Response to Referee #2

The reviewer's comments are *in italic* and our response in normal font.

General Comments

The authors present an analysis using the Standardized Precipitation Index (SPI) to assess future trends in meteorological drought in Poland. They use high resolution climate simulations of the ENSEMBLES project of six different RCM/GCM combinations under the A1B emission scenario. The results show a positive trend of the SPI in winter and a slightly negative trend in summer. Additionally, the effect of bias correction on the trend signal is only weak. However, the spread between different model realisations introduces much more uncertainty. The paper is well written and structured. It provides information on future SPI trends and also on the very important topic of the effects of bias correction on the results. In general I would recommend publishing the paper in HESS, however, some major and minor comments are summarized below and should be taken into account.

Answer: We thank the reviewer for the encouraging words and very helpful and detailed comments.

Major Comments:

The authors use the linear trend of the SPI time series as a change indicator for meteorological drought occurrence in the future. I think, although the trend estimator is a very robust one, that the approach introduces some uncertainty and difficulty in interpretation. In the results maps are displayed showing the slope of the linear regression of the SPI values against time, indicating whether the SPI shows a negative trend (→ interpretation is increase in droughts) or a positive one (less droughts). These plain numbers make it hard to assess the magnitude of change. The SPI is a probabilistic drought index, indicating the chance of a certain precipitation amount to occur. For the reader and also for a deeper justification of the title of the manuscript (meteorological drought) it would be worthwhile to assess future drought occurrence in a more profound way. One possibility would be to fit the Gamma-distribution of the precipitation time series only in the reference period (1971-2000), but calculating the SPI for the whole time series (1971-2099). That would enable to assess possibly changing probability of drought occurrence (e.g. SPI below -1, or even -2) in a future time period (2070-2099) compared to the reference period, which should follow a unit normal distribution. I think the manuscript would benefit, if these kind of analysis is added. For examples two figures for winter and summer might be added to the results, or even to a Discussion section, although not existing. This is an additional point I'd like to make, that I think the manuscript would benefit from adding a Discussion section, adding a critical discussion on bias correction, possible introduced uncertainties thereof and the necessity for bias correction in the light of the presented results (Maybe section 3.3 could be included in a Discussion section and also some parts of the Conclusions). There is also much literature cited in the introduction. The Discussion section should pick up the main findings of these and discuss them in the light of the apparent results.

Personally, I think no matter how large the biases from the model data are, the differences between raw and corrected SPI should not be too big, since calculating the SPI is some kind of quantile fitting as is the quantile mapping. As the first reviewer commented, the differences between raw and *corrected SPI might come mostly from differences in the fitting of the distributions and/or differences in the extreme values, which is particularly of concern in quantile mapping.*

Answer: We thank the reviewer for very useful and constructive comments. We agree with the reviewer that the approach of drought assessment based on SPI indices introduces uncertainty and it is not straight-forward to interpret. We hope that our paper helps the reader to learn about those difficulties. We discussed the possibility of basing the SPI indices on the reference period in the response to the first reviewer. Taking into account the pros and cons we think our choice of using the whole future period is justified and we will add a discussion on that issue in the corrected version of the paper.

The reviewer's second comment refers to expanding the discussion part of the paper. In response to this comment we will extend the discussion in the revised version of the paper (please see the response to minor comments).

Minor Comments:

- *Page 10332, Lines 1-2: Suggestion: ". . .drought severity in Poland are estimated applying an ensemble of six climate projections using. . ."; The ENSEMBLES project is described later and there is no need to introduce this abbreviation in the Abstract*

  Answer: This will be changed, as suggested.
- *Page 10332, Line 3: ". . .six different RCM/GCM runs. . ."; please also aim to avoid abbreviations in the Abstract. If it is ultimately necessary write the full name and the abbreviation in the Abstract and at that point in the text where it first appears.*
  Answer: We will make these changes. Instead of abbreviations such as RCM GCM, the full name will be given. For example we will change "...six different RCM/GCM runs..." to " ..six different climate models runs …"
- *Page 10332, Line 7: ". . . spatial resolution of 25 km for the. . ."*
  Answer: This will be corrected..
- *Page 10332, Line 9: delete "25 km x 25 km"; ". . .projection and timescale. Additionally, results obtained. . ."*
  Answer: This will be deleted.
- *Page 10332, Line20: change "with different" to "driving different"*
  Answer: This will be corrected.
- *Page 10333, Line 20 – Page 10334 Line4: Just state shortly what Rimkus et al. (2012) found out. Shift most of the text to the Discussion section and discuss it in the light of your findings.*
  Answer: We will include the following text: Analysis of the potential impact of climate change on drought in Poland has been addressed by a few studies at a regional scale. Rimkus et al. (2012) analysed 50-year trends (1960-2009) under the recent climate and drought projections for the future climate (up to 2100) in the Baltic Sea region using the Standardized Precipitation Index (SPI). For the assessment of the observed climatic conditions, gridded precipitation time series at 1-degree resolution from the Climate Research Unit at the University of East Anglia were used. The trend estimated using a Mann-Kendall test indicated an increase in the SPI values for different time averaging periods over most of the studied area, except for Poland, where decreases were found. Future dryness was projected using COSMO Climate Limited-area Model (CCLM) driven by initial and boundary conditions from ECHAM5/MPI-OM GCM for two emission scenarios (A1B and B1). According to both scenarios, the intensity of drought will likely decline in most of the Baltic Sea area, except in

the southern parts, including Poland. Following the A1B scenario, drought occurrence will increase in the summer months in the future in those regions.

Some of the findings of Rimkus et al. (2012) can be compared with the results presented here. They both include simulations following the A1B emission scenario driven by ECHAM5 GCM. Our results in some aspects (e.g. tendency of changes of annual sum of precipitation) are similar to those presented by Rimkus et al. (2012) but differences are also apparent. These differences result from different spatial resolution and an application of a different regional climate model.

The analysis of the impact of climate change on drought in Poland, carried out within the framework of the project "Development and implementation of a strategic adaptation plan for the sectors and areas vulnerable to climate change" with the acronym KLIMADA (klimada.mos.gov.pl), indicated that future predictions of annual total precipitation do not show any clear trends (Liszewska et al., 2012). The assessment of trends in seasons shows an increase in winter precipitation (DJF) of up to 20% in the eastern part of Poland and a decrease in summer precipitation in south eastern Poland. In contrast, changes in precipitation in spring and autumn tend to be much smaller (Liszewska et al., 2012). The number of dry days with daily precipitation of less than 1 mm shows an increasing trend. These changes are more pronounced in eastern and south eastern Poland (NAS, 2013). Those findings by Liszewska et al. (2012) are confirmed in this paper.

Analysis of an impact of climate change on drought using a meteorological water balance (defined as the difference between evapotranspiration and rainfall for a given period) for three periods 1971-2000, 2021-2050 and 2071-2100 was carried out by Osuch et al. (2012). The results of the assessment indicate significant differences between projections derived from the different climate models analysed. A comparison of the median of the ensemble of models in these three periods indicates an increase in water scarcity in Poland. These changes are more pronounced in the south eastern part of Poland. Those results confirm the SPI12 analysis outcomes presented in this paper.

Changes in European drought characteristics projected by PRUDENCE regional climate models were studied by Bleckinsop and Fowler (2007). In that work six climate model simulations were analysed following the SRES A2 emission scenario. Similar to our findings, a considerable model uncertainty due to inter-model variability on regional and local scales was demonstrated. The projections indicate likely decreases in summer and likely increases in winter precipitation. For longer duration droughts, the projections indicate fewer droughts in northern Europe due to larger increases in winter precipitation and more droughts of increasing severity in the south. Our results confirm these general findings with differences due to different emission scenarios as well as climate models.

The study by Orlowsky and Seneviratne (2013) presents an analysis of the SPI12 at a continental scale. The results for Central Europe show an increasing trend in median SPI 12. The new study by Stagge et al. (2015) presents an analysis of meteorological drought using the newest climate models available representing 23 simulations for the three projected emission scenarios (rcp2.6, RCP4.5 and RCP8.5) for Europe at a spatial resolution of 0.11 degree (~12.5 km). Meteorological drought was estimated using the SPI at 3, 6 and 12 month aggregation periods. In that work the relationship between aggregated precipitation and SPI was developed for the reference period (1971-2000). Then the same transformation was used for future scenarios (2011-2040, 2041-2070, and 2071-2100). The analysis of changes in SPI between future and present periods was conducted using a parametric two sample t-test and a non-parametric Mann-Whitney test. The results indicate that precipitation is likely to increase in central and northern Europe, that area is, therefore, likely to experience fewer precipitation-based droughts. In general, our study confirms the results of Stagge et al. (2015) with some differences due to different climate models, emission scenarios and the change estimation methods applied. Our selection of climate models provides larger differences between meteorological projections. In addition, an analysis of SPI at shorter aggregation periods indicates an increasing trend in the degree of dryness during the summer months and a decreasing trend for the winter months.

- *Page 10334, Lines25-26: "or drought indices such as the climatic water balance, that are insufficient for adaptation purposes." Please clarify these statements: what is the climate water balance drought index? Do you mean the SPEI? Then you will have to add a reference (Vincente-Serrano et al. 2010). Why is it insufficient? Can you justify this statement?*
  Answer: In Poland, the assessment of the degree of dryness is carried out using the climatic water balance defined as the difference between and potential evapotranspiration in the selected period. That index is an important variable using in drought monitoring. The usefulness of the climatic water balance is limited due to its simplified form and it does not include an estimation of actual evaporation or snow accumulation and melting.
- *Page 10334, Line29 – Page 10335, Line2: Merge this sentence with Page 10335 Lines 14-16, since there is much redundant information.*

  Answer: The sentences will be merged to eliminate redundancy.

- *Page 10338, Lines 4-10: Instead of listing all simulations in the text a small table would give a much better overview of the different runs and the RCM/GCM combinations.*
  Answer: A table showing applied combination of climate model will be included in the revised manuscript, as shown below.

Table 1 GCM and RCM combinations used from ENSEMBLES project. The numbers denotes number of simulations

RCM \ GCM	ARPEGE	ECHAM5	BCM	Total scenarios
DMI HIRHAM5	1	0	1	2
SMHIRCA	0	0	1	1
RM51	1	0	0	1
MPI M REMO	0	1	0	1
KNMI RACMO2	0	1	0	1
Total scenarios	2	2	2	6

- *Page 10338, Line 15: E-OBS is not a reanalysis in the usual climatological sense (like the ERA-40 or NCEP dataset). I would consider writing "E-OBS gridded observation data", or simply "E-OBS data". See also Line 27 on that page.*
  Answer: We will change this to "E-OBS gridded observation data".
- *Page 10339, Line 5: Dosio and Paruolo (2011) and Gudmunsson et al. (2012)*
  Answer: This will be corrected.

- *Page 10339, Line12: Please specify the threshold you applied for wet/dry day distinction.*
  Answer: This will be updated to P> 0mm/day
- *Page 10340, Lines 11-17: Please only cite the most important studies in the light of your investigation. This list is rather long.*
  Answer: The list of references will be shortened as follows to focus on the most important articles:.
  The index is used for both research and operational purposes in over 60 countries (e. g. Bordi et al., 2009; Moreira et al., 2012; Sienz et al., 2012; Gocic and Trajkovic, 2013; Liu et al., 2013; Dutra et al., 2014; Zargar et al., 2014; Jenkins and Warren, 2015; Swain and Hayhoe, 2015; Zarch et al., 2015).
- *Page 10340, Line 21: This is a rather sloppy formulation. Of course other distributions can be used, but what are the implications? When or where do I use other distributions?*
  Answer: This will be refined as follows: Time series of precipitation for a particular location are fitted to the gamma distribution following the recommendation by Stagge et al. (2015).
  Stagge, J. H., Tallaksen, L. M., Gudmundsson, L., Van Loon, A. F. and Stahl, K.: Candidate Distributions for Climatological Drought Indices (SPI and SPEI), Int. J. Climatol., 35, 4027–4040, doi: 10.1002/joc.4267, 2015.
- *Page 10341, Lines 10-13: This statement is not clear to me, please rephrase.*
  Answer: We will change this statement to: "Wu et al. (2005) recommended the use of the longest possible period for the derivation of SPI as the short data sets could give large errors of estimated values. For the comparison of results between different locations the choice of the same period is suggested."
- *Page 10344, Lines 3-5: Delete paragraph. It is not necessary.*
  Answer: This will be deleted, as suggested.
- *Page 10345, Line 4: rephrase: ". . .precipitation intensities are simulated by RCMs driven by ARPEGE."*
  Answer: This will be corrected.
- *Page 10346, Line 16: raw should be row.*
  Answer: This will be corrected.
- *Page 10347, Line 4: Fig. 14: Please stick to the order of the Figures referenced in the text.*
  Answer: Figure 7 should be cited there.
- *Page 10347, Line 12: Why did you choose exactly this station? Could you please justify this decision?*
  Answer: We have chosen a grid cell located in the NE Poland close to Białystok to illustrate our results. This selection was made based on the results Liszewska et al. (2012). The largest changes in winter precipitation are projected to be in that area. We will clarify this selection in the text.
- *Page 10349, Line 18: rephrase: ". . .depends on the climate model and month under consideration."*
  Answer: This will be corrected.
- *Page 10349, Lines 19-20: rephrase: ". . .of simulated data, therefore the most intense bias correction is applied in that case."*
  Answer: This will be corrected. .
- *Page 10350, Lines 22-29: Where are these results shown? (Table, Figure)*
  Answer: The results of the SPI 6 for the cold season (November-April) are similar to those for the SPI 3 winter. The results are presented in the Supplementary materials (Figure S2).

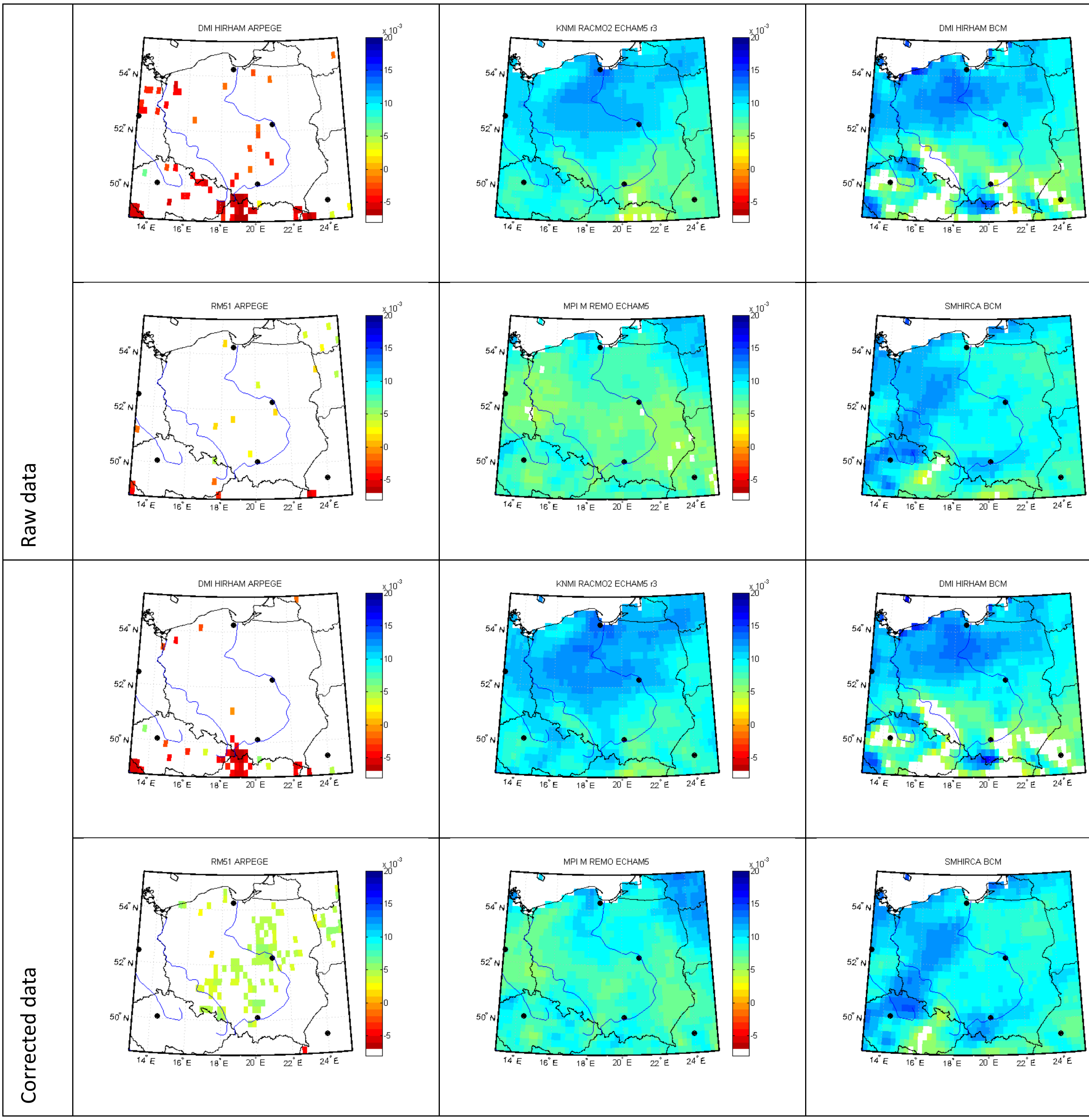

Figure S2. The results of modified Mann-Kendall trend analysis for SPI 6 cold season (NOV-APR). Colour scale denotes slope of the estimated trend. White colour denotes lack of trend.

- *Page 10353, Line 11: Why the "first six months"? Where is the justification for this? I would rather suggest using the four "core" months of the seasons: January, April, July and October.*
  Answer: In the updated version of manuscript we will show the relationships for all months,

as illustrated here.

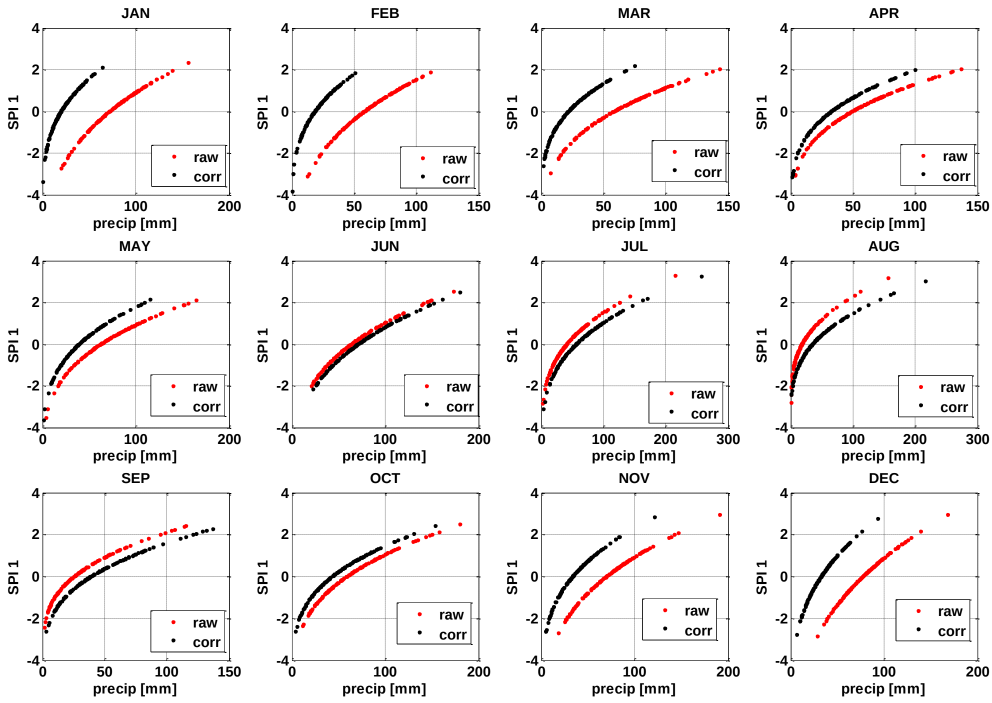

Figure 14 The scatterplots showing relationship between monthly sum of precipitation and estimated SPI 1 values for 12 months for one grid cell located close to Białystok (NE Poland) for DMI HIRHAM ARPEGE model. The colour denotes type of data used, red colour -uncorrected precipitation and SPI 1, black corrected ones.

- *Page 10354, Lines 4-6: Please add a reference to this statement.*
  Answer: Reference to Sunyer et al. (2015) will be added.
- *Page 10354, Line 20: Reference of Maurer and Pierce (2014): the authors of this study analysed precipitation, not a precipitation index. This is a complete different thing, so I think this reference is not valid for the given statement.*
  Answer: We will add this reference in order to explain bias correction methods necessary in our analysis of the influence of bias correction on SPI indices.
- *I could not find a reference in the text for Figure 7.*
  Answer: This will be included.
- *Figure 10 is a bit confusing. You produced a stacked bar chart, which is not appropriate in my opinion. A better way would be to draw the bars separately, grouped by month, or to have a line chart with one model representing one line in different colours.*
  Answer: Both of the reviewers have made this suggestion, so that we will include the revised

figure as follows: