Revision of

"Synoptic control over winter snowfall variability observed in a remote site of Apennine Mountains (Italy), 1884–2015"

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RC = Referee comment
AR = Authors' reply

REVIEWER #1

RC: Capozzi et al analyze a more than century long series of snowfall from the southern Apennines in Italy, and relate it to synoptic weather types and teleconnection indices. The analysis involves a newly digitised series of snowfall, and adds to the understanding of snowfall in a Mediterranean regime. Since there are little studies on snowfall, especially with such long series and from non-Alpine regions, it is a valuable contribution to the field.
The manuscript is generally well written, even though at times the language is flowery. However, the composition of the manuscript needs to be improved. A lot of methods can be found in the results. The discussion is missing completely (see also point 4 below). And the methods contain too much and too little (point 1 below).
The manuscript focuses a lot on "visual inspection" of time series, as well as relating different time series, but again mostly visual. The manuscript could be significantly improved if the authors would conduct some statistical analyses by relating time series in a bi-variate way, instead of visually comparing time series across pages. This would require only simple correlation analysis, which the authors conducted in other parts of the manuscript. However, extending this type of analysis would make the conclusion and results from the paper much stronger (see also comments below).

AR: We are very grateful for his/her positive evaluation of our study and for the time dedicated to the revision of our manuscript. We are also grateful for the comments and the suggestions, which help us to improve our paper and to foster the results.

Major Comments

RC (1): Methods description Sec 2.1 and 2.2 are both very detailed and at the same time miss critical information. The information on data collection and processing is only interesting for very specific readers. The authors could consider moving large parts of this into an appendix. (also the Petitt and CUSUM are standard tests, so no such detailed description is needed). On the other hand, key information is missing: Which data did you use, daily or subdaily? How did you arrive at monthly values? How did you deal with gaps in the series?

AR (1): According to the referee's suggestion, in the revised version of the manuscript a part of section 2.1 will be moved into the Appendix A (Data collection and measurements practises). Moreover, we will delete the details about the Petitt and CUSUM test for data homogenization.
Regarding the reviewer's questions, for our analysis we have used daily height of new snow data (indicated as HNS_d in the manuscript), because they are available for almost all the considered period (1884-2020). The monthly values of snow amount have been computed as a simple sum of all HNS_d data observed in a determined month. About the gaps in the time series, we are not able to reconstruct the missing data due to the unavailability of snowfall time series collected in sites close to Montevergine.

For future works, we are planning to rescue other climatological time series in Campania Region that may include information about snowfall occurrence. Therefore, we will probably able to fill the existing gaps in Montevergine time series only in terms of daily snowfall occurrence, but not in terms of daily snowfall amounts.
We will better clarify these aspects in the revised version of our manuscript.

RC (2): L309ff and Table 1: How did you define these periods? Just taking 23yr periods? Why exactly these years? I do not think it's a good idea to create these groups, since they might or might not include and exclude relevant points in the time series. If you want to discuss interannual variability and long-term changes, I suggest employing moving window averages (for long-term changes) and moving window standard deviations (for interannual variability). A period of 20 or 30 years would make sense. This would not have the "problem" of arbitrarily defining year groups.

AR (2): Following the referee comment, we have revised the Figure 5 of our manuscript. Note that this Figure is now labelled as Figure 4 after the revision process. More specifically, in order to highlight the long-term changes, we have used the moving window average (with a time span of 20 years), whereas to better emphasize the interannual variability we have computed (and plotted) the moving window standard deviation.

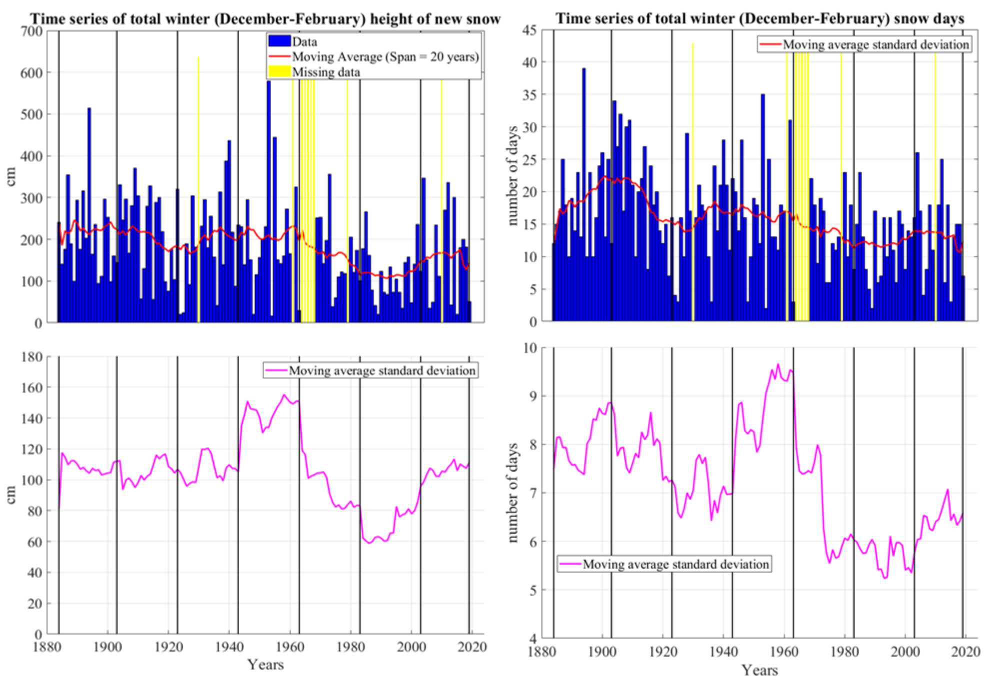

Figure 4: Winter (December to February) time series of total height of new snow (upper left panel) and total number of snow days (upper right panel). In both panels, the missing data are highlighted as yellow bars. The red line shows the 20-years moving average smoothing. The bottom panels present, for total height of new snow (left) and total number of snow days (right), the standard deviation of the moving average (magenta lines). On both panels, the vertical black lines define the limits of the 20-years sub-periods introduced in Table 1.

The subdivision of the investigated time interval into sub-periods of 23 years allowed us to emphasize the strong reduction in snowfall amount observed in the period from mid-1970s to the end of 1990s. According to the reviewer's suggestion, we have segmented the time series into more customary 20-years intervals. It should be pointed out that this choice reduces the last sub-period (2004/05-2019/20) to a length of 16 years. We have revised the Table 1 of our manuscript as follows.

Table 1. Average and standard deviation values (in cm) of total winter HNS and number of snow days (NSD) observed in MVOBS for different sub-periods.

Sub-period	**Total HNS** **Average and standard deviation (cm)**	**NSD** **Average and standard deviation (number of days)**
1884/85-1903/04	213.2 ±104.2	18.2 ±7.4
1904/05-1923/24	221.5 ±103.6	20.3 ±8.1
1924/25-1943/44	199.7 ±117.4	16.1 ±7.7
1944/45-1963/64	201.3 ±140.1	16.2 ±9.1
1964/65-1983/84	160.7 ±85.3	13.7 ±5.7
1984/85-2003/04	114.1 ±65.6	11.9 ±5.7
2004/05-2019/20	167.4 ±109.6	13.6±7.1

Moreover, we also modified the Figure 9 of our manuscript, which is now labelled as Figure 8.

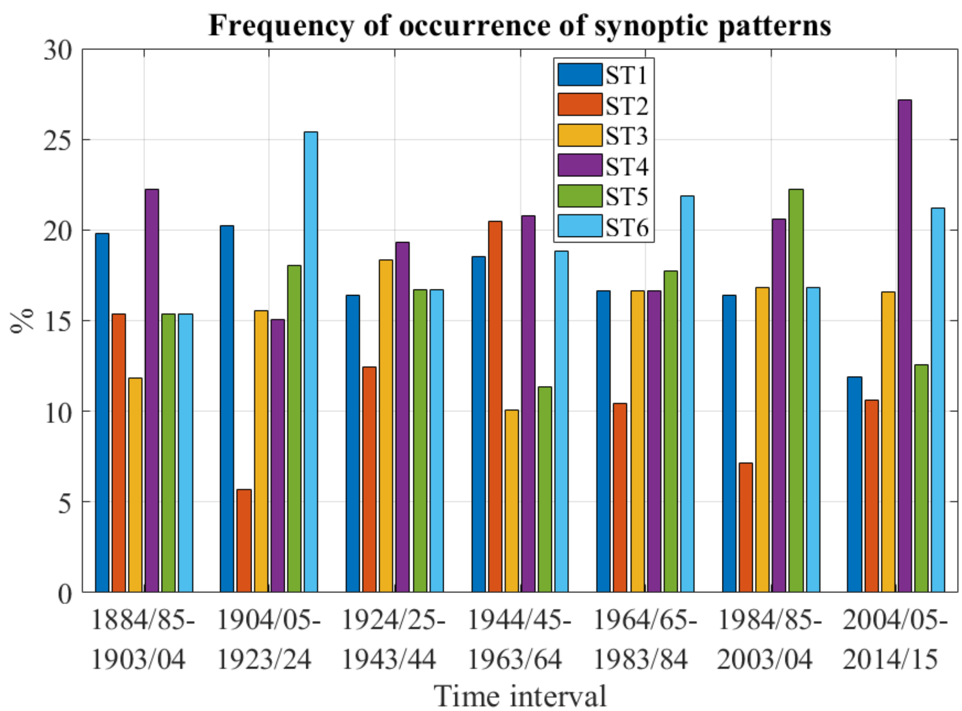

Figure 8: Each group of bar represent the frequency of occurrence of ST (expressed as percentage) in relation to the total number of snowfall events observed in a determined time interval. The six synoptic types, i.e. ST1, ST2, ST3, ST4, ST5 and ST6, are marked as blue, red, orange, magenta, green and cyan bar, respectively.

All these changes will be included in the revised version of the manuscript.

RC (3): Figure 8 and related text: Besides the issue with year groups (see comment above), I think it would be much easier if you showed scatter plots of STx versus HNS, instead of trying to compare time series across pages. You could also calculate correlations between these two to give more weight to what you identify from "visual inspection". This would make it easier for readers to see your points.

AR (3): We agree with the reviewer remarks. However, the scatter plot between STx and HNS is not a good solution to show the correlation degree between the two variables. The frequency of occurrence of ST, in fact, has a behaviour very similar to a categorical variable. This causes overlapping problems, so in some scatter diagram there are tenths of values all stacked on top of each other. For this reason, we have decided not to modify the Figure 8 of our manuscript (which is now labelled as Figure 7). According to the reviewer's suggestion, we have computed the linear correlation coefficient for each time periods presented in the new version of Table 1 (except for the last period, which reduces to 2004/05 to 2014/15). The results are presented in a following Table, which will be numbered as Table 3 in the revised manuscript.

Table 3. Linear correlation coefficient (*r*) between synoptic types frequency of occurrence and total winter height of new snow (HNS). The results are presented according to seven different sub-periods. Bold and grey values indicate correlations with 95% and 90% significance levels, respectively.

Synoptic type	1884/85-1903/04	1904/05-1923/24	1924/25-1943/44	1944/45-1963/64	1964/65-1983/84	1984/85-2003/04	2004/05-2014/15
ST1	**0.73**	**0.45**	**0.67**	0.28	**0.62**	**0.61**	0.58
ST2	**0.64**	0.13	**0.68**	**0.63**	0.33	0.43	0.29
ST3	-0.05	0.41	0.40	**0.46**	0.10	0.05	0.62
ST4	0.41	**0.58**	**0.50**	**0.78**	0.24	**0.72**	**0.75**
ST5	0.00	0.23	0.00	0.41	**0.54**	0.16	0.50
ST6	0.36	0.44	0.38	0.41	0.11	0.34	0.10

Note that the significance of the correlation coefficient has been tested through the well-known p-value method. In the revised version of the manuscript, we will clarify this aspect and we will discuss the results of the correlation analysis presented in the Table 3.

RC (4): Discussion is missing completely. Regarding the snowfall series: How do your results compare to other long-term series from Italy, such as Parma or Torino? If I remember correctly they have been published, but possibly not in international journals.

AR (4): In the revised version of the manuscript, we will add the following Discussion section, in which we compare our results with Parma and Torino time series. Thank you for the suggestions.

"The variability over the time of the total winter HNS recorded in MVOBS presents some similarities with evidences provided by past research carried out in the alpine region. The first common point lies in the strong interannual variability, which many authors reported in their analysis (e.g. Schöner et al., 2009; Scherrer et al., 2013; Terzago et al., 2013). The patterns emerged from the behaviour over time of MVOBS signal are generally in line with those identified in some previous studies. In this respect, it is important highlighting that the strong reduction in snowfall amount and frequency of occurrence occurred in MVOBS in the 1990s and the subsequent recovery in 2000s have been also observed in Switzerland, France, western Italian Alps and Austria (e.g. Laternser and Schneebeli, 2003; Micheletti, 2008; Vault and Ciafarra, 2010; Scherrer et al., 2013; Marcolini et al., 2017; Matiu et al., 2021). However, it should be noted that in most of the investigated alpine sites the decline in snowfall amount, as well as in NSD, occurred after 1980s, whereas in MVOBS it began in the mid-1970s. Moreover, it is very interesting highlight that the maximum in snowfall amount found in MVOBS time series in 1900-1920 period (see Table 1) has been also detected in Switzerland by Scherrer et al., 2013.

Unfortunately, aside from the Alpine region, the available literature does not offer many other terms of comparison in the Italian territory. In this respect, two examples are the long-term nivometric time series collected in Parma and Turin, in the Po plain. The former has been analysed in Diodato et al. (2018) for the 1777-2018 period. The authors reported a decline in snowfall frequency of occurrence, mainly in the first half of 19th century, as well as in the annual length of the snow season, attributing these changes to large-scale circulation patterns and in particular to the NAO index. However, no significant trend has been detected for the amount of fresh snow, according to the available data (1868-2018 period). The Turin snowfall series has been investigated by Leporati and Mercalli (1993). The latter detected a very strong interannual variability both in terms of NSD and snowfall amounts, similarly to the results achieved for MVOBS. The main relevant dissimilarity lies in the above-than-normal snowfall amount measured in 1981-1987 period, which are in contrast with the evidence provided not only by MVOBS, but also by many other Alpine monitoring stations.

The synoptic patterns identified in our work exhibit some analogies, but also some differences, with other synoptic types related to snowfall events in Europe. For example, Merino et al. (2014), using a methodological approach based on a multivariate statistical analysis (including both PCA and CA), found four different synoptic types associated with snowfall events on the northwestern Iberian peninsula. The first one is associated with a maritime arctic air advection over western Mediterranean region, the second one with the advection of polar maritime air masses, the third one with the incoming of polar continental air masses over western Mediterranean area, whereas the fourth-one is characterised by a closed cyclonic circulation over the Iberian Peninsula, which produces strong thermal gradient. The second and the third patterns have several commonalities with the ST6 and ST4 of our works, respectively, both in terms of involved air masses and in the upper level flow. The first and the fourth circulation types discusses in Merino et al. (2014) are unfavourable to snowfall events in the southern Apennines area, although the former traces out a large-scale configuration that promotes the incoming of maritime arctic air mass over Mediterranean basin, by analogy with the ST1 of our study.

Moreover, it is also interesting to compare our results with the study of Esteban et al. (2005), which extracted seven different circulation patterns that explain heavy snow precipitation days in Andorra (Pyrenees). Three of these patterns represent an advection from northwestern of polar maritime air masses which resembles the large-scale flow depicted by ST6, whereas other three types have some common points with ST1, ST2 and ST4, showing scenarios characterised by advection of Atlantic or Mediterranean air masses combined with the outbreak of cold air from northern and eastern Europe. There is only one situation, characterised by a low-pressure area northwestern Spain, which strongly departs from scenarios that trigger snowfall events in Southern Italy Apennines.

According to the results of our analysis, it is very reasonable ascribe the negative snowfall amounts and number of events anomaly observed between 1970s and 1990s to the increase in NAO and AO indices values, which cause a reduction of the occurrence of some synoptic patterns, mainly ST1 and ST2, very favourable to the incoming, in Central Mediterranean area, of cold air masses of maritime (polar or arctic) origin. This achievement is in accordance with the findings of Merino et al. (2014), which attribute the decrease in the number of snow days observed in Castilla y León region (Spain) to the increase in the NAO index during winter months throughout the second half of the 20th century. The impact of NAO and AO anomalies was mitigated by the incidence of ST4 and ST5, which remains quite stable due to the occurrence of some periods characterised by positive values of EMP and SCAND indices. The increase in interannual variability of snowfall events detected in the last two decades, as well as the rise in the average amount, can be attributed to large-scale conditions more beneficial for cold outbreaks in central Mediterranean regions, as well represented by rising in frequency of negative AO patterns and by the occurrence of winter seasons modulated by positive EMP and negative EAWR."

Minor Comments

RC (1): L11: mismatch of period wrt to title. OK, later I understood. The snowfall series ends 2020, but the reanalysis 2015, right? You should clarify this and be clearer.

AR (1): Yes, it is right. In the revised version of the manuscript, we will specify that the cluster analysis has been applied to 1884-2015 according to the availability of reanalysis data.

RC (2): L37ff the literature review is a bit random. It's mixing snow cover parameters (depth, fresh snow, SCD) and it's not clear why the authors chose the specific geographic limit. Btw, there are many other studies from Italy and other countries in the Alps. Also more with century long series. It's not necessary to mention all, but maybe the authors could make their point better.

AR (2): Following the referee's suggestion, we have broaden our literature review as follows, including several other references, mainly related to the alpine region.

"The study period of the climatological researches carried out in such works is generally limited to the last 55-65 years. However, few studies (mainly focused on the Alpine area) extended their analysis further back, due to the absence, in many areas, of reliable and continuous old snowfall climatological records. In this respect, it is deserving of mention the study of Scherrer et al. (2013), which investigated the snowfall variability observed in Switzerland during the 1864-2009 period, using nine different stations. According to the findings of this work, the analysed depth of snowfall time series exhibit a strong decadal variability. The highest value in depth of snowfall and days with snowfall occurred in 1900-1920 and 1960-1980 period, the lowest between 1980s and 1900s, whereas an increase in depth of snowfall has been observed in 2000s. Another important reference for mountainous areas is Laternser and Schneebeli (2003), who discovered, for the Swiss Alps, an increase in snow cover and duration from 1930 to early 1980 and, subsequently, a statistically significant decrease towards 1999. Some years later, Beniston (2012b) observed a decline in winter snow depth in the 1930-2010 period by analysing 10 time series in Switzerland. The study of Marty and Blanchet (2012), which has investigated a very large number of snowfall records collected in Switzerland during 1931-2010 period, reached similar conclusions. The authors discovered that the 44% of the considered stations show a significant decrease in the annual snow depth maxima values. Another interesting evidence can be found in the study of Schöner et al. (2009), which examined the snow depth time series collected in Sonnblick (Austria) in the 1928-2005 period: the authors reported a strong interannual variability in snow depth (with largest values in 1940-1950 period) and a decreasing trend in summer snow. Terzago et al. (2013) found a decrease in snow depth (2-14 cm per decade) in the western Italy for the period 1926-2010. Moreover, they also reported a very strong interannual variability, with maxima in 1940, 1950 and 1960, minima in 1990 and then a recovery in the 2000s. Irannezhad et al. (2017) evaluated the annual snowfall variability in Finland in the 1909-2008 period, analysing its relationship with some large-scale atmospheric patterns. From this study, it emerges a significant decline in annual snowfall in the northern part of Finland, as well as a strong relationship between the observed snowfall variability and the large-scale teleconnection patterns synthesised by Arctic Oscillation and East Atlantic indices."

RC (3): Introduction: Long series are great, but snowfall has extremely high spatial variability, so many short series can identify different aspects than one long time series. Maybe the authors could elaborate more on this topic.

AR (3): According to the referee suggestion, we have further broaden the literature review as follows, including more references about snowfall variability observed in the recent 10-years periods.

"Focusing on the Alpine region, Micheletti (2008) carried out an analysis for the Friuli Venezia Giulia (northeast of Italy) for the 1972-2007 period, by investigating the seasonal depth of snowfall records from eight stations. A positive anomaly was observed until the end of 1980s, followed by a lowering of snowfall amount between 1990 and 2000 and by a subsequent recovery (but below the level of 1980s). Valt and Ciafarra (2010) investigated the accumulated snowfall variability observed in Italian Alps (eastern and western sectors) in the period from 1960 to 2009. As general results, they found a negative trend, which is strongest in spring season and below 1500 m asl. Terzago et al. (2010) have provided a focus on the Piedmont Region (northwest of Italy), examining the monthly snow depth and depth of snowfall for the period 1971-2009; the authors discovered an increasing trend for November-December period and a decreasing tendency in January-April. Kreyling and Henry (2011) analysed 177 stations in Germany for the period 1950-2000, focusing on snow days variability: they found a negative trend for the majority of the stations, especially in the last 15 years of the considered period. Marcolini et al. (2017) investigated the snow depth time series collected in the Adige basin (North East Italy) for the period 1980-2019. According to the results of this study, a relevant reduction of both snow cover duration and mean seasonal snow depth occurred in the Adige catchment after 1988, both at low and high elevation sites. On the contrary, in the period from 2000 to 2009, an increase (although not identified as statistically significant) of mean seasonal snow depth has been recorded. Lejeune et al. (2019) found a relevant decrease in the snow depth observed in Col de Porte (France) during the period 1960-2017. Moreover, it is worth mentioning the study of Schöner et al. (2019), which examined a very high number (139) stations located in Austria and Switzerland for the period 1961-2012. The authors of this work found negative tendencies in snow depth (up to -12 cm / 10 years period for sites at elevations of about 2000 m asl) and a positive relationship between the strength of snow depth trends and the altitudes."

RC (4): L64ff: At this point in a paper, there should not be a summary of what is being done, but the aims of the paper (high-level understanding, hypothesis, etc.).

AR (4): According to the referee remarks, we have reformulated this part of the Introduction section as follows.
"The main purposes of our work can be synthetized as follows:

- To extend, from both quantitative and qualitative perspectives, the current knowledge about the past snowfall variability observed in Mediterranean mountainous sectors;
- To shed light on links between large-scale atmospheric circulation and local climate variability, by identifying and analysing the synoptic patterns favourable to winter snowfall events in Montevergine as well as their relationship with the main teleconnection indices that govern the atmospheric circulation in the Mediterranean area."

RC (5): Figure 5: why did you choose a lowess smoother? Would a simple moving average (10/20/or 30 years) be easier? For the lowess, you also need to supply the degree and the weights, not only the time span.

AR (5): We have chosen the lowess smoothing because it generally works better than moving average at the edges of the time series. However, following the referee suggestion, we have replaced the lowess smoothing with the moving average (See the Figure 4 in the previous comment).

RC (6): How are "snow days" (NSD) defined? This would belong in the methods. (related Table 1, Figure 5, …)

AR (6): Usually, a "snow day" is a day on which accumulated snowfall (i.e. daily high of new snow, HNS_d) is at least 1.0 cm. However, in our work, in applying the cluster analysis (CA) we have used a slight different definition of "snow day". More specifically, we have considered as "snowy" a day in which the recorded HNS_d value was at least 3.0 cm. This threshold allows filtering out most of some ambiguous events, characterized by the simultaneous presence of different hydrometeors types (i.e. rain, snow hail or graupel).
In the revised version of our manuscript, we will better clarified this point.

RC (7): L409: how did you determine statistical significance of trends?

AR (7): Sorry for missing this important detail. To compute the statistical significance of trend, we used the Mann-Kendall test (Mann 1945, Kendall 1962). We will clarify this aspect in the revised version of the manuscript.

RC (8): L452: How does the correlation table look like for all values, not only the upper and lower quartiles? Maybe for the supplement.

AR (8): In the following Table, we present the correlation analysis in the scenario in which all teleconnection indices values are considered. The results are generally similar to the ones obtained considering only the upper and lower quartiles, although the correlation levels appear to be generally lower. In the revised manuscript, we added a brief sentence about this aspect, but we decide to not include this Table.

Linear correlation coefficient (r) between synoptic types frequency of occurrence and teleconnection indices (all values) over the period 1950-2015. Bold and grey values indicate correlations with 95% and 90% significance levels, respectively.

Synoptic type	NAO	AO	SCAND	EAWR	EMP
ST1	-0.16	-0.19	-0.21	-0.05	0.14
ST2	**-0.49**	**-0.59**	-0.06	**-0.31**	0.05
ST3	**0.27**	**0.36**	0.17	0.07	**0.23**
ST4	-0.05	-0.04	**0.27**	-0.06	**0.35**
ST5	**0.30**	0.21	0.06	0.12	**0.32**
ST6	-0.08	-0.13	0.10	**-0.39**	-0.12

RC (9): Section 4: have you considered also correlating teleconnection indices to the HNS series?

AR (9): Our main aim is to search for relationship between the identified synoptic patterns and the teleconnection indices. However, we have welcomed the suggestion of the referee and we have computed the linear correlation coefficient between the winter HNS time series and the teleconnection indices. As demonstrated by the following table, the correlations are generally low, except for AO index, which is positively correlated to HNS time series at 95% significance level. We will include this Table in the revised version of the manuscript (Table 5).

Table 5. Linear correlation coefficient (r) between winter total height of new snow and teleconnection indices (all values) over the period 1950-2015. Bold values indicate correlations with 95% significance level.

Teleconnection index	Linear correlation coefficient
AO	**-0.41**
EAWR	-0.15
EMP	0.18
NAO	-0.22
SCAND	0.25

RC (10): Figure 11: Hovmöller plots do not work for a discrete x-axis, where you have the five teleconnection indices. Would a simple correlation analysis not work better here, too?

AR (10): We understand the doubts of the reviewer with respect to the Figure 11 of our manuscript (which is now labelled as Fig. 10). However, we feel that this picture give a complete, comprehensive and simple, even though qualitative, representation of the relationship between the analysed teleconnection indices and the HNS time series. In our opinion, a linear correlation analysis, in which the indices are considered separately from each other, does not say much about the linkages with the nivometric regime of the site of interest.

A possible approach to investigate about the relative influences of the indices on the winter HNS may be a multiple linear regression analysis (e.g. Cohen et al., 2013). However, a quantitative and in-depth evaluation of this aspect is left for a future work. Therefore, we decide to leave unchanged the Figure 10 in the revised version of the manuscript and to include the linear correlation analysis suggested by the reviewer (see the previous comment).

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