mentioned*:*

When compared with other drought indicators Sc-PDSI shows good correlation with indices of long accumulation periods. The correlation over each grid point and for entire Carpathian region and time period (1961-2010) shows high values with the SPI_9 (0.85) and SPEI_9 (0.82) detecting the drought events on comparable spatial and temporal resolution and lower values with SPI_1 (0.33) and SPEI_1 (0.35) (Antofie, et. al., 2013).

2. P 1496, L11-12: And the other indicators are not able to measure the intensity and severity of droughts?

Corrections made in the text.

3. P 1497 L7: There is not description of the region studied in the manuscript. A small description is needed to understand the characteristics of the area in the study. More- over, the location of the region in the continent/globe is not mentioned (for example: located in Central and Eastern Europe). I would be nice to enhance Fig. 1 by locating the region in the continent and then zooming to the region. Furthermore, there is no mention to observed past droughts in the region. Do droughts occur often?

Description of the region added in the text:

Stretching across Central and Eastern Europe, the Carpathian Mountains spans over seven countries, in the studied region, starting with the Czech Republic Slovakia and Poland in the northwest then continuing East and southwards through Ukraine, Hungary, Romania and Serbia. The region also spans over parts of Croatia, Bosnia Herzegovina, Bulgaria and Republic of Moldova. The Carpathian Mountains represent a prolongation of the Alps to the East and northeast, but their structure is less compact, and they are split up into a number of mountain blocks (with heights reaching over 2000 m in altitude) separated by basins (such as Pannonian and Transylvanian) and surrounded by lowlands. As climate feature, the Carpathian region receives polar-continental air masses arriving from the East and northeast in the winter, while during other seasons oceanic air masses from the West and also Mediterranean in the southern part (KEO; UNEP/DEWA 2007).

Drought occurrence in the region is presented in the text (P 1502 L7-L15).

4. P 1497 L10: What is the temporal scale of the model? Please add.

The temporal scale was added in the text: *The computation of the Sc-PDSI (Wells et al., 2004) is made on monthly temporal scale*

5. P 1497 L14: Where is this precipitation coming from? Is it reanalysis data? or coming from satellite? or measured in the ground?

Description of the precipitation data provenience was added in the text:

Temperature and precipitation gridded data have been interpolated within the CARPATCLIM project from quality-checked, completed, homogenized and harmonized station data. Please see Spinoni et al., 2014 for a more detailed description.

Spinoni, J., Szalai, S., Szentimrey, T., Lakatos, M., Bihari, Z., Nagy, A., Németh, Á., Kovács, T., Mihic, D., Dacic, M., Petrovic, P., Kržič, A., Hiebl, J., Auer, I., Milkovic, J., Štepánek, P., Zahradnícek, P., Kilar, P., Limanowka, D., Pyrc, R., Cheval, S., Birsan, M.-V., Dumitrescu, A., Deak, G., Matei, M., Antolovic, I., Nejedlík, P., Štastný, P., Kajaba, P., Bochnícek, O., Galo, D., Mikulová, K., Nabyvanets, Y., Skrynyk, O., Krakovska, S., Gnatiuk, N., Tolasz, R., Antofie, T. and Vogt, J.,: Climate of the Carpathian Region in the period 1961–2010: climatologies and trends of 10 variables. Int. J. Climatol.. doi: 10.1002/joc.4059, 2014.

6. P 1497 L16: Same question for the temperature. Where is this temperature coming from?

Description of the precipitation data provenience was added in the text.

7. P 1497 L24: What is HYPRES? This should be defined at a first mention.

The definition was added in the text: ..Hydraulic Properties of European Soils (HYPRES)..

8. P 1498 L3-6: Are runoff and recharge hydrological parameters or fluxes? Please rephrase/expand this paragraph. It is not clear what is computed and what is the input information to the model. Maybe a formula on the water balance with the terms considered in the model would help. Moreover, which are the Palmer constants and what is the meaning of the CAFEC precipitation? Which of the parameters described come from external datasets and from where? This should be clear in this section. The methods described may fit better in section2.2.1.

Correction made in the text. The paragraph moved in section 2.2.1:

The potential evapotranspiration (PET) is estimated following Thornthwaite (1948), while the other potential parameters are defined as follows: the potential recharge (PR) is the amount of moisture required to bring the soil moisture up to filed capacity (AWC less the total amount of moisture stored in both soil layers), the potential loss (PL) is the moisture that could be lost from the soil if precipitation is zero for the month and the potential runoff (PRO) is defined as total AWC less potential recharge (PR). By summing the monthly mean potential values which are previously scaled by their ratio with the monthly mean actual values, Climatically Appropriate for Existing Conditions (CAFEC) - precipitation, (or the precipitation needed to maintain a normal soil moisture level) is obtained.

9. P 1498 L7-12: What is the climate characteristic coefficient? Maybe this entire paragraph would fit better in section2.2.2? Or are any of the things described here external datasets?

Correction made in the text. The paragraph moved in section 2.2.2.

10. P 1498 15-17: This sentence is not clear, please rephrase. Originally it was computed on a monthly basis, and what is the temporal basis now?

The sentence was rephrased:

Sc-PDSI is based on the Palmer Drought Severity Index (PDSI), first introduced by Palmer (1965) and modified by Wells et al. (2004) in order to allow a more accurate comparison of the index at different locations. Sc-PDSI measures the cumulative departure of moisture supply and demand computed on monthly time scale.

11. P 1498/1499, Section 2.2.1: A brief description of the model in the methodology mentioning key parameters and fluxes would help to understand the methods used. The title of the section is "Sc-PDSI computation" and the computation methods are not described at all.

A brief description has been presented in Section 2.2.1.
We have also presented the main steps of the methodology and the modifications made to obtain Sc_PDSI in Annex I following the already common approach presented in numerous articles (Alley, 1984; Guttman et al., 1992; Weber and Nkemdirim 1998; Wells et al., 2004; van der Schrier et al., 2006). The reason behind our choice was that the methodology that was required in the main body of the paper is the one of the precipitation needed to end or ameliorate the drought recover from the drought, which is the main subject of the paper.

12. P 1499 L4: What is the sub index i in this section? Is it month?

The definition of *i* index was added in the text. The index *i* in this section denotes the monthly time scale.

13. P 1501, L9: Why was the gamma distribution used?

Reasoning has been presented in text:

Gamma distribution has been frequently used in literature to represent precipitation (Thom, 1966; Wilks, 1990; 1995, Oeztuerk, 1981) due to the advantage that it excludes negative values, being bounded on the left at zero (Thom, 1966; Wilks, 1995). Analysis of rainfall data strongly depends on its distribution pattern (Sharma, et al., 2010). This is especially important as Gamma distribution is positively skewed and represents an advantage as it mimics the actual rainfall distributions for many geographical areas (Ananthakrishnan, et al., 1989). Also it provides a flexible representation of a variety of rainfall regimes while utilizing only two parameters, the shape and the scale (Wilks, 1990).

Ananthakrishnan, R., Soman, M. K., Statistical distribution of daily rainfall and its association with the coefficient of variation of rainfall series. International Journal of Climatology 9: 485–500, 1989.

Oeztuerk, A.: On the Study of a Probability Distribution for Precipitation Totals, Journal of Applied Meteorology. 20:1499-1505, 1981.

Thom, H. C. S.,: Some Methods of Climatological Analysis. WMO Technical note 81, Secretariat of the WMO, Geneva, Switzerland, 53 pp., 1966.

Wilks, D., S.,: On the Combination of Forecast Probabilities for Consecutive Precipitation Periods. Wea. Forecasting, 5, 640–650, 1990.

Wilks, D. S.,: Forecast verification. Statistical Methods in the Atmospheric Sciences, Academic Press, 467 p, 1995.

Sharma, M. A., Singh, J. B.,: Use of Probability Distribution in Rainfall Analysis New York Science Journal, 23(9), 2010.

14. P 1502, L17-26: Was this compared with recorded droughts events in the region in the past years?

Recorded droughts in the region mentioned in the text:

The recorded drought occurrence in the region presented through country reports at UNCCD's 1st Regional Workshop on Capacity Development to Support National Drought Management Policies for Eastern European Countries (July 9-11, 2013, Bucharest) confirms the drought-prone characteristic of the region. The years with the highest drought incidence mentioned in the region are 2000, 2003, 2007 and 2012, (Holjevac, et al.,2013,), beginning of the 1990's (Gregorič, et al., 2013), the sequences from 1961 -1965, 1973-1974 and also 1980's since when it is noticed an increasing in the number of droughts (Mateescu, et al., 2013, Gregorič, et al., 2013).

Mateescu, E., Smarandache, M., Jeler, N., Apostol, V.,: Drought conditions and management strategies in Romania, Country Report, 1st Regional Workshop on Capacity Development to Support National Drought Management Policies for Eastern European Countries, Initiative on “Capacity Development to support National Drought Management Policy”(WMO, UNCCD, FAO and UNW-DPC, July 9-11, Bucharest Romania, 2013.

Holjevac, M.C., Pavlovic, D., Pandzic, K.,: Drought conditions and management strategies in Croatia, Country Report, 1st Regional Workshop on Capacity Development to Support National Drought Management Policies for Eastern European Countries, Initiative on “Capacity Development to support National Drought Management Policy”(WMO, UNCCD, FAO and UNW-DPC, July 9-11,Bucharest Romania, 2013.

Gregorič, G., Sušnik, A.,: Drought conditions and management strategies in Romania, Country Report, 1st Regional Workshop on Capacity Development to Support National Drought Management Policies for Eastern European Countries, Initiative on “Capacity Development to support National Drought Management Policy”(WMO, UNCCD, FAO and UNW-DPC, July 9-11, Bucharest Romania, 2013.

15. P 1503, L29 - P1504 L2: If the months mentioned here correspond to the points tagged in Fig.5 there are some that do not match. E.g: August 1990 for moderate droughts, and January 1990 for severe droughts.

Corrections made in the text. After correction for moderate droughts is July 1990 and for severe droughts is January 1991.

16. P 1504, L28 - P1505 L3: Please rephrase this sentence to clarify. Should it say "...beginning of summer (May/June/July) and end of summer (July/August) respectively, ..."?

Sentence rephrased as indicated.

17. P1505 L4-5: Is this on average for the whole period? Indicate in the text.

Corrections added in the text.

18. P1505 L9: Add "in the next month" after "to end a drought".

Corrections added in the text.

19. P1506 L13: Is it "May and June" or "April and May"?

Corrections made in the text.

20. P1506 L15: And also Oct/Nov/Dec for the north-eastern area.

Corrections added in the text.

21. P1506 L16: Corresponding with which months of the annual precipitation cycle?

Correction added in the text: *... corresponding with the driest months of the annual precipitation cycle.*

22. P1506 L27: January and February?

Correction made in the text.

23. P1508 L2-5: Were the results verified in some way with observed/recorded data?

The 'drought –prone' characteristic of the region has been mentioned. Results obtained with Sc-PDSI have been validated by comparison with other drought indicators.

24. P 1509, L7: What do you mean by "... until the layer is full"?

Correction made in the text: "….*until the layer is saturated*.."

25. P 1509, L9: Are actual values of evaporation, recharge and runoff hydrological parameters or fluxes? How are the potential values estimated? A formula on the model water balance would help.

Definitions added in the text:

The potential evapotranspiration was computed using the Thorntwaite formula while the other potential parameters are computed as follow (Weber and Nkemdirim 1998): the potential recharge (PR) is the amount of moisture required to bring the soil moisture up to filed capacity (AWC less the total amount of moisture stored in both soil layers), the potential loss (PL) is the moisture that could be lost from the soil if precipitation is zero for the month and the potential runoff (PRO) is defined as total AWC less potential recharge (PR).

26. P 1525: Fig 8. Please make sure that the figure is clear and the text is readable in the final format. The font size seems very small (unreadable) but it might be to the

format provided in HESSD.

All the figures have been provided to the publisher with the requested resolution (300dpi)

Technical corrections:

27. P 1495, L20: Why 2010b? Is there a 2010a?

Correction made in the text.

28. P 1495, L26: Why 2000a? There is not another reference to Wilhite et al. in the 2000.

Correction made in the text.

29. P 1495, L27: The reference on WMO, 2006 is missing. Also, the reference on ISDR, 2007 is missing.

References added:

ISDR, International Strategy for Disaster Reduction: Drought Risk Reduction Framework and Practices: Contributing to the Implementation of the Hyogo Framework for Action. United Nations Secretariat of the International Strategy for Disaster Reduction (UN/ISDR), Geneva, Switzerland, 98+vi pp, 2007.

WMO, World Meteorological Organization: Drought monitoring and early warning: Concepts, progress and future challenges. WMO-No. 1006, 2006.

30. P 1497, L1: 4 sections?

Correction made in the text.

31. P 1498, L20: The reference on Weber and Nkemdirim, 1998 is missing.

Reference added: *Weber, L., Nkemdirim, L.: Palmer's drought indices revisited Geogr. Ann., 80 A(2):153-172, 1998.*

32. P 1498, L21: Remove the b after Vicente-Serrano et al., 2010.

Correction made in the text.

33. P 1499, L1: Remove the comma after "presented in"

Correction made in the text.

34. P 1501, L8: Replace "precipitations" for "precipitation"

Correction made in the text.

35. P 1502, L17: Remove "the" previous to "Fig.4"

Correction made in the text.

36. P 1503, L3 and L6: Change "SC-PDSI" to "Sc-PDSI" to uniformize.

Correction made in the text.

37. P 1505, L29: The reference Busuioc, 2001 is missing.

Reference added:

Busuioc, A.,: Large-scale mechanism, influencing the winter Romanian climate variability, Detecting and Modelling Regional Climate Change and Associated Impacts, M. Brunet and D. Lopez eds Springer-Verlag, 333-343. 2001.

38. P 1508, L24: Reference is not correct, change "Thornthwaite's method, 1948" for "Thornthwaite, 1948"

Correction made in the text.

39. P 1511, L13: Shouldn't it say "dry/wet spells" instead of "drought/wet spells"?

Correction made in the text.

40. P 1511, L23: Shouldn't it say "dry" instead of "drought"?

Correction made in the text.

42. P 1512, L9: Is the reference on Allen et al., 1998 mentioned somewhere in the manuscript?

Correction made in the text.

Reviewer no.2.

We would like to thank the Reviewer for the positive comments and suggestions to improve the manscript. The specific comments are addressed in detail below. Please note that the Reviewers' comments are shown in bold text and authors' replies are in plain or italic text.

\textbf{**Main comments:}**

1. \textbf{**The authors come to the conclusion that the most likely end of a drought is during the wet season, and vice versa. This reasoning is not correct. Obviously, a wet climatological period will on average end a dry period, but that is not how the end of a dry period is usually defined. A drought is defined as the anomaly of a time period (month, several months, season) against its own climatology. For longer periods of accumulation, a wet season will obviously dominate the drought signal, therefore a wet anomaly in the normally wet**

season leads to a recovery regardless of the precipitation of the dry season. This is trivial, and hardly something to discuss. The most trivial example is the dry season being interrupted by the monsoon/rain season. The real problems starts when there is a dry anomaly in the wet season. The recovery of droughts should rather be studied with regards to the inter-annual variation of the precipitation and what governs this. Obviously, even a wet anomaly in the dry season could compensate for this. Therefore, my suggestion in the review process: Can the recoveries be related to large-scale patterns, or are they random variations? If the answer to the former is yes, then can they be predicted?}

Recommendations considered in text.

We agree with the reviewer in that fact that obviously a wet period will end a dry period. Also we agree with the definition of droughts regarding to abnormally dry periods compared with its own climatology. The reviewer also pointed out the extreme case of a monsoon dominated area.

We agree with the fact that the main climatological results are in line with greater scale atmospheric features and obviously related with precipitation patterns. The intention of the methodology is to assess the potential of recovery for single events. As shown in Figure 5, the drought events are centred in different seasons but the potential recovery should be benchmarked with the climatological values. As this drought recoveries are associated with different circulation patterns (that are outside the scope of this paper) this can be predicted with the same skill of the state of art seasonal forecast systems for the region.

Moreover, even if the information related to the water needed to recover is not a forecast, it can be used to re-define irrigation schemes even with the only knowledge of the climatology.

A brief description of the main circulation patterns are depicted below:

For both, the required precipitation and the probabilities of recovery from drought, a spatial pattern linked with the atmospheric circulation responsible for the climate variability in the Carpathian region can be noticed. The southern and southwestern Carpathians and the western Carpathians act like a barrier for the main sources of moisture (Mediterranean and North Atlantic air masses; Busuioc and von Storch, 1996, Busuioc, 2001). The intra-annual variability of these systems are causing firstly high precipitation amounts and a pronounced annual precipitation cycle, as it is the case of North Atlantic circulation in the western, northern and northwestern part of the Carpathian region. Secondly, highly variable precipitation intensity and a relatively constant distributed precipitation regime through the year (by creating a second precipitation peak in autumn), as it is the case of Mediterranean cyclones in the southwestern and southern part of the Carpathian region.

The cyclonic presence and trajectories have been the subject of extensive climatological research (e.g. W. van Bebber, 1891; Radinovic, 1987; Katsoulis, 1980; Flocas, 1988; Maheras, 2001). Often these studies establish a connection between the advance of the cyclones from the Mediterranean area and intense precipitation events. High amounts of precipitation with genesis in the Mediterranean space (Gulf of Genoa) are produced on the cyclonal trajectory V (from the Tyrrhenian Sea to Ukraine). Most important for the Carpathian region are the trajectory Vc, that crosses from west to east, the south of Carpathian region, in spring and very rarely in summer and trajectory Vb, important for the western part of the Carpathian region, passing over the Pannonian Plain, towards Poland. For both trajectories, the cyclones circulate especially in autumn, winter and spring with the largest probability of occurrence in April and a secondary maximum in early autumn. The cyclone circulation diminishes and migrates southwards in December-January, due to the intensification of the Azores and Siberian anticyclones (Maheras, 2001).

Even if the annual cycles of the moisture supply and demand follow a continental pattern (imposed by the North Atlantic circulation) with a maximum of supply and demand at the beginning of the summer (May/June/July) and end of summer (July/August) respectively a minimum in the winter months (December/January/February) the months with the higher probability of substantial excess of precipitation from the normal (April/May in spring and October/November in autumn) will be related with the cyclonic presence from the Mediterranean area.

Flocas, A. A.,: Frontal depressions over the Mediterranean Sea and central southern Europe. Méditerranée 4: 43 – 52, 1998.

Katsoulis, B. D., Makrogiannis, T. D, Goutsidou, Y. A.,: Monthly anticyclonicity in southern Europe and the Mediterranean region. Theoretical and Applied Climatology 59: 51 – 59, 1998.

Maheras, P., Flocas, H. A., Patrikas, I., and Anagnostopoulou, C.,: A 40 year objective analysis of surface cyclones in the Mediteranean region: Spatial and temporal distribution, Int. J. Climatol., 21, 359–367, 2001.

van Bebber, W.,: Die Zugstrassen der barometrischen Minima, Meteorol. Z., 8, 361–366, 1891.

Radinovic, D.,: Mediterranean Cyclones and their Influence on the Weather and Climate. Programme on Short and Medium Range Weather Prediction Research (PSMP), W.M.O Sofia 24, 1987.

2. \textbf{**The authors do not mention the motivation of the study until the end of the results section, where the winter wheat is mentioned. Please start off**

the paper with this information. Furthermore, there is little information on when is the sensitive period for these crops. I would assume that most important would be to have enough water during the initial growing period, but it is important to have a wet winter, or it is enough with spring rains? My point is that the authors should concentrate on the most important and sensitive season and accumulation time. This would also make the analysis easier.}

Recommendations considered in the text. Sensitive periods for the crops provided:

\textit{*As shown, in Carpathian region, the water deficits occur throughout the whole year. As the agriculture is an important economic sector in the Carpathian region the drought impact could be essential. Most crops may experience water stress (deficit) at various stages in their growth cycle. The sequences of vegetative growth with their key physiological phases (i.e. crop phenology) and their sensitivity to water deficit can be used to highlight the importance of seasonal analysis of drought occurrence. Winter crops (i.e. winter wheat) are planted in Carpathian region in September through October and harvested July through August of the next year, while the spring crops (i.e. maize, spring wheat, sunflower, potatoes) are planted April through May and harvested August through September or even October (potatoes) of the same year (KEO; UNEP/DEWA 2007).*
Early drought in the growing season - the end of autumn in October and November for winter crops and the end of spring in late April and May for spring crops - are affecting wheat germination and crop establishment (Bouaziz and Hicks, 1990). The water stress during the vegetative stages – the months of April and May for winter crops and late May and June for spring crops – may affect the leaf index development (Rickman et al., 1983). Soil water deficit increased towards harvesting – early summer for winter crops and late July or beginning of autumn in August for spring crops - is likely to produce a severe reduction in grain growth and quality which eventually cause reduction in final yields. Nevertheless it has been noted that water deficit in the maturity (anthesis) and harvesting period accelerates development (Simane et al., 1993) and significantly contribute to grain yield (Palta et al., 1994).}

Bouaziz, A., Hicks, D.R.,: Consumption of wheat seed reserves during and during and early growth as affected by soil water potential. Plant Soil, 128: 161-165, 1990.

Palta, J.A., Kobata, T., Turner, N.C., Fillery, I.R.,: Remobilization of carbon and nitrogen in wheat as influenced by post-anthesis water deficits. Crop Sci., 34: 118-124, 1994.

Rickman, R.W., Klepper, B.L., Peterson, C.M.,: Time distribution for describing appearance of specific culms of winter wheat. Agron. J., 75: 551-556, 1983.

Simane, B., Peacock, J.M., Struik, P.C.,: Differences in development and growth rate among drought-resistant and susceptible cultivars of durum wheat (Triticum turgidum L. var. durum). Plant Soil, 157: 155-166, 1993.

3. \textbf{**Why was the Palmer drought index used? It is not very commonly used outside the US and it has clear disadvantages? SPI is the index recommended by WMO, and it should at least be used as a comparison index. If you want to include soil moisture also standardized soil moisture index could be used.}**

Motivation for using Sc-PDSI provided in text. More detailed motivation presented below.

Palmer Drought Severity Index (PDSI) was developed (Palmer, 1965) with the intention of measuring the departure of soil moisture from the normal conditions, using a hydrological accounting system. Other drought indices (Standardized Precipitation-Evapotranspiration Index - SPEI, Standardized Precipitation Index - SPI, Reconnaissance Drought Indicator - RDI, and Palfai Drought Index - PADI) are based on past statistics of certain climate variables and often include precipitation alone (Dai, 2011). For example SPI is an exclusively precipitation-based drought indicator which assumes that droughts are directly controlled by the temporal variability of the precipitations. Recent studies have sustained the importance of the effect of other variables, such temperature, on drought conditions. These studies (Williams et al., 2011; Martínez-Villalta et al., 2008; McGuire et al., 2010; Linares et al., 2011) have shown that temperature rise affects the severity of the droughts and mainly the drought stress induced by heat waves on net primary production and tree mortality. As examples, the heat waves in Europe in 2003 and 2010 are mentioned due to their extreme role on drought severity which increased evapotranspiration and aggravated the drought severity (Rebetez et al., 2006). As result major decreasing in net primary production (Ciais et al., 2005) and high forest mortality under precipitation shortages (Adams et al., 2009) occurred. This illustrates at the end, how drought stress – through increased evapotranspiration - is determined, to a large degree, by the availability of soil moisture. The standardized precipitation evapotranspiration index (SPEI) developed by Vicente-Serano et al. (2010), considers also the temperature (in the computation of potential evapotranspiration - PE) however it is the actual evapotranspiration that affects the soil moisture availability and thus the drought conditions (Dai, 2011). Therefore, the use of drought indices which is based on a physical soil water balance model, such PDSI or modified versions as Sc-PDSI (used in this paper), is required in order to calculate current soil moisture conditions. In addition, Dai et. al, (2004) shows that PDSI is significantly correlated with measured soil moisture especially in warm season. Moreover, PDSI model, takes the precedent conditions into account in contrast with other drought indices that are based purely on past statistics (Dai. 2011). It uses previous and current moisture supply (precipitation) and demand (potential evapotranspiration) into a hydrological accounting system.

The PDSI or modified versions of PDSI have been used to quantify drought as a recurrent extreme climate event both at continental (Europe, North America) and global level (Dai, 1998; 2004; 2011; Wells et al., 2004; van der Schrier et al., 2006; 2007). By changing the standardization used by Palmer, (1965), which was based on data from US, Wells et al., (2004) proposed the Sc-PDSI – drought indicator used in our article - and it was recognized as an improvement of the original PDSI (Dai, 2010).

Moreover, the statistical based drought indices, such SPI and SPEI are normalized measures with respect to location and period, which makes the frequency of their severity classes climatologically consistent for any site (Heinrich, G., 2012). Practically they were not designed to identify regions that are more 'drought-prone' than others (Hayes et al., 1999). Therefore, Sc-PDSI has been used as it allows for comparison of drought frequency within different severity classes on different locations and it is suitable to account the drought under global warming conditions.

Various aspects (CAFEC precipitation - precipitation needed to maintain a normal soil moisture level, a climate characteristic coefficient and the moisture anomaly index) of the Palmer Drought Model, on which the Sc-PDSI is based on, are directly used in the calculation procedures of the precipitation required to end or ameliorate the drought, which not only confers homogeneity but also offers means of validation of the results obtained.

Adams, H.D., Maite, G. C., Greg, A. B. G., Juan, C. V., David, D. B., Chris, B. Z., Peter, A. T., Travis, E. H.,: Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global-change-type drought. *Proceedings of the National Academy of Sciences of the United States of America* 106: 7063-7066, 2009.

Ciais, Ph., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A.D., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Sanz, M.J., *Schulze, E.D., Vesala, T., Valentini, R.,: Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437, 529-533, 2005.*

Heinrich, G., Gobiet, A.,: The future of dry and wet spells in Europe: a comprehensive study based on the ENSEMBLES regional climate models. Int. J. Climatol., 32: 1951–1970. doi: 10.1002/joc.2421, 2012.

Linares, J.C., Camarero, J.J.,: From pattern to process: linking intrinsic water-use efficiency to drought-induced forest decline. *Global Change Biology* 18: 1000-1015, 2011.

Martínez-Villalta, J., López, B.C., Adell, N., Badiella, L., Ninyerola M.,: Twentieth century increase of Scots pine radial growth in NE Spain shows strong climate interactions. *Global Change Biology* 14: 2868–2881, 2008.

McGuire, A.D., Ruess, R. W., Lloyd, A., Yarie, J., Clein, J.C., Juday, G. P.,: Vulnerability of white spruce tree growth in interior Alaska in response to climate variability: dendro-chronological, demographic, and experimental perspectives. *Canadian Journal of* Forest Research, 40: 1197-1209, 2010.

Rebetez, M., Dupont, O., Giroud, M.,: Heat and drought 2003 in Europe: A climate synthesis. *Annals of Forest Science* 63: 569-577, 2006.

Vicente-Serrano S.M., Beguería, S., López-Moreno, J. I.,: A Multi-scalar drought index sensitive to global warming: The Standardized Precipitation Evapotranspiration Index – SPEI. Journal of Climate 23: 1696-1718, 2010.

Williams A.P., Xu, Ch., McDowell, N.G.,: Who is the new sheriff in town regulating boreal forest growth?. *Environmental Research letters* 6: doi: 10.1088/1748-9326/6/4/041004, 2011.

4. \textbf{**Figure 3 and 4 nicely shows what I think is an inherent problem in the Palmer index.**

From this it is obvious that the number of severe and extreme droughts are grossly overexaggerated. I cannot from this draw any conclusions on the reason behind this, but it might be a problem in the calibration of PDSI or the fact that it is a cold region, or that two short time periods are evaluated. Using the numbers from table 1 you can see that the categories slightly wet to extremely wet comprise 25% of the cases, whereas slightly dry to extremely dry 41%. There is a dry bias in the current setup of PDSI which will also bias your results.}

We would like to bring some arguments to support that the current severity frequencies of Sc-PDSI datasets presented in our work might have a common characteristic encountered also in other studies:

Recent studies have shown that the temperature rise, noticed mainly in the last decades had an important impact on drought magnitude producing an increase in the severity, areal extend and duration of drought events. Analyzing the impact of the temperature rise on drought, these studies - Brázdil et al., 2008 (for Czech Republic), Brunet M., et al., 2007 (for Spain), Szinell et al. (1998) (for Carpathian Basin), Briffa et al., 2009 (for Europe in summer) and Vicente-Serrano et al., 2010 (for a few locations around the world), Vicente-Serrano et al. 2014 (for Southern Europe), M. Sousa et al. 2011 (for Mediterranean, Iberian and Balkan area), van der Schrier et al. 2007 (for the Alpine region) - showed that, the extreme temperature, in particular, caused an increased evapotranspiration and aggravated the drought severity. This increasing in severity of drought caused an extension of the areas with drought conditions by the upscalling of the frequency of normal or mild spells towards a more severe class. As an example Schrier et al. 2007 concludes that in Alpine regions by 'temperature-related' effect only since 1992 an increasing of the areal extent of moderate (or worse) droughts is noticed. When backed up by anomalously low precipitation, as it happened in 2003, an increase in the percentage area with moderate (or worse) drought of 31.2% occurs, increasing the frequency of droughts with higher severity for these areas. Moreover 8.4% of the total area of the Alpine region examined experienced extremely dry conditions, of which 7.1% can be explained by high temperatures alone. Briffa et al., 2009, when analyzing the areal extend of summer droughts at European level concludes that, mostly in the last decades of the 20th , the dry areal extend is increasing, the dry summer are more frequent than the wet and this results are particularly strong in central Europe . Also in Central Europe, in Hungary, Szinell et al. (1998) using PDSI and two statistical tests showed that frequencies of moderate and severe drought events became greater in the 20th century, when analyzing data for the period 1881 – 1995.

In the Carpathian region the frequency of extremely dry spells is 4.0%, severely dry is 7.6%, moderately dry 12.5% and slightly dry is 16.7% of the entire dataset. It is the moderately and slightly dry spells that presents values that could be considered over exaggerated compared with slightly (11.6%) or moderate (7.4%) wet spell frequencies, not the extreme. For the Carpathian region van der Schrier et al., 2007 found between 2.5% and 5% frequency of the extreme dry spell and less than 2.5% for the extreme wet spells, values comparable with what we found. No data is presented for the frequency of other severity classes. It remains for a future analysis of the data to fully prove the origins of this frequency distribution per classes if not accepting the drought severity aggravation due to 'temperature-related' effect.

Brázdil R., M. Trnka, P. Dobrovolny, K. Chromá, P. Hlavinka, Z. Zalud (2008). Variability of droughts in the Czech Republic, 1881-2006. Theoretical and Applied Climatology 97:297-315, doi;10.1007/s00704-008-0065-x.

Briffa K. R., Van der Schrier G., P. D. Jones (2009). Wet and dry summers in Europe since 1750: evidence of increasing drought. International Journal of Climatology. 29:1894-1905, doi:10.1002/joc.1836.

Brunet M., P.D. Jones, J. Sigró, O. Saladié, E. Aguilar, A. Moberg, P.M. Della-Marta, D. Lister, A.Walther and D. López (2007), Temporal and spatial temperature variability and change over Spain during 1850-2005. Journal of Geophysical Research-Atmospheres 112:D12117, doi:10.1029/2006JD008249

van der Schrier, G., Efthymiadis, D., Briffa, K.R., Jones, P.D.,: European alpine moisture variability 1800–2003. Int. J. Climatol. 27, 415–427

Szinell Cs., Bussay A., Szentimrey T., 1998, Drought Tendencies in Hungary, Int. J. Climatol., 18, 1479−1491.

Vicente-Serrano, S.M.; López-Moreno, J.I.; Beguería, S.; Lorenzo-Lacruz, J.; Sanchez-Lorenzo, A.; García-Ruiz, J.; Azorin-Molina, C.; Morán-Tejeda, E.; Revuelto, J.; Trigo, R.; Coelho, F. and Espejo, F., : Evidence of increasing drought severity caused by temperature rise in southern Europe. Environmental Research Letters, 9, 044001, doi:10.1088/1748-9326/9/4/044001, 2014.

5. \textbf{**How exactly do the authors define a drought? In the Appendix you mention that extreme "wet/dry spells" should be at least 3 months? But in the results you talk of extreme droughts occurring 5-45 days per year? I assume you mean the daily index temporarily goes below extreme values, but that is a short dry spell, not a drought.}**

Correction made in the text.

The drought is considered in this paper as Dry/wet spell. A monthly value, which represents a negative/positive departure from the normal of the soil moisture.
In the Appendix the authors' intention was to refer to extremely dry/wet periods (no smaller than 3 consecutive months and with highest/lowest intensity of Zi) of various lengths which are used in the computation of the duration factors. Practically the Zi values accumulated over these periods of different lengths of time was regressed against its duration (months) aiming at representing the most extreme dry/wet periods of various lengths.

\textbf{**Minor comments:}**

1. \textbf{**You used the term "ameliorate" in the title, and that is correct English. However, even though I consider myself to be able to read English at a professional level I had to look up the word to be certain what it meant. I would seriously consider to replace it with something more common.}**

Correction made in the title.

2. \textbf{**P1496, L14. You state here that PDSI can be used as meteorological, hydrological and agricultural drought index, but also indexes like SPI and SPEI can be used the same way, it is more a matter of the time scale.}**

Corrections made in the text. The authors mend to underline the use of a physical model based on a rather complex soil water budget system that can account for a meteorological, hydrological and agricultural drought index.

The time period from the arrival of water inputs to availability of a given usable resource differs considerably. Thus, the time scale over which water deficits accumulate becomes important and functionally separates different types of drought (hydrological, meteorological, and agricultural) McKee et al. (1993). Nevertheless, the relationship between accumulation period and impact depends on a wide range of physical parameters (geology, soil properties, hydro-meteorological characteristics, vegetation) not only on its time scale of accumulation.

SPI for example, allows for estimating different potential impacts (immediate, medium, long impacts) of a meteorological drought, through its different rain fall accumulation periods. Sims et al. (2002) indicated that SPI, even if it appears to be suited for estimating soil moisture deficit, it gives errors in indicating drought conditions when it is calculated at short time scales or for precipitation regimes when zero precipitation value is climatologically expected. From the acceptance of agricultural drought the soil moisture is a key variable for the evaluation of this type of drought.

On the other side PDSI has been criticized because of its inability to indicate drought conditions for time scales shorter than 12 months (Vicente-Serrano. et al., 2010). However the Z index (Soil moisture anomaly index) from the Palmer Drought Model it is known for its high sensibility to changes in soil moisture (Karl, 1986).

Sims, A.P.; Niyogi, D.; Raman, S. Adopting drought indices for estimating soil moisture: A North Carolina case study. Geophysical Research Letters, v.29, p.24.1-24.4, 2002.

3. \textbf{**P1496, L22-25. Sentence is not easy to understand, please rephrase.}**

Corrections made in the text:

Based on these considerations and using the assumptions of the Palmer Drought Model (PDM), the precipitation needed to end or ameliorate a drought (in 1,3 or 6 months period) for different levels of severity (moderate when Sc-PDSI ≤ -2, severe when Sc-PDSI ≤ -3, extreme when Sc-PDSI ≤ -4) and their climatological probability have been computed.

4. \textbf{**Figure 1. Please improve the figure with country names, colorbar for elevations, and put it into a European context.}**

Figure improved.

5. \textbf{**Figure 8 is too small and cannot be interpreted.}**

All the figures have been provided to the publisher with the requested resolution (300dpi)

Estimating the water needed to end the drought or ~~ameliorate~~ reduce the drought severity in the Carpathian region

Comment [T1]: Ref2 in Minor comments 1

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Abstract

A drought severity climatology for the Carpathian Region has been produced using the self-calibrating Palmer Drought Severity Index (Sc-PDSI) for the period 1961-2010. Using the Sc-PDSI and the assumptions of the Palmer Drought Model (PDM) the precipitation required for drought termination (when Sc-PDSI reaches -0.5) and amelioration (when Sc-PDSI reaches -2.0) are computed for periods of 1, 3 and 6 months. We discuss the reduction of the uncertainty in the determination of the beginning and ending of drought conditions and provide a quantitative measure of the probability that any drought could be ameliorated or terminated. We present how the spatial variability of the amount of water needed for drought recovery and the climatological probability of receiving that amount of water is determined by the local conditions against the general climate characteristics of a small area such as the Carpathian Region. Regionally, the Pannonian Basin, the Transylvanian Plateau and the external Carpathians foothills and plains in the southern and eastern part of the region require the highest quantity of precipitation to recover from a drought while having the lowest climatological probabilities for such amounts of rainfall. High precipitation amounts over the North and northwest part of the region result in higher soil moisture supplies and higher climatological probabilities to end a given drought event. Moreover the succession and/or predominance of particular types of general atmospheric circulation patterns produce a seasonal cycle and inter-annual variability of precipitation that is quantitatively reflected in the excess of precipitation above normal required for drought recovery. Overall, the results of this study provide an overview on the chances of recovery from a drought period with

moderate or severe drought and present information useful in decision making in water and drought management.

Keywords: Carpathian Region, Sc-PDSI, drought recover, drought risk management

1 Introduction

Drought is one of the most far-reaching natural and socio-economic disasters (WMO/UNCCD/FAO/UNW-DPC, 2013). Traditionally, the acknowledgement and attempts to manage droughts were mostly orientated towards crisis management, while little attention has been given to pro-active drought risk management. More recently, European as well as international policies and initiatives have highlighted the need for a more pro-active, risk-based management of droughts. Examples are the requirement for the set-up of River Basin Management Plans, including Drought Management Plans under the European Water Framework Directive (WFD), the High Level Meeting on National Drought Policies (HMNDP, http://www.hmndp.org), or the Integrated Drought Management Programme (IDMP, http://www.droughtmanagment.info) established by the World Meteorological Organization (WMO) and the Global Water Partnership (GWP) in 2013 .

An essential element in risk management is the reduction of drought impacts (i.e. mitigation) based on an assessment of the cost of damages associated with droughts as compared to the costs for efficient early warning and preparedness, including the adaptation to climate change. Drought as a natural hazard has been the subject of a great number of studies, focusing on the definition of drought and the development of drought indicators (e.g., Palmer, 1965; McKee et al., 1993; Wells et al., 2004; Vicente-Serrano et al., 2010~~b~~) as well as on drought assessment and monitoring (e.g., Briffa et al., 1994; Guttman et al., 1998; Lloyd-Hughes and Saunders 2002; Dai et al., 2004; van der Schrier et al. 2006; Dai, 2011~~–~~). However, little attention was given to the analysis of probabilities that a given drought (and its impacts) could be ameliorated or terminated through adequate rainfalls. The number of studies addressing the drought recovery topic are few (Karl et. al., 1986, 1987) and articles focused on drought as a natural hazard (Wilhite et al., 2005, 2000~~a~~) as well as reports on drought management and monitoring (e.g., WMO, 2006, IPCC, 2007; ISDR, 2007;), address the subject only in a general manner.

Comment [T2]: Ref1 comment **P 1495, L20**

Comment [T3]: Ref 1 comment **P 1495, L26**

This paper provides a quantitative measure of the probability that any drought could be ameliorated or terminated over some defined period of time - using the assumption of the Palmer Drought Model (PDM) (Karl et al., 1987). The study was partially implemented in the framework of the CARPATCLIM project (http://www.carpatclim-eu.org). Within this project a consortium of meteorological services and environmental institutes of 9 countries of the region joined forces with the purpose of improving the availability and accessibility of quality controlled meteorological and climatological data. Based on the CARPATCLIM daily and monthly gridded data (0.1°x 0.1° resolution for the 1961-2010 period), a series of indicators (Self-calibrating Palmer Drought Severity Index - Sc-PDSI, Standardized Precipitation-Evapotranspiration Index - SPEI, Standardized Precipitation Index - SPI, Reconnaissance Drought Indicator - RDI, and Palfai Drought Index - PADI) were computed with the purpose of defining the climate characteristics of the region. Among the ~~Self-calibrating Palmer Drought Severity Index (~~Sc-PDSI~~), which~~ was selected due to its ~~ability~~ use ~~to~~ in measur~~e~~ing the intensity and severity of drought events in Europe (van der Schrier et al., 2006,2007) and to quantify the impact of droughts on a wide range of economic sectors (it serves as a meteorological, hydrological and agricultural drought index, Karl, 1983; Karl and Knight, 1985), using a physical model based on a complex soil water budget system. In addition, it can be used (following the assumptions of the Palmer Drought Model) to assess the chances of drought recovery. Despite its importance, quantifying drought recovery has not been examined yet, in the Carpathian region. Moreover, the agriculture is a major economic sector in the Carpathian region (KEO; UNEP/DEWA 2007). The main agricultural crops in the region are winter wheat, maize and potatoes (KEO; UNEP/DEWA 2007), which are highly vulnerable to droughts throughout the whole year. Therefore information on ending or ameliorating the droughts, climatological probability that the droughts could be recovered and the seasonal analysis of drought occurrence could be useful in decisions concerning the water and agricultural resources management.

The Sc-PDSI is a drought indicator based on the principles of balance between moisture supply and demand. A series of articles have pointed out the assumptions, strengths and weaknesses of the Palmer Drought Model along with details on calculation procedures (Alley, 1984; Karl, 1987, 1986 a,b; Wells et al., 2004; van der Schrier et al., 2006). The PDSI or modified versions of PDSI have been used to quantify drought as a recurrent extreme climate event both at continental (Europe, North America) and global level (Dai, 1998; 2004; 2011;

Comment [T4]: Ref 1 comment **P 1496, L8-10 . Comparison also provided.**

Comment [T5]: Ref 1 comment **P 1496, L11-12**

Comment [T6]: Ref 2 comment 2 of main comments

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Wells et al., 2004; van der Schrier et al., 2006; 2007). By changing the standardization used by Palmer, (1965), which was based on data from US, Wells et al., (2004) proposed the Sc_PDSI and it was recognized as an improvement of the original PDSI (Dai, 2010). PDSI was developed with the intention of measuring the departure of soil moisture from the normal conditions, using a hydrological accounting system. Different from PDSI other drought indicators are based on past statistics of certain climate variables which often include only precipitation (Dai, 2011) and assumes that droughts are directly controlled by the temporal variability of the precipitation. Recent studies have sustained the importance of the effect of other variables, such temperature, on drought conditions. These studies (Williams et al., 2011; Martínez-Villalta et al., 2008; McGuire et al., 2010; Linares and Camarero, 2011) have shown that temperature rise affects the severity of the droughts and mainly the drought stress induced by heat waves on net primary production and tree mortality. For examples, the heat waves in Europe in 2003 and 2010 had an extreme role on drought severity which increased evapotranspiration and aggravated the drought severity (Rebetez et al., 2006). As result major decreasing in net primary production (Ciais et al., 2005) and high forest mortality under precipitation shortages (Adams et al., 2009) occurred. This illustrates at the end, how drought stress – through increased evapotranspiration - is determined, to a large degree, by the availability of soil moisture. Therefore, the use of drought indices which is based on a physical soil water balance model, such PDSI or modified versions as Sc_PDSI, is required in order to calculate current soil moisture conditions. Moreover, the statistical based drought indicators are normalized measures with respect to location and period, which makes the frequency of their severity classes climatologically consistent for any site (Heinrich, 2012), not being able to identify regions that are more ‘drought-prone’ than others (Hayes et al., 1999). Therefore, PDSI has been used as it allows for comparison of drought frequency within different severity classes on different locations and it is suitable to account the drought under global warming conditions. Various aspects of the hydrological model, on which the PDSI is based on, are directly used in the calculation procedure of the precipitation required to recover from drought, which not only confers homogeneity but also offers means of validation of the obtained results.

Based on these considerations and using the ~~the~~ assumptions of the Palmer Drought Model (PDM), the precipitation needed to end or ameliorate a drought (in 1, 3 or 6 months period) ~~at a specific~~ for different levels of severity ~~(Sc-PDSI ≤ -2, Sc-PDSI ≤ -3, Sc-PDSI ≤ -4)~~ (moderate when Sc-PDSI ≤ -2, severe when Sc-PDSI ≤ -3, extreme when Sc-PDSI ≤ -4), and

Comment [T7]: Ref2 comment 3 from Main comments their climatological probability ~~that this precipitation could fall~~ have been computed ~~for time periods of 1, 3 and 6 months ahead~~. A spatial and temporal analysis of these results is presented, including information on the deviation (%) of the required precipitation from the normal annual rainfall cycle and an analysis of the months of the year with the highest/lowest probability for terminating a drought at different levels of severity.

Comment [T8]: Ref 2 comment P1496 L22-25

The paper is organized in ~~3~~4 sections. Following the introduction, in Sect.2 we detail the data and computation methodologies used in this study and in Sect. 3 we present the results of the spatio-temporal analyses. Final conclusions are then drawn in Sect. 4, followed by an appendix where we detail the Sc-PDSI calculation.

Comment [T9]: Ref1 comment P1497,L1

2 Data and Methodology

2.1 Data

The region covered by this study, depicted in Fig. 1, is centred on the Carpathian Mountains and the surrounding lowlands (17˚-27˚E, 44˚-50˚N). Stretching across Central and Eastern Europe, the Carpathian Mountains spans over seven countries (in the studied region), starting with the Czech Republic Slovakia and Poland in the northwest, then continuing East and southwards through Ukraine, Hungary, Romania and Serbia. The region also spans over parts of Croatia, Bosnia Hertzegovina, Bulgaria and Republic of Moldova. The Carpathian Mountains represent a prolongation of the Alps to the East and northeast, but their structure is less compact, and they are split up into a number of mountain blocks (with heights reaching over 2000 m in altitude) separated by basins (such as Pannonian and Transylvanian) and surrounded by lowlands. As climate feature the Carpathian region receives polar-continental air masses arriving from the East and northeast in the winter, while during other seasons oceanic air masses from the West and also Mediterranean in the Southern part (KEO; UNEP/DEWA 2007). The data required to calculate the water needed to recover from drought events are reprocessed from the Palmer Drought Model used to compute the Sc-PDSI. The computation of the Sc-PDSI (Wells et al., 2004) is made on monthly temporal scale and is based on the moisture demand and supply (water-balance model) and takes into account precipitation, evapotranspiration and soil moisture conditions. The basic input data are the following:

Comment [T10]: Ref1 comment P1497 L7. .Drought occurance presented in Results.

Comment [T11]: Ref1 comment P1497 L10.

- Gridded monthly precipitation (from the CARPATCLIM project at 0.1˚x 0.1˚ spatial resolution for the 1961-2010 period) ;
- Gridded monthly mean surface air temperature (from the CARPATCLIM project 0.1˚x 0.1˚ resolution for the 1961-2010 period) used to compute Thornthwaite's Potential Evapotranspiration – PET, (Thornthwaite, 1948);

Temperature and precipitation gridded data have been interpolated within the CARPATCLIM project from quality-checked, completed, homogenized and harmonized station data. Please see Spinoni et al., 2013 for a more detailed description.

Comment [T12]: Ref1 comment P1497 L14 and P1497 L16.

- The Available Water Holding Capacity (AWC) of the soil, computed from the soil texture classes and soil profile depths in the European Soil Database (http://eusoils.jrc.ec.europa.eu/) and the Soil Geographical Database of Eurasia (Toth and Weynants, 2012). The AWC values per grid cell, shown in Fig. 2, are assumed to be constant over the considered period and calculated using the van Genuchten equation for which the parameters are obtained from the Hydraulic Properties of European Soils (HYPRES) pedotransfer class functions (based on the texture classes) (Wosten et al., 1999).

Comment [T13]: Ref 1 comment P1497 L24

~~In addition the climatic water balance was used (computed as a difference between gridded accumulated precipitations and potential evapotranspiration) together with 6 hydrological parameters of the soil water balance: recharge, runoff, and water loss from the soil and their potential values (used in the calculation of Palmer's constants to give the Climatically Appropriate for Existing Conditions for the specific location, i.e. the so called CAFEC precipitation).~~

Comment [T14]: Ref 1 comment P1498 L3-6. Moved in section 2.2.1

~~Finally,~~ For the computation of the precipitation needed to recover from drought gridded datasets of CAFEC precipitation (precipitation needed to maintain a normal soil moisture level), ~~the~~ climate characteristic coefficient ~~(K_i)~~ and the moisture anomaly index ~~(Z_i) (~~from the Palmer Drought Model~~)~~ for ~~the~~ 1961-2010 period were used. ~~were used for the computation of the precipitation needed to end and ameliorate a drought. The climatological probabilities of receiving these precipitations were calculated using the probability density function and the cumulative probability function of the gamma distribution.~~ A complete description of these variables is presented in section 2.2.2

Comment [T15]: Comment P1498 L 7-12 . Moved in section 2.2.2

2.2 Computation methodologies

2.2.1 Sc-PDSI computation

Sc-PDSI is based on the Palmer Drought Severity Index (PDSI), first introduced by Palmer (1965), ~~and originally computed on a monthly basis~~ and modified by Wells et al. (2004) in order to allow a more accurate comparison of the index at different locations. ~~It~~ Sc-PDSI measures the cumulative departure of moisture supply and demand from the normal conditions and is computed on monthly time scale. The supply in this model is the precipitation, the water demand is the potential evapotranspiration and the outputs are the actual evapotranspiration and runoff. Often discussed in other studies (e.g., Alley 1984; Karl 1986a; Guttman et al., 1992; Weber and Nkemdirim 1998; Wells et al., 2004; Dai et al., 2004; Vicente-Serrano et al., 2010~~b~~) the strengths, weakness and differences of these two drought indicators will not be examined in this study. The major difference lays in the reduced frequency of extreme events of Sc-PDSI when compared with PDSI as an overall effect of the calibration based on the actual climatic characteristics of a given location that allows Sc-PDSI to be more comparable between different locations.

Basically, the Sc-PDSI calculation procedure starts with the calculation of the monthly hydrological parameters of a rather complex soil water balance system-: evapotranspiration, recharge, runoff, water loss from the soil and their potential values. The hydrological system is confined by the assumptions that the soil is split in two layers (with the upper soil layer holding 25.4 mm of water) and the saturation level (of both soil layers) is conditioned by the top layer, both on supply and demand.

The potential evapotranspiration (PET) is estimated following Thornthwaite (1948), while the other potential parameters are defined as follows: the potential recharge (PR) is the amount of moisture required to bring the soil moisture up to filed capacity (AWC less the total amount of moisture stored in both soil layers), the potential loss (PL) is the moisture that could be lost from the soil if precipitation is zero for the month and the potential runoff (PRO) is defined as total AWC less potential recharge (PR). By summing the monthly mean potential values which are previously scaled by their ratio with the monthly mean actual values, Climatically Appropriate for Existing Conditions (CAFEC) - precipitation, (or the precipitation needed to maintain a normal soil moisture level) is obtained.

Comment [T16]: Ref1 commentt P1498 L15-17

The difference between monthly precipitation and CAFEC-precipitation, weighted by a local climate characteristic coeficient (an empirical derived normalisation factor) results in Palmer moisture anomaly index (Palmer's Z-Index).

A description of the modifications made to obtain Sc-PDSI is presented in~~,~~ Appendix A.

2.2.2 Ending and ameliorating the drought

The Sc-PDSI$_i$ values and the assumptions of the Palmer Drought Model (PDM) were used for setting the theoretical basis of the calculation of precipitations needed to recover from the drought. Gridded datasets of CAFEC precipitation ($\hat{P}$), the climate characteristic coefficient (K_i) and the moisture anomaly index (Z_i) (from the Palmer Drought Model) for the 1961-2010 period are employed. The ~~precipitations needed to end or ameliorate the drought are~~ calculat~~ed~~ion starts by rewriting PDM's equation used to compute the moisture anomaly index (Z_i), from:

$$Z_i = (P_i - \hat{P}_i)K_i \qquad (1)$$

to $$P_i = \left(\frac{Z_i}{K_i}\right) + \hat{P}_i \qquad (2)$$

where,

i denotes the months of the year, P_i = precipitation needed to end or ameliorate the drought, $\hat{P}_i$ = CAFEC precipitation and K_i = the coefficient of climate characteristic;

However, before being able to compute P_i, Z_i has to be adapted to recovering drought conditions (end or ameliorate) and $\hat{P}_i$ has to be related with the Sc-PDSI$_{i-1}$ (of the previous month) as CAFEC precipitation (with its soil water balance variables) cannot be computed until the end of the month.

a. *The first step* represents the transformation of the moisture anomaly index (Z_i) from the self-calibrated drought severity formula in Eq. (3) into the moisture anomaly index needed to end the drought (Z_e) and the moisture anomaly index needed to ameliorate the drought (Z_a).

$$Sc\text{-}PDSI_i = pSc\text{-}PDSI_{i-1} + qZ_i \qquad (3)$$

From the PDSI severity classes (Palmer, 1965), adopted also for the Sc-PDSI (Table 1), it can be stated that a drought event ends when the Sc-PDSI increases above - 0.5. Therefore, when

Comment [T17]: Ref 1 comment P1498 L7-L12

Comment [T18]: Ref 1 comment P1498/P1499 Section 221.

Comment [T19]: Ref1 comment P1499,L1

Field Code Changed

Comment [T20]: Ref 1 comment P1498 L7-L12

Comment [T21]: Ref 1 P1499 L4

the Sc-PDSI$_i$ in (3) is set to -0.5 and solving for $Z_{i,}$ - which now should be mentioned as the moisture anomaly index needed to end the drought *(Z_e)* – the new formula becomes:

$$Z_e = \left(\frac{-0.5}{q}\right) - \left(\frac{p}{q} \cdot Sc\text{-}PDSI_{i-1}\right) \tag{4}$$

Considering the same severity classes, it can be assumed that a drought is ameliorated when the Sc-PDSI reaches a value of - 2.0. Applying the same hypothetical basis when trying to calculate the moisture anomaly index needed to ameliorate the drought *(Z_a)*, the Sc-PDSI$_i$ in Eq. (3) is set to -2.0 and the formula becomes:

$$Z_a = \left(\frac{-2.0}{q}\right) - \left(\frac{p}{q} \cdot Sc\text{-}PDSI_{i-1}\right) \tag{5}$$

The *q* and *p* are weighted factors - computed at all the locations (grid points) - specific for the dry spells. They are site-dependent which make the Z_a and *Ze* unique for every grid point. Moreover, these two formulas can be computed not only for different values of Sc-PDSI$_{i-1}$ but also for periods of time longer than a month. Once these simultaneous equations are solved, moisture anomaly indexes needed to end *(Z_e)* or ameliorate *(Z_a)* a drought are computed for different Sc-PDSI$_i$ intensities and different time periods (1, 3 and 6 months in our study).

b. *The second step* is assigning values to the CAFEC precipitation ($\hat{P}_i$) in Eq. (2) since the balance of the demand and supply at the level of soil moisture is solved only at the end of the month. Once this balance reaches a deficit of water, the anomaly is reproduced at the level of the drought indicator in the next month. So, in order to supply the model with precipitations needed to recover the drought at the time when this anomaly happens, the values of CAFEC precipitations were regressed at the level of Sc-PDSI$_{i-1}$ for each month during a drought. In order to solve this relation $\hat{P}_i$ is linearly regressed against Sc-PDSI$_i$ at time *i-1*, *i-3* and *i-6*. The new $\hat{P}_i$ can be called the CAFEC precipitation regressed, matching the time (month) when the drought indicator registers the drought event.

c. In the *third step* the precipitation needed to end or ameliorate the drought is computed as in Eq. (2), using the moisture anomaly index needed to end *(Z_e)* or ameliorate *(Z_a)* the drought and the regressed CAFEC.

2.2.3 Probability calculation

The climatological probability of receiving the amount of precipitation~~s~~ needed to end and ameliorate the drought was calculated using the Gamma distribution. Gamma distribution has

Comment [T22]: Ref1 comment P1501,L8

been frequently used in literature to represent precipitation (Thom,1966; Wilks, 1990; 1995, Oeztuerk, 1981) due to the advantage that it excludes negative values, being bounded on the left at zero (Thom, 1966; Wilks, 1995). Analysis of rainfall data strongly depends on its distribution pattern (Sharma, et al., 2010). This is especially important as Gamma distribution is positively skewed and represents an advantage as it mimics the actual rainfall distributions for many geographical areas (Ananthakrishnan, et al., 1989). Also it provides a flexible representation of a variety of rainfall regimes while utilizing only two parameters, the shape and the scale (Wilks, 1990).

Comment [T23]: Ref 1 comment P1501, L9 from specific comments

The ~~statistics~~ calculations were performed separately for each month and each location (grid point) on the basis of the entire 50 years of available data (1961-2010). Input data were the computed precipitation needed to end or ameliorate the drought (0.1˚x 0.1˚ resolution) in the next 1, 3 and 6 months and the actual gridded monthly precipitation (0.1˚x 0.1˚ resolution) accumulated for the same time periods. The probability statistics should not be considered as a forecast. They represent a quantitative measure of the probability computed on the basis of past actual precipitation data. Practically, the *probability density function* (PDF) of the actual precipitation data is used to find the *cumulative probability* (CDF) of the precipitation needed to recover from the drought for the required month and temporal scale.

All the procedures followed in the calculation of the climatological probability of recovering from a drought are based on the processes used by Oeztuerk (1981) to compute the probability distribution for precipitation. In a *first step* the actual precipitation data on “moving windows” of 1, 3, 6 months are matched with the precipitation needed to recover from the drought in the next 1, 3 and 6 months. In a *second step* the cumulative probability (CDF) of the computed precipitation needed to end or ameliorate the drought is derived.

3 Results

~~The spatial and temporal analysis of the results for precipitations needed to recover from a drought and their climatological probability is related to 3 levels of severity: moderate drought when $-3 < \text{Sc-PDSI} \leq -2$, severe drought when $-4 < \text{Sc-PDSI} \leq -3$ and extreme drought when $\text{Sc-PDSI} \leq -4$, which are evaluated on a temporal window of 1, 3, and 6 months.~~

Previous studies of drought in the Carpathian region were based on the analysis of intensity, duration and spatial extent, either at national level (e.g., Palfai, 1990; Snizell, et al., 1998;

Szalai, 2000; Popova, et al., 2006; Trnka, et al., 2009; Cheval, 2013) or at inter-regional level (e.g., Bartholy, et al., 2013; Spinoni et. al, 2013). Our results show that the incidence of drought in this region is rather high. During the period 1961-2010, every part of the region experienced on average between 0.5 and 4 to 6 drought months per year, (Sc-PDSI ≤ -2, Fig. 3 left). Moreover the incidence of extreme drought (Sc-PDSI ≤ -4) has an occurrence of ~~5 to 45 days~~less than a month per year for the same time interval as shown in Fig. 3, right. When compared with other drought indicators Sc_PDSI shows good correlation with indices of long accumulation periods. The correlation over each grid point and for entire Carpathian region and time period (1961-2010) shows high values with the SPI_9 (0.85) and SPEI_9 (0.82) detecting the drought events on comparable spatial and temporal resolution and lower values with SPI_1 (0.33) and SPEI_1 (0.35) (Antofie, et al., 2013).

Comment [MP24]: Ref1 comment 1496, L8-L10

The spatial and temporal analysis of the results for precipitations needed to recover from a drought and their climatological probability is related to 3 levels of severity: moderate drought when -3 < Sc-PDSI ≤ -2, severe drought when -4 < Sc-PDSI ≤ -3 and extreme drought when Sc-PDSI ≤ -4, which are evaluated on a temporal window of 1, 3, and 6 months. In order to ease the interpretation of the results with their temporal and spatial variability a review of the climatological conditions of the area related with the physical characteristics of the Palmer Drought Model will be presented.

PDSI originally was designed to measure the soil moisture departures as a difference between a climatological moisture supply which in our case is the actual precipitation and the precipitation needed to maintain a normal soil moisture level (CAFEC precipitation, Palmer, 1965). In this study other means of moisture supply such as precipitation in form of snow water equivalent are not considered. Since the regional spatial variation of precipitation in this region is mainly determined by the mountain orography and the large scale atmospheric processes (KEO; UNEP/DEWA 2007), it is expected (in a temperate-continental climate) that moisture supply is more significant in the high altitudes while the moisture demand is higher in the low altitudes (higher rate of evapotranspiration due to higher temperatures). With increasing continental conditions from West to East and temperature decreasing from North to South, a higher moisture demand in the South and southwest and higher moisture supplies in the North, West and southwest parts of the region are expected.

Based on these general climatological characteristics the physical properties of the PDM will produce the highest Z values (soil moisture) in the areas and for the period of the year with highest precipitation amount. The same properties of the model will indicate as the most favourable period of the year for recovering from drought the months that have the greater frequency of excess of precipitation compared to the normal. This is not necessarily the wettest month of the year but the month with the largest positive skew as the PDM is based on departures from the normal.

For both the required precipitation and the probabilities of recovery from drought a spatial pattern linked with the atmospheric circulation patterns responsible for the climate variability in the Carpathian region can be noticed. The southern and southwestern Carpathians and the western Carpathians act like a barrier for the main sources of moisture (Mediterranean and North Atlantic air masses; Busuioc and von Storch, 1996, Busuioc, 2001). These systems are causing first a high precipitation amounts and a pronounced annual precipitation cycle, as it is the case of North Atlantic circulation in the western, northern and northwestern part of the Carpathian region and secondly, an highly variable precipitation intensity and a relatively constant distributed precipitation regime through the year (by creating a second precipitation peak in autumn), as it is the case of ~~Mediteranean~~Mediterranean cyclones in the southwestern and southern part of the Carpathian region. The cyclonic presence and trajectories have been the subject of extensive climatological research (e.g. W. van Bebber, 1891; Radinovic, 1987; Katsoulis, 1980; Flocas, 1988; Maheras, 2001). Often these studies establish a connection between the advance of the cyclones from the Mediterranean area and intense precipitation events. High amounts of precipitation with genesis in the Mediterranean space (Gulf of Genova) are produced on the cyclonal trajectory V (from the Tyrrhenian Sea to Ukraine). Most important for the Carpathian region are the trajectory Vc, that crosses from west to east, the south of Carpathian region, in spring and very rarely in summer and trajectory Vb, important for the western part of the Carpathian region, passesing over the Panonic Plain, towards Poland. For both trajectories, the cyclones circulate especially in autumn, winter and spring with the largest probability of occurrence in April and a secondary maximum in early autumn. The cyclone circulation diminishes and migrates southwards in December-January, due to the intensification of the Azoric and Siberian anticyclones (Maheras, 2001).

Even if the annual cycles of the moisture supply and demand follow a continental pattern (imposed by the North Atlantic circulation) with a maximum of supply and demand at the beginning of the summer (May/June/July) and end of summer (July/August) respectively a minimum in the winter months (December/January/February) the months with the higher

Comment [T25]: Ref 1 comment P 1504, L28 - P1505, L3 probability of substantial excess of precipitation from the normal (April/May in spring and October/November in autumn) will be related with the cyclonic presence from the Mediteranean area. Nevertheless the joined influence of the circulations moving either from the Atlantic or the Mediteranean Sea is a common characteristic of the Carpathian region (Busuioc and von Storch, 1996, Busuioc, 2001).

Comment [MP26]: Ref 2 Main comment 1

a. Drought recovery and its temporal variability

As shown in ~~the~~ Fig. 4 the incidence of drought events (Sc-PDSI ≤ -2) is most pronounced during the early years of the 1960’s, 1970’s and 2000’s, as well as during almost the entire decade of the 1980’s and 1990’s and more isolated in the years 1968, 2007 and 2009. The recorded drought occurrence in the region presented through country reports at UNCCD's 1st Regional Workshop on Capacity Development to Support National Drought Management Policies for Eastern European Countries (July 9-11, 2013, Bucharest) confirms the drought-prone characteristic of the region. The years with the highest drought incidence mentioned in the region are 2000, 2003, 2007 and 2012, (Holjevac et al.,2013,), beginning of the 1990's (Gregorič, et al., 2013), the sequences from 1961 -1965, 1973-1974 and also 1980's since when it is noticed an increasing in the number of droughts (Mateescu, et al., 2013, Gregorič, G., et al., 2013).

Comment [T27]: Ref1 comment P1502,L17

Comment [T28]: Ref1 commentP1502, L17- L26 from technical comments

One of the characteristics of these drought events is the strong prevalence (% from the area) of extreme droughts (Sc-PDSI ≤ -4) as compared to other severity levels. This can be seen especially in the years with the highest general incidence over the region: 1961, 1964, 1968, 1987, 1990, 1992, 1993, 2001-2003, 2007. For these cases most of the drought events happened either in the summer period (from June to August) or in the winter months (December to February), for a few cases drought occurred in October or March and April.

As shown in Table 2 for selected drought events between 200% to more than 480% of the normal 1-monthly precipitation would have been required for recovery (i.e. bringing Sc~~C~~-PDSI to a level of -0.5). For a 3-month period, the percentage is reduced from 100% to almost 230% of the 3-monthly precipitation, and for a 6-month period still up to 50% above the normal 6-monthly precipitation would have been required. To ameliorate a drought (i.e. reaching Sc~~C~~-PDSI of ≥ -2) smaller amounts of precipitation would be sufficient: 70-100% above the normal precipitation in 1-month, 30-60% in 3-months and less than 20% in 6-months.

Comment [T29]: Ref1 comment P1503,L3 and L6

In order to get a better idea of the climatological probabilities to recover from such droughts, we analysed the first 25 most significant events (droughts occurring on >75% of the area) for different drought intensity levels. Fig. 5 shows the required precipitation in per cent of the climatologically expected precipitation and the associated probabilities for different drought intensities and precipitation accumulation periods. It can be seen that a moderate severity droughts (-3 < Sc-PDSI ≤ -2) required between 110% and 550% of the normal 1-monthly precipitation for recovery (top left), while for 3-months the range between 50 and 200% and the values for 6-month are well within the climatologically expected. For the same drought cases, during the peak intensity of the drought (Sc-PDSI ≤ -4) the quantity of precipitation required, increased up to approximately 8 times above the normal 1-month precipitation, while for 3-month the values reach up to 300%, only for the 6-monthly precipitation the required values are close to the climatologically expected (bottom left). Severe droughts (-4 < Sc-PDSI ≤ -3) would have been ended with rainfall between 2 to 7 times the 1-month normal precipitation and approximately 100% of the 6-month normal precipitation (centre left).

Most of these values indicate the improbability of ending or ameliorating the drought, in a short period of time, as their climatological probability is (extremely) low. If we settle a limit of 50% probability, above which the quantities of precipitation could be considered more likely than not (IPCC 2007), none of the drought events could have been ended in the next month. However, a few of the moderate droughts (~~08~~07.1990, 12.1986, 12.2000, 01.1991) and of the severe droughts (07.1990, 12.2000, 01.~~1990~~1991) could have been ameliorated with 48% to 140% above the normal precipitation in 1-month (top right). On the other hand in 6-months almost all drought events considered could most probably have been ended with 10% to 80% above the normal precipitation (188% for the extreme drought of 04.1991). Only the severe drought in January and February 1964 and the extreme droughts in July 2007 could not have been ended even in 6-months, making them the most excessive droughts of the studied period in the Carpathian region. Nevertheless, they could have been ameliorated with 45% to 65% above the normal 6-month precipitation. In 3-months, only one drought event of extreme intensity (07.1990, requiring 136% above the normal precipitation), 12 events of the moderate and 6 events of severe droughts could have been ended with high probability. All the other events could only have been ameliorated with a range of 15% to 140% (08.1992) above the normal 3-monthly precipitation.

b. Drought recovery and its spatial variability

Comment [T30]: Ref1 comment P 1503 L 29 – P1504 L2

~~PDSI originally was designed to measure the soil moisture departures as a difference between a climatological moisture supply which in our case is the actual precipitation and the precipitation needed to maintain a normal soil moisture level (CAFEC precipitation, Palmer, 1965). In this study other means of moisture supply such as precipitation in form of snow water equivalent are not considered. Since the regional spatial variation of precipitation in this region is mainly determined by the mountain orography and the large scale atmospheric processes (KEO; UNEP/DEWA 2007), it is expected (in a temperate-continental climate) that moisture supply is more significant in the high altitudes while the moisture demand is higher in the low altitudes (higher rate of evapotranspiration due to higher temperatures). With increasing continental conditions from West to East and temperature decreasing from North to South, a higher moisture demand in the South and southwest and higher moisture supplies in the North, West and southwest parts of the region are expected. The annual cycles of the moisture supply and demand follow a continental pattern with a maximum of supply and demand at the beginning of the summer (May/June/July) respectively end of summer (July/August) and a minimum in the winter months (December/January/February).~~

Figure 6 presents the averaged positive deviations (in per cent) from normal precipitation needed to recover from a drought computed for the period 1961-2010. The Pannonian Basin, the Transylvanian Plateau and the external Carpathians foothills and plains in the southern and eastern part of the region require the highest relative quantities of precipitation to recover from a drought. In these regions, moderate droughts and extreme droughts needed between 250 and 300 % (sometimes up to 600%) above normal precipitation to end a drought in the next month, a decrease being noticed with increasing altitude. The topographic pattern is lost when the moisture supply is required for a larger time window. This is due to the general climate characteristics that overwrite the variability introduced by the local physical conditions. Also, the longer time intervals require less relative amounts of precipitation to recover from droughts (i.e. from 20 up to 40%-60% for all the drought intensities).

Comment [T31]: Ref1 comment P1505, L4-5.

Comment [T32]: Ref1 comment P1505, L9.

Figure 7 shows the corresponding probabilities. The probability of ending or ameliorating an extreme drought (Sc-PDSI $\leq$ -4) or a severe drought (-4 < Sc-PDSI $\leq$ -3) in 1-month is low (< 8%), showing the improbability of recovering the high intensity droughts in such a short time interval. The probability remains below 20% even for the moderate droughts. For a 3-month period the probability of ending a drought is increasing from below 10 to 40% for the extreme droughts, but is still unlikely (<33%) or about as likely as not (33 to 66%). More likely, with a probability of 60 to 80% a moderate drought could be ended over almost the entire region in the 3-month time interval. Once we advance to the 6-month interval, all droughts, indifferent of their intensity level, move from likely (>66%) to virtually certain (>99%) to be ended.

~~For both the required precipitation and the probabilities of recovery a spatial pattern linked with the atmospheric circulation patterns responsible for the climate variability in the Carpathian region can be noticed. The southern and southwestern Carpathians and the western Carpathians act like a barrier for the main sources of moisture (Mediterranean and North Atlantic air masses; Busuioc and von Storch, 1996, Busuioc, 2001). This systems are causing high precipitation amounts over the southwestern, northern and northwestern part of the region, which produce high moisture supply and higher climatological probabilities when affected by drought events and less precipitation in the Carpathian foothills and plains in the southern and eastern part of the region, the Pannonian Basin and the Transylvanian plateau, causing low moisture supply and lower climatological probabilities.~~

As presented at the beginning of this section ~~T~~the succession, intensity and the predominance of the~~se air masses~~ cyclonic circulation may lead to a seasonal variability of the precipitation needed to recover from a drought and their climatological probability. The soil moisture supply and demand follow the annual cycle of precipitation and temperature (imposed by the general atmospheric circulation) ~~which is~~ but they are reflected differently at the level of the month with the highest and lowest probabilities of recovering from a drought ~~.~~ More likely to recover from drought are the months with higher probability of substantial excess of precipitations from the normal and especially for the regions with a constant precipitation regime throughout the year. The more the precipitation regime presents a pronounced peak ~~the more~~the more the preferred recovery moths are variable.

Close to these characteristics, ~~I~~in almost the entire Carpathian region, the preferred months for ending a drought event are the months of April and May ~~and June~~ as in Fig. 8, corresponding with the months with the largest probability of receiving high precipitation amounts compared with the normal and a maximum activity of Mediteranean cyclones. ~~peak of the annual precipitation cycle for most of the Carpathian region~~. The least preferred months for ending a drought are the months of January and February for South, southwestern, northwestern regions and October, November, December for northeastern part, corresponding with the months with largest probability of receiving low precipitation amounts compared with the normal and a minimum activity of the Mediterranean cyclones. ~~months of the annual~~

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Comment [T33]: Ref1 comment P1506, L13

Comment [T34]: Ref1 comment P1506, L27 and P1506, L15

~~precipitation cycle~~. This situation can be observed in Fig. 8 where we present the months with the highest and lowest probability for ending droughts at different intensity during the next month in Fig.8a, next three months in Fig. 8b and next six months in Fig. 8c.

Moderate drought events in April appear to have the highest probability for being ended in the next month. Also, severe and extreme droughts in April and May (for North and northeastern regions) are characterized by highest probabilities of being ended in following month. The late summer (July, August) and early autumn (September, October) drought events are ended with highest probability in the South, West and northwestern parts of Carpathian region as seen in the Fig. 8a, top.

In Fig. 8b top, we show that the drought events with the highest probability of being ended in 3 months are the droughts from the end of winter (January and February) in the West, South and northwestern regions for the moderate droughts and spring droughts (from April to May) in North and northeastern regions, especially for the extreme droughts. The late autumn drought events (October, November) present the highest probability of being ended in the next 6-months as seen in Fig. 8c, top.

Concerning the lowest probabilities for ending a drought event, the worst months for ending the droughts are the winter months, corresponding with the driest period of the annual precipitation cycle and the minimum activity of the Mediterranean cyclones ~~of~~ in the Carpathian region. This makes drought events between October (in the North, northeast area of the Carpathian region) and February (in the southern and eastern part of the region and Pannonian Basin) the least probable to be ended in the next month as seen in the Fig.8 a, bottom.

In Fig. 8b bottom, we show that the drought events with the lowest probability of being ended in 3 months are the droughts from the December in the North and northeastern regions and autumn droughts in the other regions.

The least probable to be ended in the next 6-month are the summer droughts ~~that occur after or during the peak of the annual precipitation cycle~~ (June, July, August), especially in the South and southwestern regions while the winter droughts are the least probable to be ended in the North and northeastern part of the region as seen in Fig. 8c.

~~This drought analysis reveals that the possible impact of droughts could be major especially because the agriculture is a major economic sector in the Carpathian countries (KEO;~~

~~UNEP/DEWA 2007). Moreover the main agricultural crops in the Carpathian region are winter wheat, maize and potatoes (KEO; UNEP/DEWA 2007), which are highly vulnerable to droughts throughout the whole year. Therefore information on ending or ameliorating the droughts, climatological probability that the droughts could be recovered and the seasonal analysis of drought occurrence could be useful in decisions concerning the water and agricultural resources management.~~

Comment [T35]: Ref2 comment 2from main comments. Text moved at the begining of paper.

As shown, in Carpathian region, the water deficits occur throughout the whole year. As the agriculture is an important economic sector in the Carpathian region the drought impact could be essential. Most crops may experience water stress (deficit) at various stages in their growth cycle. The sequences of vegetative growth with their key physiological phases (i.e. crop phenology) and their sensitivity to water deficit can be used to highlight the importance of seasonal analysis of drought occurrence. Winter crops (i.e. winter wheat) are planted in Carpathian region in September through October and harvested July through August of the next year, while the spring crops (i.e. maize, spring wheat, sunflower, potatoes) are planted April through May and harvested August through September or even October (potatoes) of the same year (KEO; UNEP/DEWA 2007).

Early drought in the growing season - the end of autumn in October and November for winter crops and the end of spring in late April and May for spring crops - are affecting wheat germination and crop establishment (Bouaziz and Hicks, 1990). The water stress during the vegetative stages – the months of April and May for winter crops and late May and June for spring crops – may affect the leaf index development (Rickman et al., 1983). Soil water deficit increased towards harvesting – early summer for winter crops and late July or beginning of autumn in August for spring crops - is likely to produce a severe reduction in grain growth and quality which eventually cause reduction in final yields. On the other hand it has been noted that water deficit in the maturity (anthesis) and harvesting period accelerates development (Simane et al., 1993) and significantly contribute to grain yield (Palta et al., 1994).

Comment [MP36]: Ref2 Main comment 2

4 Conclusions

The main characteristics of the spatial and temporal variability of precipitation needed to end or ameliorate a drought in the Carpathian region are presented in this study. Sc-PDSI was used as a drought indicator for the region and the Palmer Drought Model assumptions were considered for the theoretical basis to calculate moisture supply and demand. The incidence of drought in the region is considerable. During the study period (1961-2010) the region experienced, on average, drought events from at least 0.5 months to 4 to 6 months per year for moderate droughts and from 5 to 45 days per year for extreme droughts.

The amount of precipitation needed to end a drought in the next month, reached, on average, between 200% and 480% above the normal 1-month and up to 50% above the 6-month total of the normal precipitation. It was also shown that most of the drought events, no matter their intensity, are extremely unlikely (<5%) to be ended in the next month.

Regionally, the Pannonian Basin, Transylvanian Plateau and the external Carpathians foothills and plains in the southern and eastern part of the region require the highest quantity of precipitation to recover from a drought~~, corresponding to~~ and present the lowest climatological probabilities. In almost the entire Carpathian region, the preferred months for ending a drought event are the months of April and May corresponding with months with the largest probability of receiving high precipitation amounts. Often during this period of the year a connection between the advance of the cyclones from the Mediterranean area and intense precipitation events is established. The worst months for ending the droughts in the Carpathian region are the late autumn and winter months, corresponding with the driest period of the annual precipitation cycle and the minimum activity of the ~~Mediteranean~~Mediterranean cyclones in the Carpathian region.

High precipitation amounts over the North and northwestern part of the region are causing higher moisture supply and higher climatological probabilities to recover from drought.~~when affected by drought events.~~ On the other hand eastern and northeast area of the Carpathian region in October and the southern and eastern part of the region and Pannonian Basin in February are the least probable to be ended.

The early drought events for winter crops (in October and November) cause a high stress effect especially on germination and early crop establishment. On the other hand the water stress is much lower for the spring crops from April and May and for the same physiological phase due to a high cyclonic activity.

For the the summer droughts, that have a low probability to be ended, especially in the South and southwestern regions, if in the maturity (anthesis) and harvesting period of the crops, the water deficit can cause less damage in crop development producing even an increase in the grain yield.

~~In almost the entire Carpathian region the best months for ending a drought event are the months of May and June, corresponding with the peak of the annual precipitation cycle for most of the Carpathian region and the worst months are the months of December and February corresponding to the driest period of the annual precipitation cycle.~~

Appendix A: Sc-PDSI calculation

The computation of the Self-calibrating PDSI was done in 4 steps: a) computation of the soil water budget (Thornthwaite~~'s method~~, 1948), b) normalization with respect to demand, c) normalization with respect to location and d) computation of the drought severity.

Comment [T37]: Ref1 comment P1508,L24

a. Computation of the soil water budget was done considering the following assumptions: the soil is divided in two layers, the AWC value is site dependent - representative of the soils type, the top layer contains 25.4mm of available moisture at field capacity, the moisture stored in the soil layers changes according to the priority conditions imposed by the top layer on supply and demand. Rainfall surplus is first added to the top layer until this layer is ~~full~~ saturated and only then it passes to the second layer while on the other hand moisture is withdrawn from the top layer first, before removing from the second soil layer.

Comment [T38]: Ref1 comment P1509, L7

Following these rules eight hydrological parameters of the water balance are computed: the actual evapotranspiration (ET), the soil water recharge (R), the runoff (RO), the water loss from the soil (L) and their potential values used in the calculation of Palmer's constants to define the Climatically Appropriate for Existing Conditions (CAFEC) precipitation. The potential evapotranspiration was computed using the Thorntwaite formula while the other potential parameters are computed as follows (Weber and Nkemdirim 1998): the potential recharge (PR) is the amount of moisture required to bring the soil moisture up to filed capacity (AWC less the total amount of moisture stored in both soil layers), the potential loss (PL) is the moisture that could be lost from the soil if precipitation is zero for the month and the potential runoff (PRO) is defined as total AWC less potential recharge (PR). By dividing the mean actual quantity by the mean potential quantity, coefficients defining the usual climate for a specific location were obtained (for evapotranspiration - α, recharge - β, runoff - γ, and loss - δ) as in Eq. (A2). The four coefficients are determined for each of the 12 months. The mean of the actual and potential quantities were computed over a baseline equal to the data period available (1961-2010).

Comment [T39]: Ref 1 comment P1509, L9 *b.* *Normalization with respect to demand* (or moisture departure for the month - *D*) was calculated by subtracting from the normal precipitation the amount of precipitation needed to maintain a normal soil moisture level (CAFEC precipitation - $\hat{P}$, computed from the potential values of the water balance and their coefficients):

$$D = P - \hat{P} = P - (\alpha_i PE + \beta_i PR + \gamma_i PRO - \delta_i PL) \quad \text{(A1)}$$

where,

D = moisture departure for the month, *P* = actual precipitation, $\hat{P}$ = CAFEC precipitation,

α, β, γ, δ = water-balance coefficients computed as:

$$\alpha = \overline{ET}_i/\overline{PE}_i, \beta = \bar{R}_i/\overline{PR}_i, \gamma = \overline{RO}_i/\overline{PRO}_i, \delta = \bar{L}_i/\overline{PL}_i \quad \text{(A2)}$$

where,

ET, R, RO, L are the evapotranspiration, recharge, runoff, and soil moisture loss. $\overline{PE}$, $\overline{PR}$, $\overline{PRo}$, $\overline{PL}$ are their potential values, the bars indicate the average value and *i* ranges over the months of the year.

c. *Normalization with respect to location* was done by converting the moisture departure for the month (*D*) into an indicator of moisture anomaly (Z_i) by multiplying the moisture departure with a climatic characteristic coefficient (*K*). This is the point where the Sc-PDSI becomes different from the PDSI. The purpose of the climatic characteristic, *K*, is to adjust the value of PDSI according to the tails of its distribution in order to allow for an accurate comparison of PDSI values over time and space. Practically, the values of every location (pixel in this case) and each value of $PDSI_i$ were weighted according to the 2nd and 98th percentile of the PDSI and compared with the expected -4.0 and +4.0 calibration:

$$K = \begin{bmatrix} \frac{-4.0}{PDSI_{2nd}} \acute{K}, & if\ D < 0 \\ \frac{4.0}{PDSI_{98th}} \acute{K}, & if D \geq 0 \end{bmatrix} \quad \text{(A3)}$$

where $PDSI_{2nd}$ and $PDSI_{98th}$ are the 2^{nd} and 98^{th} percentile of the PDSI distribution computed using *K':*

$$K'_i = 1.5 log_{10} \left[\left(\frac{\overline{PE} + \bar{R} + \overline{RO}}{\bar{P} + \bar{L}} + 2.8 \right) \bar{D}^{-1} \right] + 0.5 \quad \text{(A4)}$$

where, $\overline{D}$ = average absolute value of the moisture departure and $\overline{PE}$, $\overline{R}$, $\overline{Ro}$, $\overline{P}$, $\overline{L}$ are the parameters of water balance values of evapotranspiration, recharge, runoff, precipitation and loss.

Using the climate characteristic coefficient (*K*) and the moisture departure (*D*) for the month *i*, the moisture anomaly index is computed as:

$$Z_i = D_i \cdot K_i \tag{A5}$$

d. *Computation of drought severity*. Once *Z* is computed for the month *i*, the computation of *the drought severity* begins by relating the previous month's $PDSI_{i-1}$ with the current moisture anomaly Z_i. The weights assigned to these two components are given by the duration factors (*p* and *q*):

$$PDSI_i = pPDSI_{i-1} + qZ_i \tag{A6}$$

Differently from the original computation (the original PDSI is computed using the duration factors p = 0.897 for $PDSI_{i-1}$ and q =1/3 for Z_i) the Sc-PDSI duration factors for wet and dry ~~conditions~~ spells are computed separately, as it is assumed that different locations have different sensitivities to precipitation events. These duration factors (*p* and *q*) were computed using the least squares method by fitting straight lines to the lowest (highest) Z_i values accumulated over different lengths of time, aiming at representing most extreme dry/wet periods of various lengths~~for both extremely wet and extremely dry conditions, separately~~. Practically the accumulated Z_i was regressed against its duration (months) taking into account the most extreme ~~drought~~dry/wet ~~spell~~ periods of various lengths as shown in Fig. A1.

Comment [T40]: Ref1 comment P1511,L13

The most extreme ~~Extremely~~ wet/dry ~~spells~~ period ~~are~~ is defined, in this study, as events with duration greater or equal to 3 consecutive months and with the highest intensity of Z_i (less/higher than 0.05/0.95 percentiles of accumulated negative/positive Z_i values are omitted). Once the intercepts of the most extreme wet/dry ~~spells~~ periods were computed, 2 sets of *p* and *q* (for dry/wet spells) were calculated as follows:

Comment [T41]: Ref2 comment 5

$$p = (1 - m/(m + b)) \tag{A7}$$

$$q = C/(m + b) \tag{A8}$$

where, *m* = slope, *b* = intercept of the extreme wet/dry ~~spell~~ period and *C* is a calibration factor, in this study -4 and 4 were assigned for ~~drought~~ dry and wet spells. Finally, $PDSI_{i-1}$

Comment [T42]: Ref1 comment P1511,L23

and Z_i from Eq. (A6) were added to compute the Sc-PDSI$_{i,}$ using the p and q as weighting factors. The obtained values shown in Figure A2 vary between 0.85 and 0.95 for p and 0.08 and 0.38 for q of a dry spell. These values are very important as they are to be used in the calculation of the moisture anomaly index needed to end (Z_e) and ameliorate (Z_a) a drought.

Acknowledgements

This study was supported, in part, by the results of the CARPATCLIM project (www.carpatclim-eu.org). We would like to acknowledge the work of (alphabetical order): Igor Antolovic, Ingeborg Auer, Oliver Bochnicek, Zita Bihari, Sorin Cheval, Natalia Gnatiuk, Johann Hiebl, Peter Kajaba, Piotr Kilar, Gabriela Ivanakova, Danuta Limanowka, Monika Lakatos, Monica Matei, Janja Milkovic, Dragan Mihic, Yurii Nabyvanets, Pavol Nejedlik, Predrag Petrovic, Robert Pyrc, Radim Tolasz, Tatjana Savic, Oleg Skrynyk, Sandor Szalai, Tamás Szentimrey, Pavel Štastný, Petr Štěpánek, Pavel Zahradníček.

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Table 1. Cumulative frequency, severity classes, and SC-PDSI values in the Carpathian region.

Cumulative frequency (%)	Severity classes	Sc-PDSI value
2.4	Extremely wet	4 or more
4.1	Severe wet	3.00 - 3.99
7.4	Moderately wet	2.00 - 2.99

11.6	Slightly wet	1.00 -1.99
7.2	Incipient wet spell	0.50 - 0.99
17.3	Near normal	0.49 to −0.49
9.1	Incipient dry spell	−0.50 to −0.99
16.7	Slightly dry	−1.00 to −1.99
12.5	Moderately dry	−2.00 to −2.99
7.6	Severely dry	−3.00 to −3.99
4.0	Extremely dry	−4 or less

Table 2. Percentage above the normal of precipitation needed to end a drought – Pp(%) - in the next 1, 3, 6 months for the drought events with the highest incidence (% surface from the region)

Years	2003	1990	1990	2003	1986	2003	1990	1990	1991	1990
Month	8	8	7	9	12	6	9	6	3	10
Incidence(%)	93.3	92.6	88.5	88.1	85.8	85.6	85.5	84.7	83.9	83.9
1-month Pp(%)	414.5	376.9	625.1	204.1	368	228.2	415.7	374.3	462.5	482.3
3-month Pp(%)	195.7	230.8	160.9	172.5	110.7	129.7	360.3	118.7	99	233.3
6-month Pp(%)	25.2	57.9	52	21	36.3	34.3	63.1	49.2	48.2	62.3

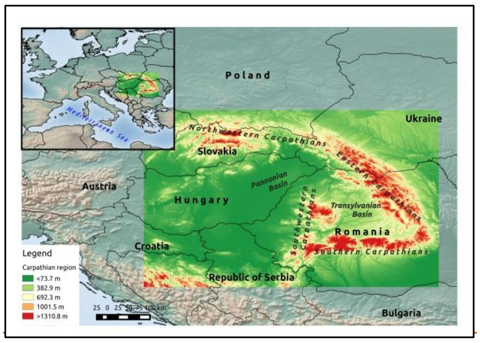

Figure 1. Carpathian region – geographical units

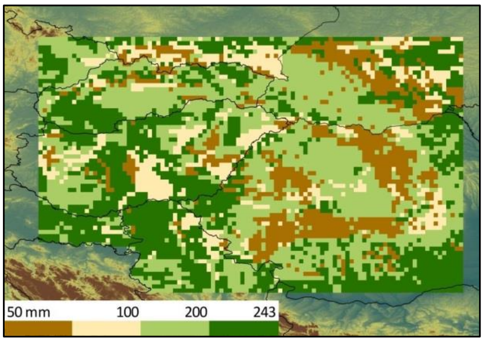

Figure 2. Available Water Holding Capacity (AWC) of the soil (mm) in the Carpathian region.

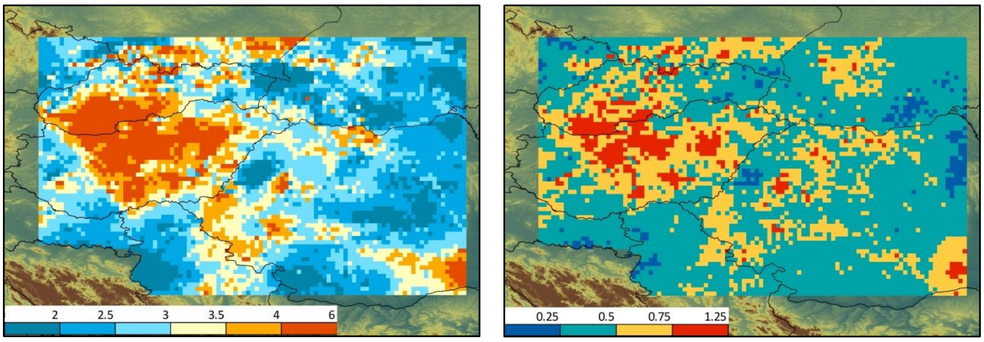

Figure 3. Average number of months per year with moderate drought (Sc-PDSI ≤ -2.0) *(left)* and extreme drought (Sc-PDSI ≤ -4.0) *(right)* in the Carpathian region (1961-2010)

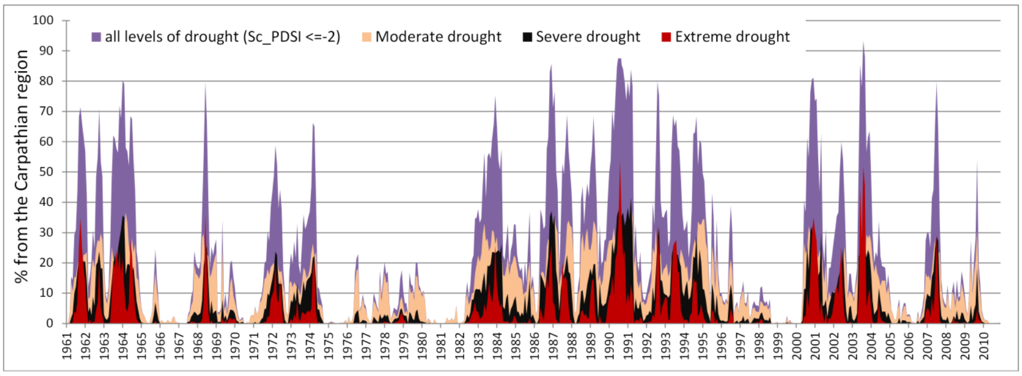

Figure 4. Incidence (% surface of the region) of different severity levels of drought per month

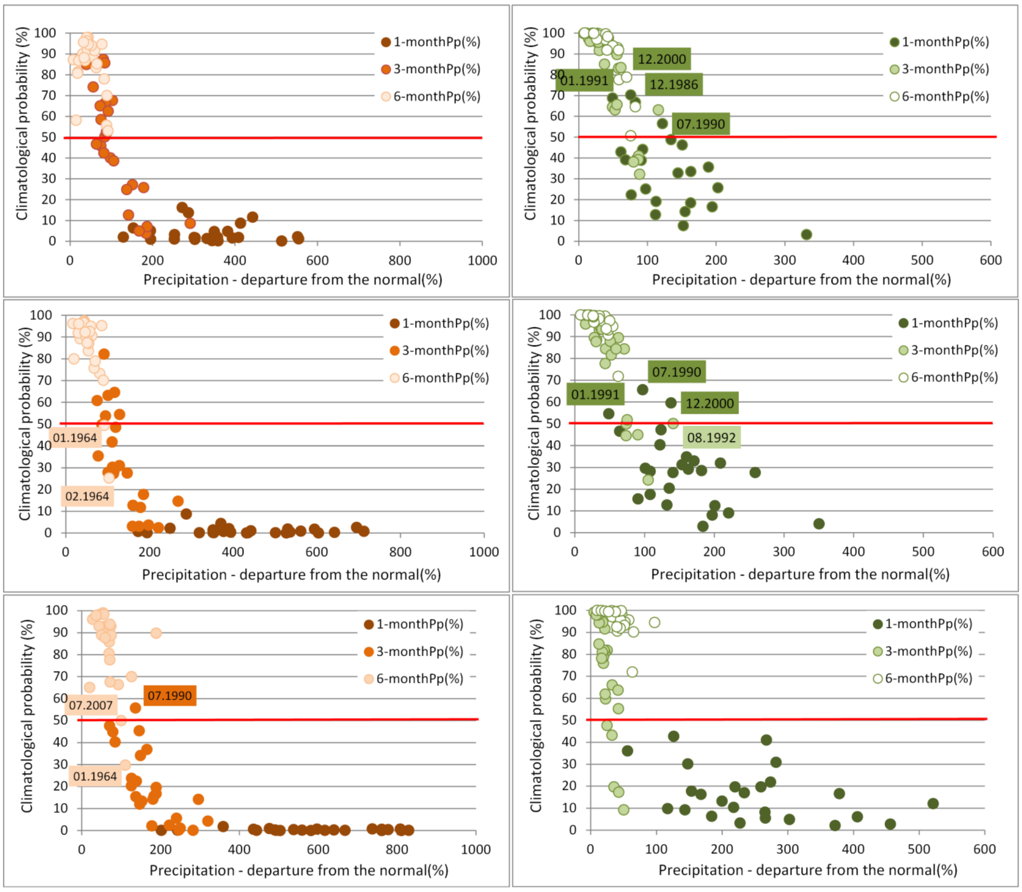

Figure 5. Probability (%) of ending *(left)* or ameliorating *(right)* moderate *(top)*, severe *(centre)* and extreme drought *(bottom)* events with the highest incidence in the Carpathian region in the next 1, 3, 6 months

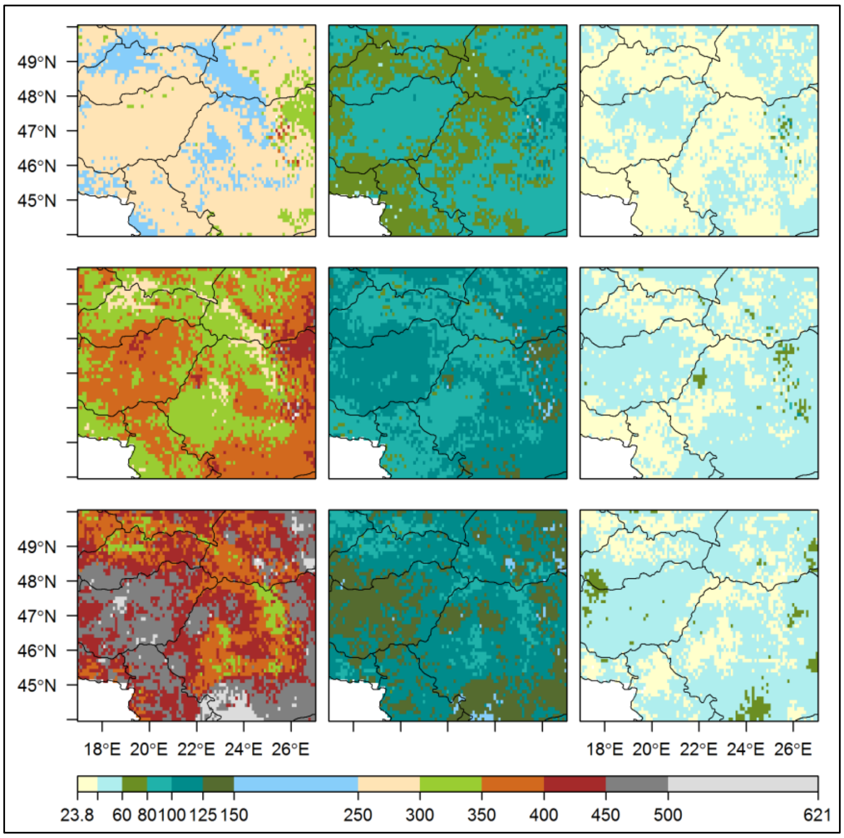

Figure 6. Percentage (%) above the normal of precipitation needed to end a *(top)* moderate ($-3 <$ Sc-PDSI ≤ -2), (*centre*) severe ($-4 <$ Sc-PDSI ≤ -3) and *(bottom)* extreme drought (SC-PDSI ≤ -4) in the next month *(left)*, next 3 months *(centre)* and next 6 months *(right)* (1961-2010).

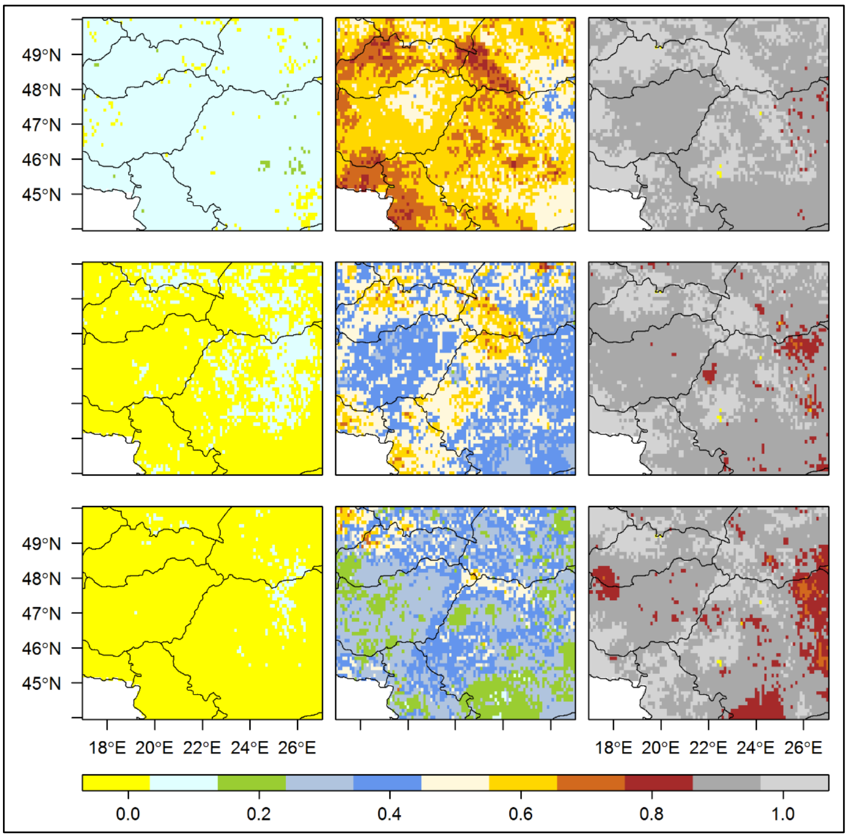

Figure 7. Climatological probability (%) of receiving the precipitation needed to end a *(top)* moderate (-3 < Sc-PDSI ≤ -2), *(centre)* severe (-4 < Sc-PDSI ≤ -3) and *(bottom)* extreme drought (SC-PDSI ≤ -4) in the next month *(left)*, next 3 months *(centre)* and next 6 months *(right)* (1961-2010)

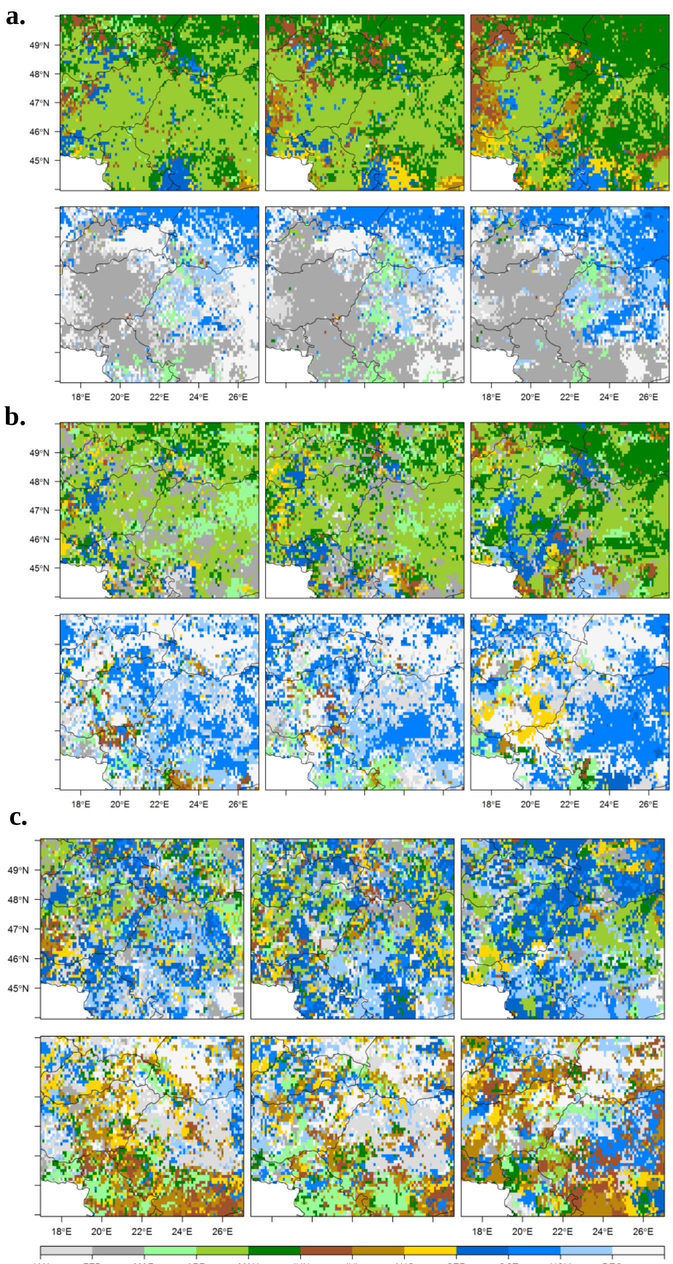

Figure 8. The months with the highest (top), and lowest (bottom) probability of having *(left)* a moderate drought (-3 < Sc-PDSI ≤ -2), *(centre)* severe (-4 < Sc-PDSI ≤ -3) and *(right)* extreme drought (-4 ≤ Sc-PDSI) terminated in a). the next month, b). the next 3 months and c). the next 6 months.

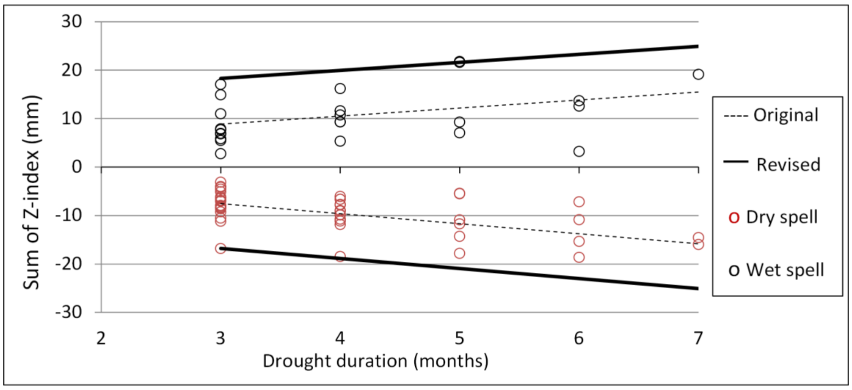

Figure A1. Accumulated z-index (mm) versus duration (months) with the intercept of the most extreme drought/wet spell

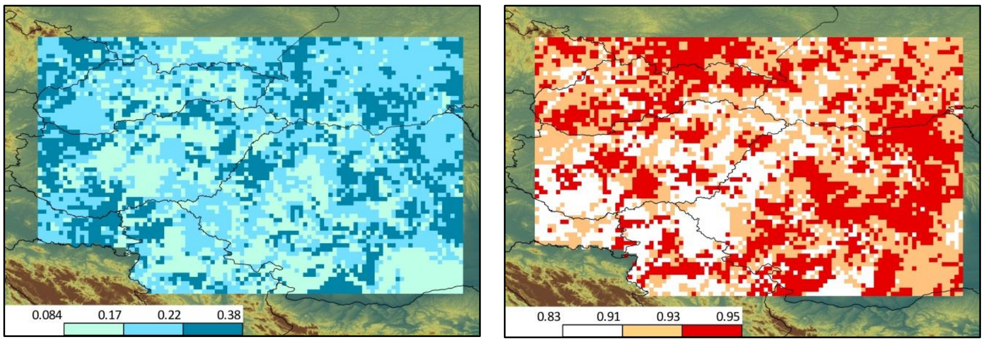

Figure A2. Duration factors *p* (left) and *q* (right) for dry cases in the Carpathian region (1961-2010)