Revision of

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

V. Capozzi, C. De Vivo, G. Budillon

RC = Referee comment
AR = Authors' reply

REVIEWER #2

RC: I appreciate the opportunity to review this very interesting and generally well-written work related to snowfall in Italy. This study uses a unique snowfall record from the Montevergine Observatory in Italy's
Apennine Mountains to investigate snowfall variability over the winter months (DJF) between 1884 and 2015. Via cluster analysis, the authors identify six synoptic atmospheric circulation patterns conducive to snowfall in the Apennine Mountains and link observed snowfall variability in their time series to changing frequencies in these synoptic types. Finally, the authors analyze the relationship between the synoptic types identified in this work and five teleconnection patterns important for winter weather in Europe. The findings from this study indicate synoptic-scale atmospheric variability largely controls snowfall variability at the Montevergine Observatory. This work falls squarely within TC's scope. The unique snowfall time series presented here provides snow information from a lesser-studied region and is particularly noteworthy and interesting for its broad temporal coverage and daily resolution. By combining this record with analyses of synoptic-scale atmospheric circulation, this study contributes valuable climatic information and knowledge about the mountain cryosphere which will be of interest to a broad audience. I found the manuscript enjoyable to read and generally well-written. Grammatical errors do occasionally hinder understanding or serve as a distraction to the authors' overall message (see examples under Technical corrections) – however, I believe the authors can quickly correct most of these errors. Similarly, figures are relevant and mostly readable, although I have made some suggestions for improvements in the specific comments below. The organization of the manuscript made sense to me, but I think a discussion of the results should be more explicitly highlighted either via the addition of a Discussion section or via individual discussion subsections throughout Sections 3 and 4.

AR: Dear Dr. Hancock, we are very grateful for your positive comments about our study. We are very grateful for all suggestions and remarks, which contributed to improve our manuscript in a substantial way. Thank you very much for the time dedicated to the revision of our work.

In the revised version of the manuscript, we will include the following Discussion section, in which we compare our findings with the results of previous studies.

"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."

RC: My main concerns with the manuscript relate to the analyses of the snowfall time series (Section 3.1) and the section analyzing synoptic type variability in time (Section 3.3). In these sections, the combination of the subjective sub-period time interval selection and the visual time series inspections impede result robustness. A more objective method for analyzing variability in the time series – I like the other review's moving window suggestion – would mostly resolve my concerns in these sections by eliminating the subjectivity in the sub-period selection. If the authors wish to continue using the subperiods as presented in the current manuscript, the rationale behind the sub-period selection should be specifically addressed in Section 2 (Materials and methods). In this case, employing some statistical time series analyses in addition to the visual time series inspections would be necessary.

AR: 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 this suggestion and to remarks of the referee #1, we have segmented the time series into a more standard 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 (see Table 1 of the revised manuscript). Moreover, we have applied the moving average smoothing to both HNS and NSD time series, using a window of 20 years. To better emphasize the interannual variability we have computed (and plotted) the moving window standard deviation (see the following Figure, which will be labelled as Figure 4 in the revised version of the manuscript).

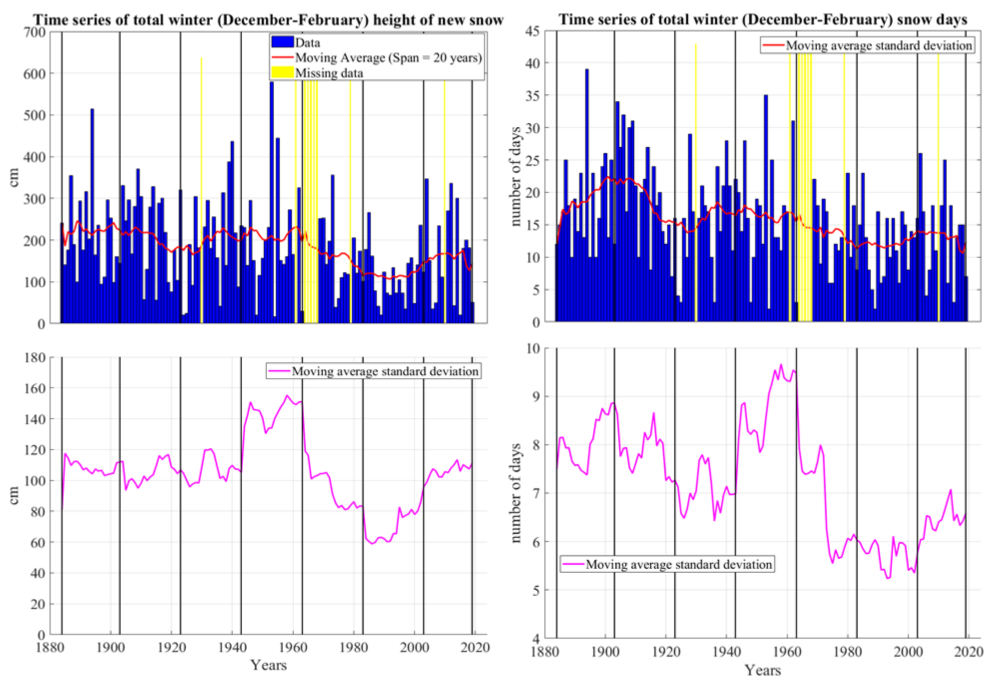


Figure 4: Winter (December to February) time series of total height of new snow (upper left panel) and total number of snow days (upper right panel). In both panels, the missing data are highlighted as yellow bars. The red line shows the 20-years moving average

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.

Specific comments:

RC (1): Line 160 – On Figure 3, it appears several HNSd values exceeded the 35 cm threshold and would actually have been detected by the gap check? Am I misinterpreting what you have done here in terms of identifying outliers?

AR (1): In the framework of quality control, the gap check has been applied as follows. Firstly, for each month we have sorted in ascend order the HNS_d data recorded over the entire available period (1884-2020). Subsequently, we have calculated the difference between two-consecutive values: if a certain HNS_d value is at least 35 cm larger than the previous record, then that value and subsequent ones are flagged as outliers. Therefore, in the Figure 3 (which will be labelled as Figure 2 in the revised manuscript), the HNS_d values exceeding the 35 cm threshold should not to be interpreted as outliers. This figure simply present the frequency distribution of HNS_d data for the three investigated winter months (December, January and February) and it demonstrates that there are not cases in which the difference between two consecutive bins exceeds the selected threshold (35 cm).

RC (2): Lines 226-227 – a sentence or reference justifying the selection of your domain would be helpful here.

AR (2): In the revised manuscript, we will add the following sentence: **"**The dimensions of the domain were selected to be consistent with the synoptic scale analysis of the present work and to avoid circulation features in regions remote from the study area (Merino et al., 2014)".

RC (3): Line 237 – here the HNSd threshold to determine NSD is 3 cm, but in Lines 331-332 related to Figure 5 you state that the right panel of Figure 5 includes days with over 1 cm of snow. Why do you display different data in Figure 5 than you use to determine the snow days for synoptic typing? Since Figure 5 is the only location where the total NSD is displayed as a time series (e.g. Figure 8 does not include a panel showing aggregate snow days from all synoptic types), I think it is important the NSD in Figure 5 match the 1986 days used in the cluster analyses.

AR (3): Ok, we have modified the right panel of the Figure according to the referee suggestion (see the Figure 4 in the previous comment). Therefore, in the revised version of the manuscript, the total winter NSD will be computed by considering a "snow day" as a day on which accumulated snowfall is at least 3.0 cm.

RC (4): Lines 336-340 – I appreciate the plain-language labelling of the synoptic types here, but these names are not used consistently throughout the remainder of the work. I'd recommend sticking with just one of the naming conventions, e.g. either ST1 or Arctic Maritime, or including the plain language name parenthetically as in Table 2.

AR (4): Ok, we have adopted the "ST" convention to label the synoptic patterns. Therefore, we have removed the labels "Arctic Maritime", "Central Europe Low", "Continental Air", "Mediterranean Low", "Arctic Trough" and "Polar Maritime".

RC (5): Section 3.2 – This section would really benefit from discussion comparing the synoptic types you have identified with other synoptic work related to snowfall in Europe. I realize you only included snow days in your analyses, but I am also curious about the prevailing synoptic conditions which do not result in snowfall in the Apennines. Even just a couple sentences about this in a discussion would be helpful.

AR (5): In the revised version of our paper, we will discuss this point as follows:

"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."

RC (6): Lines 397-400 – Are these differences statistically significant?

AR (6): We have evaluated the significance of these differences using the popular t-test method. The latter test the hypothesis that two independent samples come from distributions with equal means. More specifically, we have tested the significance between the average HSN_d found for ST1, ST2 and ST4 (11.8, 12.0 and 12.6 cm, respectively) and the average HSN_d values found for ST3, ST5 and ST6 (9.9, 9.7 and 10.2 cm, respectively). According to the p-value, (i.e. the probability of observing the given result, or one more extreme, by chance if the null hypothesis is true), the null hypothesis (i.e. the average

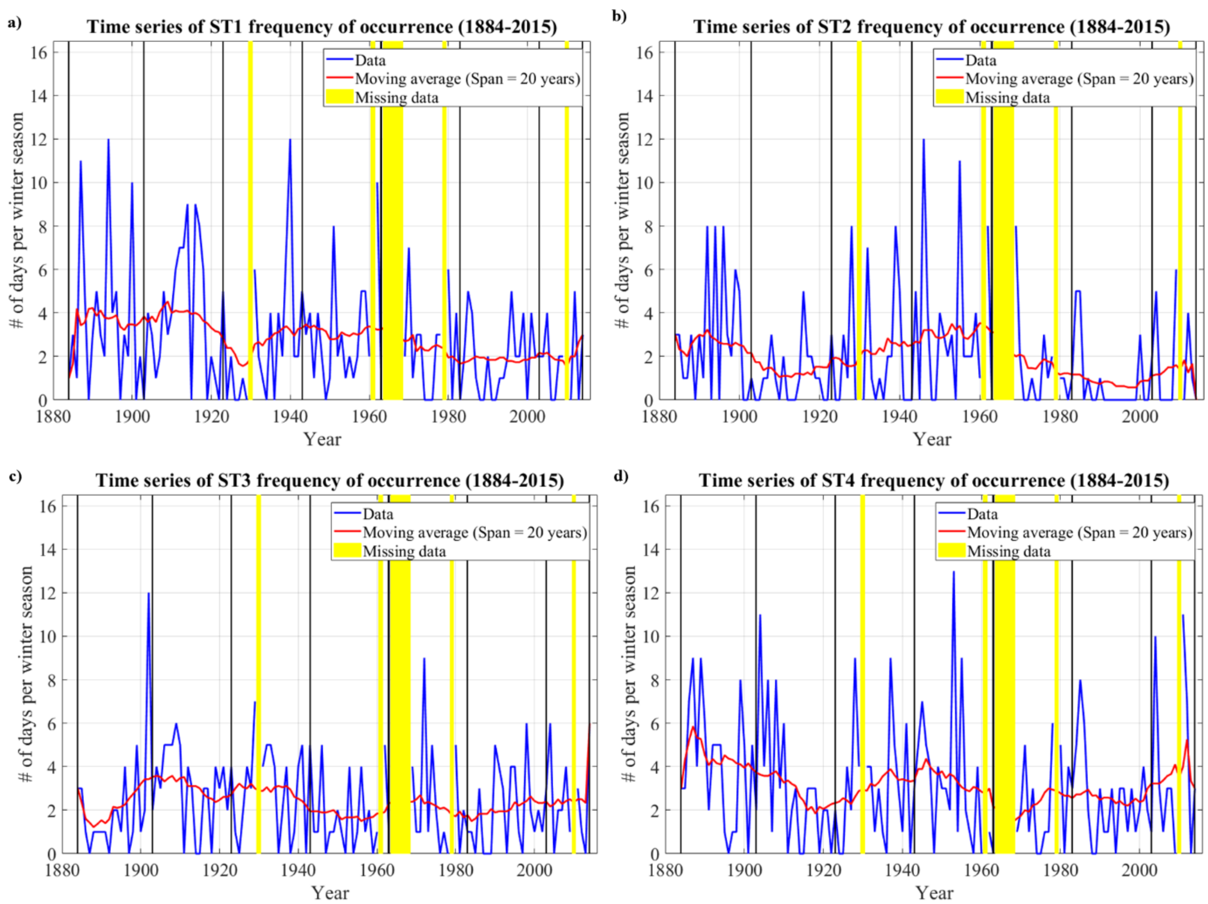
HSNd values are equal) can be rejected at the 5% level for all ST couples (for examples, ST1 vs ST5, ST2 vs ST6 and ST4 vs ST3). In the revised version of the manuscript, we will better clarify this point.

RC (7): Figure 5 – See the comments above related the number of snow days in the right panel. If you elect to continue with the sub-periods, please delineate the time periods in the graph to help the reader.

AR (7): Ok, we have modified the Figure 5 (which is now labelled as Figure 4) according to the referee's comment.

RC (8): Figure 8 – If you elect to continue with the sub-periods, please delineate the time periods in the graph to help the reader. Please also consider including a panel showing the total NSD, if the data in Figure 5 are different.

AR (8): Ok, we have modified the Figure 8 (which is now labelled as Figure 7) according to the referee's comment.



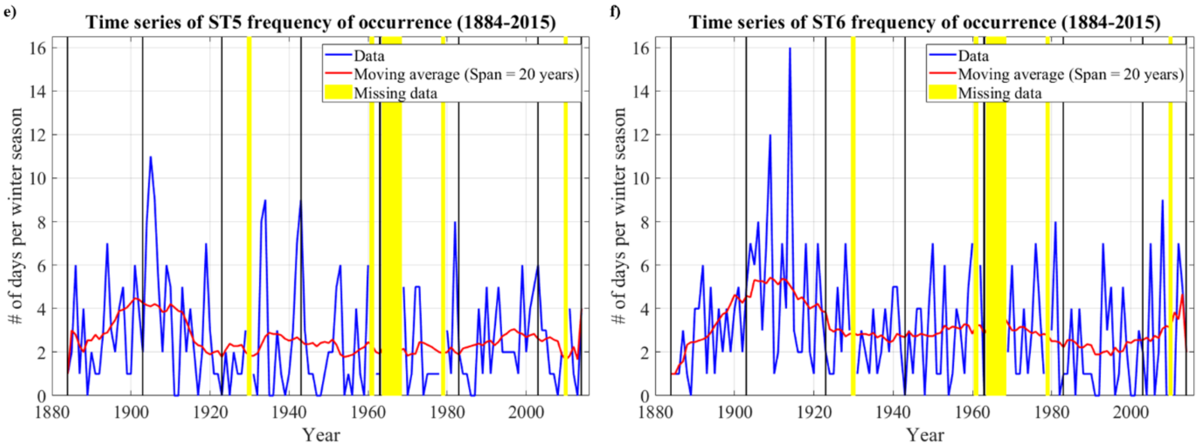


Figure 7: Time series of the frequency of occurrence, expressed in terms of number of days per winter season, of the six synoptic types (ST) emerged from the cluster analysis, i.e. ST1 (a), ST2 (b), ST3 (c), ST4 (d), ST5 (e) and ST6 (f). In all panels, the missing data are highlighted as yellow bars, whereas the red line shows the 20-year moving average smooth. The period from 1884 to 2015 has been considered. The red line shows the 20-years moving average smoothing. On all panels, the vertical black lines define the limits of the 20-years sub-periods introduced in Section 3.1, except for the last period, which reduces to 2004/05 to 2014/15.

Technical corrections

RC (1): Line 39 – the mid-1970s.

AR (1): Ok, we have corrected, thank you.

RC (2): Line 43 – the Castilla y Leon region

AR (2): Ok, we have corrected, thank you.

RC (3): Line 54 – few studies extended their analyses further back (?)

AR (3): Ok, we have corrected, thank you.

RC (4): Line 61 – to provide

AR (4): Ok, we have corrected, thank you.

RC (5): Line 89 – emphasized

AR (5): Ok, we have corrected, sorry for the mistake.

RC (6): Line 93 – to point

AR (6): Ok, we have corrected, thank you.

RC (7): Line 155 – ascending order

AR (7): Ok, we have corrected, thank you.

RC (8): Line 280 – where the air pressure is lower than.

AR (8): Ok, we have corrected, thank you.

RC (9): Line 428 – I would write XX as 20th here.

AR (9): Ok, we have corrected, thank you.

RC (10): Line 479 – to inspect

AR (10): Ok, we have corrected, thank you.

RC (11): Line 557 – left for future studies

AR (11): Ok, we have corrected, thank you.

RC (12): Figure 2 – is there any way to increase the resolution of the photo? I can't really read it even zooming in and would really like to see what the records look like!

AR (12): Ok, we tried to increase the definition of this figure. Note that, according to the suggestions of the referee #1, we have moved this figure into the Appendix A. Therefore, in the new manuscript version this figure will be labelled as Figure A1.

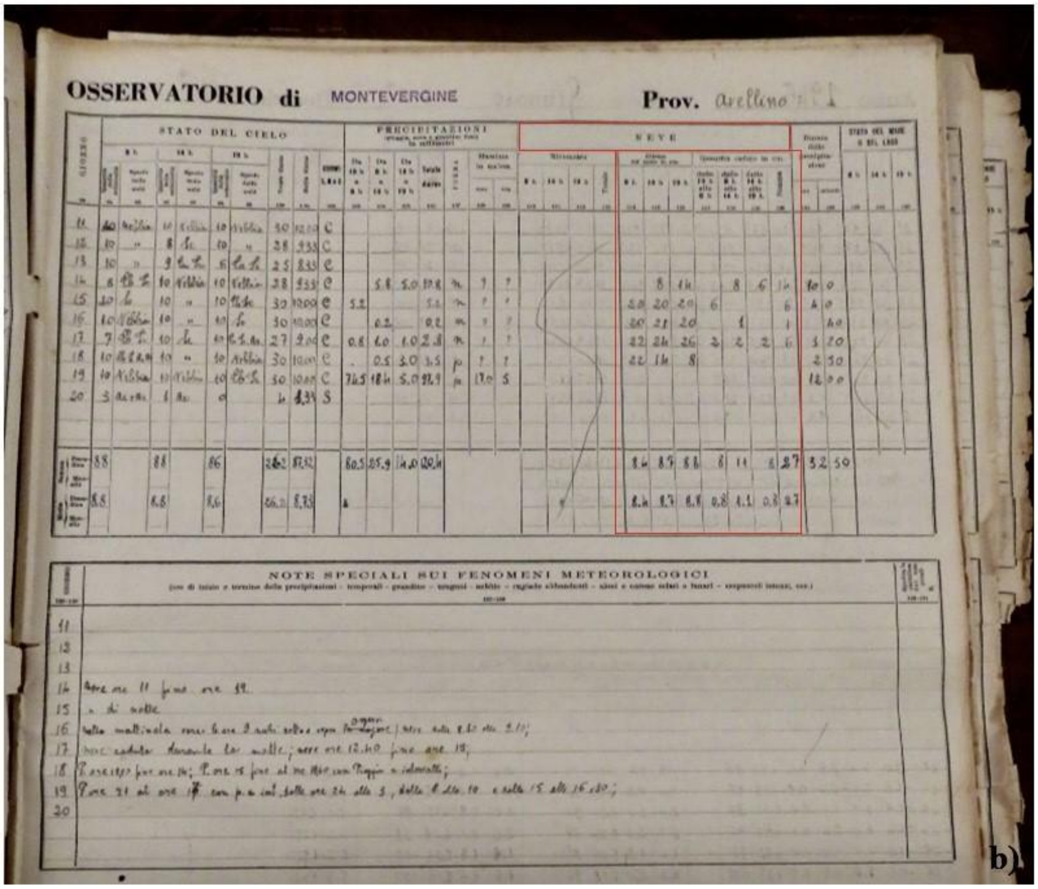


Figure A1. This picture presents an example of the original data source (related to the second 10-day period (i.e. from day 11 to 20) of January 1946). Each row accounts for the observations of a specific day, and each column is devoted to the records of a determined parameter at a specific hour of the day. The columns including snowfall measurements are bordered with red lines.

RC (13): Figure 3 – it's pretty hard to find the panel labels in this figure.

AR (13): Ok, we have corrected, thank you. Note that this figure is now labelled as Figure 2.

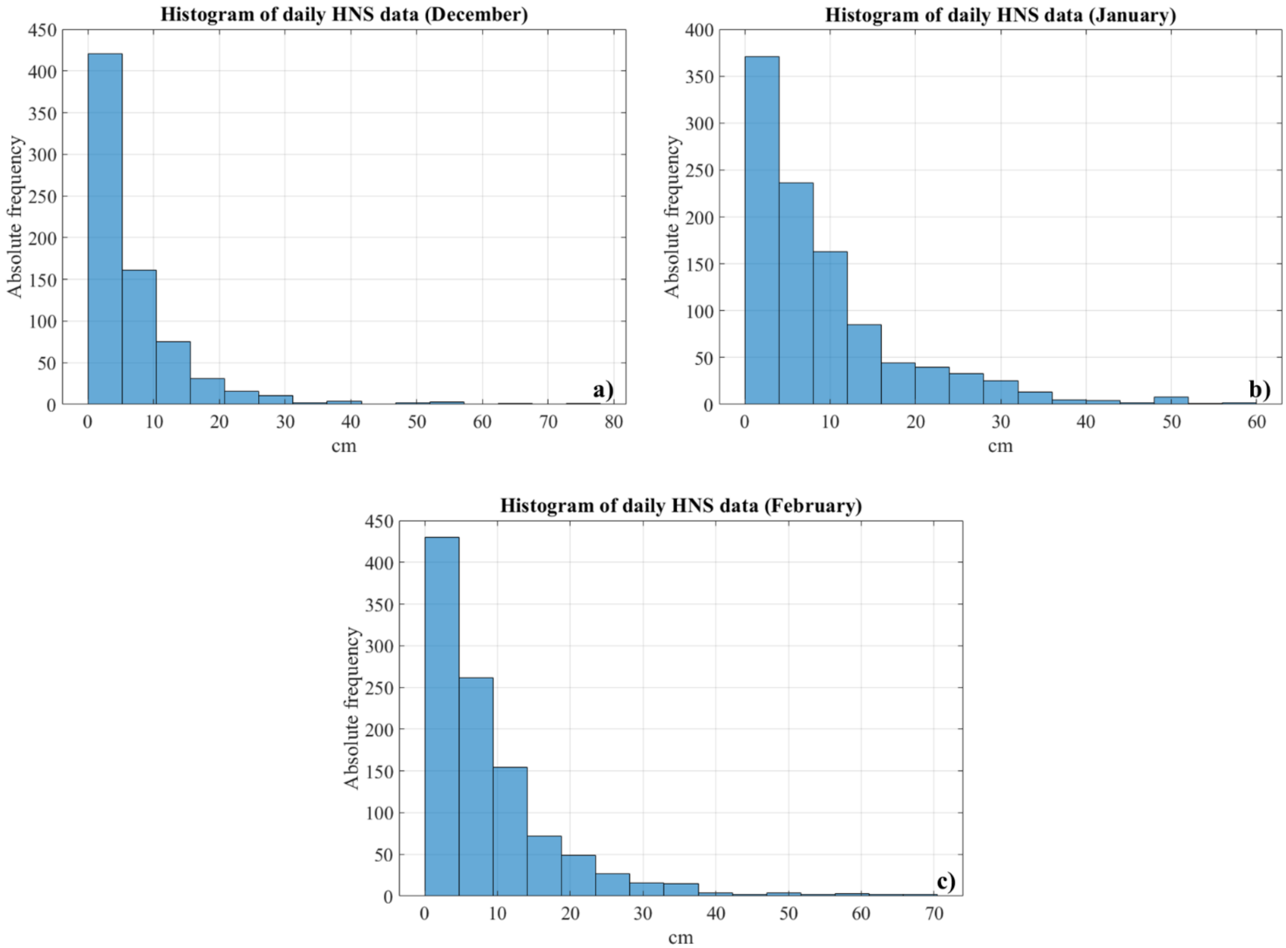


Figure 2: Histograms of daily height of snow (HNS_d) observed in MVOBS in December (a), January (b) and February (c). The y-axis is the absolute frequency (expressed as number of days), whereas the x-axis is the HNS_d amount at the bin centre (in cm). Data collected between 1884 and 2020 have been taken into account.

RC (14): Figures 6 and 7 – Beautiful. Is it possible to project these data so the higher latitude portions take up less of the map? I understand this can be a huge headache, however.

AR (14): The maps sketched in Figures 6 and 7 (numbered as Figure 5 and 6 in the revised manuscript) have been elaborating in MATLAB using the Miller Cylindrical projection. We have tried all other projection options offered by the MATLAB toolbox m_map (https://www.eoas.ubc.ca/~rich/mapug.html#p29): the only good alternative is the Equidistant cylindrical projection, which consists of equally-spaced latitude and longitude lines. We hope that this solution met the referee's requirement.

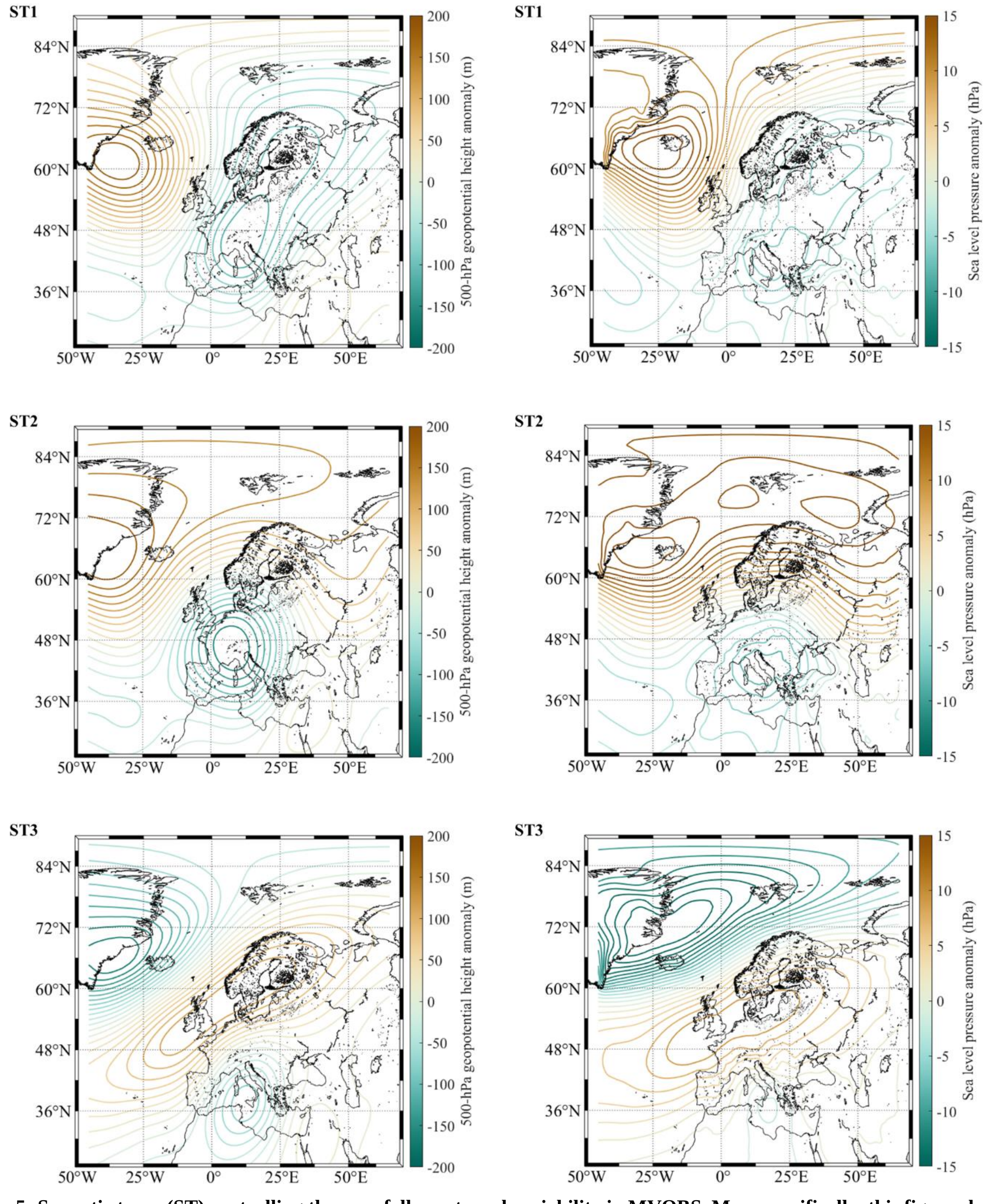


Figure 5: Synoptic types (ST) controlling the snowfall events and variability in MVOBS. More specifically, this figure sketches the ST1 ("Arctic Maritime"), the ST2 ("Central Europe Low") and the ST3 ("Continental Air"). The left panels (a, c and e) show, for ST1, ST2 and ST3, respectively, the 500-hPa geopotential height anomaly (in m) with a contour interval of 20 m; the right panels (b, d and f) present the sea level pressure anomaly (in hPa) with a contour interval of 1.5 hPa. The ST have been obtained from 20CRV3 reanalysis product (1884-2015 period), considering an area embracing the entire European territory (25-90°N, -45-65°E).

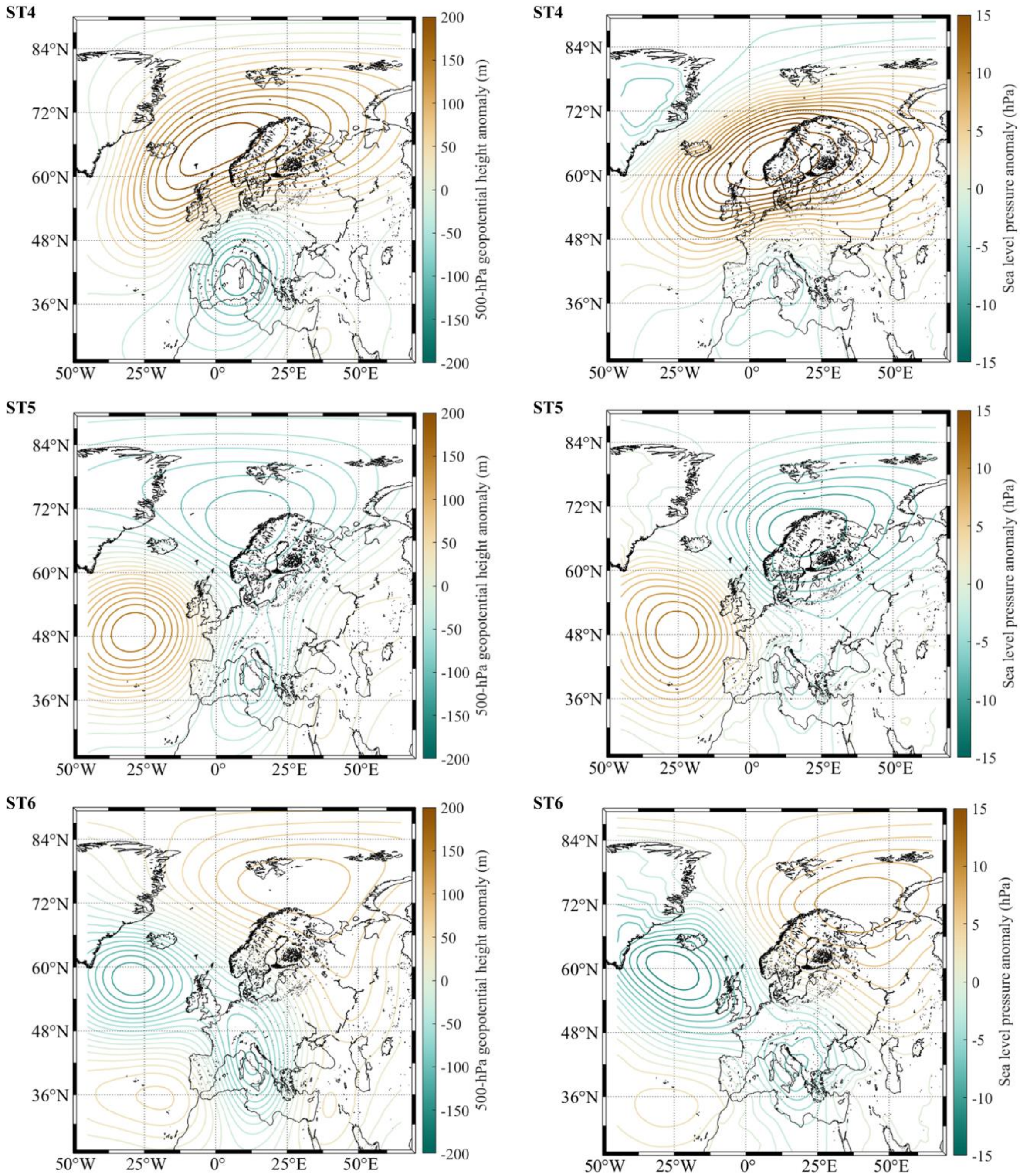


Figure 6: Synoptic types (ST) controlling the snowfall events and variability in MVOBS. More specifically, this figure sketches the ST4 ("Mediterranean Low"), the ST5 ("Arctic Trough") and the ST6 ("Arctic Maritime"). The left panels (a, c and e) show for ST4, ST5 and ST6, respectively, the 500-hPa geopotential height anomaly (in m) with a contour interval of 20 m; the right panels (b, d and f) present the sea level pressure anomaly (in hPa) with a contour interval of 1.5 hPa. The ST have been obtained from 20CRV3 reanalysis product (1884-2015 period), considering an area embracing the entire European territory (25-90°N, -45-65°E).

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