REVIEWER #1

The manuscript addresses an interesting and challenging topic. Information on the re- lationships between Eurasian autumn snow cover and following winter North Atlantic Oscillation would be very useful for seasonal prediction. The manuscript has its mer- its: (a) it convincingly presents a statistical relationship between the November snow cover and winter NAO and the lack of relationship between October snow cover and winter NAO, (b) it addresses the stability of the relationships over a period of 150 years, and (c) it also pays attention to other relevant factors such as Barents – Kara sea ice cover, the Atlantic Multidecadal Oscillation, and El Nino. Further, the Introduction is very well written, demonstrating thorough knowledge on the study topic and its remain- ing challenges. However, the manuscript also has weaknesses, which I summarize below. Whether the revisions needed are minor or major, depends above all on how convincingly the novelty of the results can be demonstrated (my first comment below).

Major comments

1. It should be made clearer which of the results found are novel. In the Discussion section, it is mentioned in several places that the findings support the results shown by previous studies (Gastineau et al., 2017; Han and Sun, 2018; Douville et al., 2017; Cohen et al., 2014; Wegmann et al., 2015; Yeo et al., 2016), but the novelty of the results presented remains unclear for a reader.

REPLY: Thank you for your comment. We agree that the focus of this study needed to be clarified. We therefore edited the introduction and discussion part substantially to allow the reader to focus on the key messages we want to deliver.

2. The manuscript includes parts that are carelessly written, and generate a lot of confusion.

a) In Figure 5, the projection between BKS ice concentration and November SLP anomalies shows positive values over a large region just east of Urals, but in general from the manuscript (and previous studies) I have got an impression that the decline of sea ice in BKS should favour Ural Blocking. Shouldn't this be reflected as negative projection in Figure 5b (similarly to Figure 5a)?

REPLY: Thank you for your comment. We realize that we forgot to mention that for Figure 5 sea ice concentration is multiplied by -1, thus Figure 5b and 5c show strong blocking together with a decline of BKS sea ice. We added that information in the figure caption of Figure 5.

b) I guess that on line 350 you should refer to Figure 7e instead of Figure 7c, and make it very clear that in Figure 7e the sea ice concentration is multiplied by -1 (I guess). Also, the positive correlation seems to last until late 1960s instead of late 1970s. The improved description of Figure 7 can now be found from Line 361-374

REPLY: Thanks for pointing out that mistake. We fixed the error with the Figure description and edited the whole paragraph accordingly.

c) It is not clear for me how Figure 8 supports the text on reduced variance of the snow index time series on lines 442-446. The standard deviation seems lowest in early 1900s and in 1960s.

REPLY: We reshuffled and rewrote large parts of the discussion to make the link between Arctic warm periods, increased cryospheric variability and the link to the prediction skill more apparent.

3. The Discussion includes vague parts, such as what could be done ("doubble could" on lines 389-392), references to preliminary results not shown on lines 453-455, and lines 476-479 (this paragraph should be removed). Also, how do centennial trends impact the results, if these trends were subtracted (lines 464-466)?

REPLY: Thanks for the comment. We agree that the discussion part was both incoherent and repetitive. We edited large part of the old discussion section and hopefully improved the train of thought throughout the section. We reworded the notion about the centennial trends, which are in fact not significant for the snow cover indices we use in this study (nevertheless we detrended the data just to be in line with comparable studies). What we wanted to mention are decadal trends found by Wegmann et al. 2017 for snow in long-term reanalyses. We changed the wording accordingly in lines 552-558.

Minor comments:

Line 82: remove comma

REPLY: removed

Line 112: months

REPLY: corrected

Line 243: which snow indices?

REPLY: clarified

Line 244: separate "and" words

REPLY: corrected

Line 271: The impact does not look weak.

REPLY: Clarified this point

Line 329: Remove "slightly"

REPLY: removed

Line 421: Supplementary Figure 6

REPLY: not sure what is the issue with this statement. We keep it like this for the time being.

Line 428: Remove “that”

REPLY: removed

Please note that the new line references are valid for the new Manuscript and not for the marked version, where the comments are counted as lines.

REVIEWER #2

This study presents and discusses statistical relations (diagnostics based on correla- tions and linear regressions) between Eurasian snow cover in autumn and wintertime atmospheric circulation anomalies, claiming a causal link (forcing and response rela- tionship) the strength of which varies in different historical epochs. The authors make valid references to recent and past literature on this broad topic and show original and valuable results. The Reviewer would recommend this study for publication after some minor points are addressed (minor revision). In particular : (i) the authors should account for serial correlation in the timeseries when assessing statistical significance, this is an important point since it can potentially affect (quite strongly) the discussed statistics and the associated conclusions. (ii) the authors should make an effort to be more explicit when referring to dynamical pathways, even if they do not directly assess any of the mentioned dynamical relationships (a weakness of this study). (iii) the authors should explain (otherwise remove) their line of argument on the likely driving role of ENSO in respect to low-frequency (decadal to multi-decadal) variability.

REPLY: Thank you very much for your comments. We address the topics for the specific comments below. We removed most of the discussion concerning the low frequency impact of ENSO and make sure to highlight the dynamical pathway more.

Specific Comments

1. Line 17 Perhaps the mathematical term “non-stationarity” does not convey the right message here. Obviously, predictability due to ESC varies from year to year for two basic reasons: (i) ESC anomaly may be small, thus not providing a strong forcing leading to a predictable signal, (ii) other processes affecting predictability may be more dominant.

REPLY: Nonstationarity appears to be a common phrasing in climate science for the time dependance of the predictor to the predictand (see e.g. Kolstad & Screen 2019) and as such we keep this phrase for now but are open to specific suggestions.

2. Line 20 “tendency” also means time derivative. For this reason, avoid this expression, or clarify.

REPLY: We changed the wording to “NAO-like impact” throughout the document

3. Line 23 Delete “slowed”

REPLY: deleted

4. Line 24 “correlation power” is not approved terminology.

REPLY: We changed the wording to “strength”

5. Line 29 Three times using “power” in the abstract alone.

REPLY: We changed the wording to “value”

6. Line 34 “climate mode... over” → climate variability pattern affecting winter climate over

REPLY: We changed the wording

7. Lines 36–37 Here and elsewhere, please put a comma between “et al.” and the publication year and use semicolons to separate different references.

REPLY: Changed accordingly

8. Line 38 The NAO is not defined as the strength of the gradient, it rather refers to the variability of this gradient (seesaw). Please rephrase.

REPLY: Rephrased accordingly

9. Line 40 “its configuration” → its variability

REPLY: Changed accordingly

10. Line 42 high-priority (with hyphen)

REPLY: Changed accordingly

11. Line 59 manifests itself / occurs / is manifested

REPLY: Rephrased accordingly

12. Line 79 a mechanism described by...

REPLY: Rephrased accordingly

13. Line 89 What exactly is meant here? “forming...” how?

REPLY: Specified the dynamic linkage

14. Line 93 summarized → discussed

REPLY: Rephrased accordingly

15. Line 110 consequences → conclusions

REPLY: Changed accordingly

16. Line 111 who point to the prediction power of

REPLY: Changed accordingly

17. Line 114 link → chain (?)

REPLY: rephrased accordingly

18. Line 129 For a detailed description

REPLY: Rephrased accordingly

19. Line 143 “found” → defined (?)

REPLY: Rephrased accordingly

20. Line 148 The NAO centers of action are known to migrate zonally, but not so much meridionally [e.g. Barnston and Livezey (1987)].

REPLY: Deleted the mentioning of NAO and instead replaced with “jet”

21. Line 159 “normalized” → standardized

REPLY: Rephrased accordingly

22. Line 165 “is above” → is higher than

REPLY: Rephrased accordingly

23. Line 182 “the second dimension” → two dimensions (meridional and zonal direc- tion)

REPLY: Rephrased accordingly

24. Line 188 Blocks do not always divert the westerlies (they can also block).

REPLY: Rephrased accordingly

25. Line 190 fulfill the two above-mentioned conditions

REPLY: Rephrased accordingly

26. Lines 213–214 “window” → period (?)

REPLY: Rephrased accordingly 27. Line 217 “any” → each

REPLY: Rephrased accordingly28. Line 233 This hints toward

REPLY: Rephrased accordingly

29. Line 244 Please check typos (missing spaces)

REPLY: Corrected

30. Line 269 increase polar (“heights” is plural).

REPLY: Corrected

31. Line 287 “increase” → aid

REPLY: Rephrased accordingly 32. Line 306 anomalies are regressed

REPLY: Corrected

33. Line 309 Remove “a” (two occurrences)

REPLY: Corrected34. Line 310 “is able to support” : please rephrase

REPLY: Rephrased accordingly 35. Line 325 “it” : please be more explicit for lucidity, what does “it” refer to?

REPLY: Clarified and extended the sentence

36. Lines 327–328 “which in turn favors...” : how and why?

REPLY: Added additional information for the reader

37. Line 329 “slightly” : this undervalues the significant differences (4 half periods vs 3 half periods, not just “slightly out of phase”). In this paragraph the authors jump from an NAO reasoning to a direct connection of continental anomalies to the BKS, yet the respective dynamics are not compatible: the NAO links to more/less zonal advection, while Ural blocking links to meridional advection.

REPLY: We removed the slightly notion and clarified the train of thought for the connection between the BKS and the continental anomalies (lines 340-352).

38. Lines 338–341 This approach requires a proper evaluation of the effective number of degrees of freedom, which most likely are seriously reduced due to serial correlation (related to the low-frequency nature of the discussed variability but also to the applied filter).

REPLY: We addressed the question of serial correlation by performing Durbin-Watson tests for every pair shown in Figure 7 and did not find compelling evidence for the existence of serial correlation in these relationships. We added that information to the text (lines 384-389) and show the Durbin-Watson test statistics in the Supplement.

39. Lines 342–353 So the previously-discussed dynamics work in one decade but fail to work in another?

REPLY: Thank you for your comment. We are not able to exclude the possibility that the dynamics (as in physical mechanism) are still working during times with weak correlation. However, the mechanism might be weaker due to reduced variability in the predictor. Therefore we focus here on the statistical strength of this relationship rather than excluding the possibility of the mechanism still being the same mechanism, even in times of low correlation.

40. Lines 371–373 Please help the reader see whether there is anything new here in respect to the cited studies.

REPLY: We edited the introduction and discussion part substantially to allow the reader to focus on the key messages we want to deliver and to highlight new findings.

41. Lines 375 “popular” (is this the right word?)

REPLY: deleted

42. Lines 397 low-frequency (with hyphen)

REPLY: Changed accordingly

43. Line 412 . . ..pattern via a stratospheric pathway.

REPLY: We add information about this in the discussion (lines 464-474)

44. Line 428 Remove “that” before “seem”. Referring to this paragraph, the reviewer finds the reasoning related to ENSO to be poorly based given that ENSO itself cannot be claimed to be a primary driver of (multi)decadal variability. This is an important point that should be addressed in a revised version of the manuscript.

REPLY: We agree with the reviewer that the ENSO discussion is weak and not helping the focus of this manuscript. We therefore deleted this paragraph.

45. Line 435 strength (not in plural)

REPLY: Deleted this sentenced and moved the necessary information to the beginning of the discussions section

46. Lines 433–443 Even two noisy processes after 21-year smoothing will exhibit periods of correlation and anticorrelation (purely an artifact related to limited samples and sub-samples). For robust statistics, the time window / period considered should contain at least a few periods... otherwise any result can be expected.

REPLY: Thank you for your comment. It is not entirely clear for the authors what is meant by considering different time windows for which analysis. However we show now in the Supplement a new Figure 8, which is basically Figure 7b for different running correlation windows ranging from 5 years to 31 years. We find that the main outcome of the analysis is not dependent on the time window changing from 11 to 21 to 25 to 31 years. The 5year window is noisy due to the nature of the high frequency variability in the system. These findings are consistent between ERA20C and 20CRv2c. We also added that information to the text (lines 384-389).

47. Lines 513 “counterintuitive” → contrasting (?)

REPLY: We stay with counterintuitive but now it refers to “anthropogenic global warming”

FIGURE 2: How is statistical significance assessed? A suitable and rigorous test is required accounting for serial correlation (which tends to decrease the effective number of degrees of freedom). The colorbar (in this and other plots) is not a good choice as it does not allow distinguishing high from moderate values (e.g. 50 and 100 have very similar tones). Please choose a colormap with more colors. Also, add more ticks and labels in the colorbar, including the max and min values covered.

REPLY: Thank you for your comment. We now assess auto-correlation of the ERA20C snow index time series, the 20CRv2c snow index time series, the ERA20C 10hPa GPH time series and the BKS time series with auto-correlation function plots in Supplement Figure 5. We found no clear auto-correlation signal in the snow and stratosphere, however we found auto-correlation in the BKS sea ice index. We now highlight that fact in the text concerning Figure 2 to make the reader aware of that issue. Moreover, we found auto-correlation for the AMO index (as expected for) and no auto-correlation for the ENSO index. We do not show that information in the Supplement but we mention it in the manuscript text. Furthermore we updated the colormaps for Figures 2&3 and 5b with a higher range of values as well as higher color step change resolution.

FIGURE 4: The figure caption was found in a different page (unacceptable).

REPLY: Moved up the figure caption

FIGURE 5: The pressure unit is “Pa”, not PA. Also, please define what is meant by “time unit”.

REPLY: Clarified and corrected

REFERENCES: Why some appear gray and other in black font?

REPLY: That seems to be an artifact of the conversion process to pdf. We double checked and hope to have fixed that issue.

Please note that the new line references are valid for the new Manuscript and not for the marked version, where the comments are counted as lines.

REVIEWER #3

Eurasian autumn snow impact on winter North Atlantic Oscillation depends on cryospheric variability

This study investigates the changes in the relationship between the November snow- dipole and the following winter NAO using century-long reanalyses and modern reanal- ysis data. The relationship between snow variability and the NAO is an important topic. The study demonstrates the correlations between the November snow-dipole, BKS sea-ice, stratospheric variability and the NAO. Using long-term reanalyses to study these correlations is a good point, although they were produced with the assimilation of limited observations. I think this is important given that most of the existing studies are based on short temporal-range data. However, I have a few questions with the current version of the manuscript, which may be addressed by the authors.

Major comments:

1) Conclusions in this study are drawn mostly from correlations/regressions, which would affect the robustness of them. Causality is also thus hard to determine. The November Snow-dipole does have some correlations with the following wintertime NAO variability (Fig. 2). This is also true for the November BKS sea-ice (Fig. 3a). However, the physical mechanisms remain unclear since studies often contradict each other and modeling results often don't support observational relationships. I think more analyses may be considered in order to generate more convincing evidence. In addition, as argued by Peings (2019), both anomalies in the snow/sea-ice and the winter stratospheric warmings can be driven by a common driver – Ural blocking. This raises the possibility that the correlations between snow/sea-ice and the wintertime NAO are statistical ones.

REPLY: Thank you very much for your comment. The focus on this study is not to determine causality between sea ice and snow cover. In fact other studies showed that link much better than we could here. Our study focuses on the fact that a) snow is a better predictor than sea ice and b) on the skill of the snow dipole for more than 150 years which is a novelty in the current scientific literature. We are well aware of the ongoing debate in the scientific literature about the dispute between observational studies and modeling studies. Here we argue that extending the investigation period from commonly 30 years to 150 years is important for the scientific discussion. Identifying strong relationships for 150 years is clearly a stronger argument for the existence of a physical mechanism than investigating 30 years. Our study helps to put modeling studies as well as the ongoing cryosphere changes in context. Concerning the very idealized study of Peings (2019) we mention in the discussion part the differences with our study and Peings (2019) as well as investigations we performed with blockings calculated from reanalyses. Nevertheless our study, even showing a linkage that is in line with the physical theory of snow to stratosphere to surface climate for 150 years, can not exclude the possibility of non-causality, that is correct. We made sure to underline that aspect in the discussion part.

2) The authors argue that the variability of the November snow-dipole largely determines the strength of the correlations between it and the wintertime NAO. But this conclusion is inferred from the 21-year running correlations and the 21-year standard deviations of the snow-dipole. The authors actually assume that the November snow- dipole is a driver of the wintertime NAO. As also mentioned in 1), causality may not be determined only from correlations/regressions.

REPLY: Thank you for your comments. It is unclear to the authors were exactly the issue is with the idea that increased variability in the predictor can strengthen the statistical relationship to the predictand. We still assume that the November snow-dipole is the physical driver behind the link to the wintertime NAO, we just highlight that the change in strength of this relationship is determined by the year-to-year variability of snow cover. We agree that our wording in the discussion of Figure 8 implied causality and we changed the wording accordingly. We also restructured the Discussion section to make highlight the implications of Figure 8 (now Figure 9)

3) The authors attribute increased correlation of the November snow-dipole (BKS sea- ice) with the wintertime NAO in recent years to the increased variability of the November snow-dipole (BKS sea-ice). Was the standard deviation of the BKS sea-ice displayed in the figures? From the analysis presented, it is hard to see how the three are correlated in a physical sense and which component of the cryosphere is more important in contributing to the recent NAO variability. There are a few studies exploring the impacts of the Arctic sea-ice on Eurasian snow. For example, Xu et al. (2019) studied the correlation between Autumn Arctic sea-ice and the winter snow cover in Northern Eurasia.

REPLY: Thank you for your comments. You raised an important point. Indeed the overlay of correlation and standard deviation was not visible. We now incorporated a new figure (Figure11) in the supplement that shows both the running standard deviation of BKS sea ice and the running correlation of BKS sea ice with the wintertime NAO. We mention it now in the discussion part. We used partial correlation to highlight the fact that snow cover is a stronger predictor for the winter NAO over long time periods that than the BKS, especially since Figure 7 shows that the BKS has a very weak relationship with the NAO for most of the 20th century. We mention the Xu et al. (2019) study and highlight that the authors looked at DJF only where as we focus on the autumn period.

4) I think the focus of this study needs to be clarified. The stratospheric pathway for either sea-ice or snow to impact the wintertime NAO variability is not new which can be found in many studies already cited in the introduction. Does the study emphasize the predictive nature of the correlation between the November snow-dipole and the wintertime NAO? If this is the case, why not consider some techniques such as cross-validation procedure to assess the predictive skills of the November snow- dipole? Empirical models such as those used in Chen et al. (2019; Section 6) may also be considered.

REPLY: Thank you very much for your comments. We agree that the focus of this study needed to be clarified. We therefore edited the introduction and discussion part substantially to allow the reader to focus on the key messages we want to deliver. As you rightly pointed out neither the stratospheric connection nor the impact on the wintertime NAO are new findings. Showing however, that these linkages are substantial and detectable for more than 100 years is a new scientific finding and an important puzzle piece for the ongoing debate that you mentioned above. Moreover highlighting the strengths of this relationship for Arctic warm periods is a new puts the current warm period in context and helps the scientific community to assess current cryopshere–atmosphere links in the framework of past climatic variations. We also newly added a very basic comparison of multiple regression prediction models based on cryosphere predictors for the 20th century and beyond at the end of the results section (lines 396-439), which we then also discuss in the discussion section.

Minor comments:

1) In addition to Han and Sun (2018) and Gastineau et al. (2017), the November snow- dipole was identified in an EOF analysis by Ye and Wu (2017).

REPLY: Thank you for pointing out this study. We added Ye and Wu (2017) to the references.

2) L28-29: Does the increased sea-ice variability enhanced that of the snow?

REPLY: There is a correlation of variability on decadal timescales especially with October snow cover, yes. It is however more non-linear than the correlation between standard deviation of snow cover and standard deviation of stratospheric polar cap height as shown in Figure 8 (now Figure 9). We added that information to the supplement.

3) The section of Data and Methods may need some modification. In particular, more details of the reanalysis data may be given. In particular, recent satellite observations of the snow cover can be included in the analysis.

REPLY: Rather than describing the snow representation of the reanalyses in this process oriented paper we refer to the studies by Wegmann et al. (2017) and Orsolini et al. (2019). If that is not enough information for the reader, we would ask the reviewer to provide specific points of information that are missing.

REPLY: From this comment it is unclear as to what information can be gained by incorporating satellite information since reliable snow cover information during by satellites is limited to the beginning of the 1980s and this study focuses on long term relationships. Nevertheless we incorporated a comparison of the Rutgers snow cover product with the reanalyses products in recent decades in Figure 2 of the new Supplementary Information and mention them in the Data & Method section.

4) L153-154: In the analysis, were all the atmospheric fields detrended as well?

REPLY: yes, we added that detail to the description of the data,

5) L244: Change ‘aandd’, ‘bande’ and ‘candf’ to ‘a and d’, ‘b and e’ and ‘c and f’.

REPLY: Changed accordingly

6) Labeling those multi-panel figures such as Figure 2 with additional text to indicate which variable is correlated with or regressed on to which variable may be considered to help the readers.

Eurasian autumn snow impact on winter North Atlantic Oscillation strongest for Arctic warming periods

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Abstract:

In recent years, many components of the connection between Eurasian autumn snow cover and wintertime North Atlantic Oscillation (NAO) were investigated, suggesting that November snow cover distribution has strong prediction power for the upcoming Northern Hemisphere winter climate. However, nonstationarity of this relationship could impact its use for prediction routines. Here we use snow products from long-term reanalyses to investigate interannual and interdecadal links between autumnal snow cover and atmospheric conditions in winter. We find evidence for a negative NAO-like impact after November with a strong west-to-east snow cover gradient, which is valid throughout the last 150 years. This correlation is linked with a consistent impact of November snow on the stratospheric polar vortex. Nevertheless, interdecadal variability for this link shows episodes of decreased correlation strength, which co-occur with episodes of low variability in the November snow index. On the contrary, periods with high prediction skill for winter NAO are found in periods of high November snow variability, which co-occur with the Arctic warming periods of the 20th century, namely the early 20th century Arctic warming between 1920-1940 and the ongoing anthropogenic global warming at the end of the 20th century. A strong snow dipole itself is consistently associated with reduced Barents-Kara sea ice concentration, increased Ural blocking frequency and negative temperature anomalies in eastern Eurasia.

Keywords: SNOW, NAO, SEA ICE, VARIABILITY, PREDICTION

1. Introduction

Deleted: depends on cryospheric variability

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Deleted: Increased sea ice variability in recent years is linked to increased snow variability, thus increasing its power in predicting the winter NAO.¶

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As the leading climate variability pattern affecting winter climate over Europe (**Thompson and Wallace 1998**), the North Atlantic Oscillation (NAO) has been extensively studied over the last decades (**Wanner et al., 2001; Hurrell and Deser 2010; Moore and Renfrew 2012; Pedersen et al., 2016; Deser et al., 2017**). The NAO has been defined as the variability of the pressure gradient between Iceland (representing the edge of the polar front) and the Azores (representing the subtropical high ridge). The sign of the NAO is related to weather and climate patterns stretching from local to continental scales. Since its variability has severe socioeconomic, ecological and hydrological impacts for adjacent continents, seasonal to decadal predictions of the state of the winter NAO are high priority research for many climate science centers (**Jung et al., 2011; Kang et al., 2014; Scaife et al., 2014; Scaife et al., 2016; Smith et al., 2016; Dunstone et al., 2016; Wang et al., 2017; Athanasiadis et al., 2017**).

Deleted: mode to explain wintertime climate variability variability pattern affecting winter climate over Europe (**Thompson and Wallace 1998**), the North Atlantic Oscillation (NAO) has been extensively studied over the last decades (**Wanner et al., 2001, … Hurrell and Deser 2010; , Moore and Renfrew 2012; , …edersen et al., et al. …016; , Deser et al., et al. …017**). The NAO has been defined as the strength …ariability of the pressure gradient between Iceland (representing the edge of the polar front) and the Azores (representing the subtropical high ridge). The sign of the NAO is related to weather and climate patterns stretching from local to continental scales. Since its variabilityconfiguration…has severe socioeconomic, ecological and hydrological impacts for adjacent continents, seasonal to decadal predictions of the state of the winter NAO are high– …riority research for many climate science centers (**Jung et al., et al. …011; , …ang et al., et al. …014; , Scaife et al., et al. …014; , …caife et al., et al. …016; , Smith et al., et al. …016; , …unstone et al., et al. …016; , Wang et al., et al. …017; , …thanasiadis et al., et al.** ... [1]

Together with the rapid warming of the Arctic and the increased frequency of severe winters over Eurasia and North America (**Yao et al., 2017; Cohen et al., 2018; Kretschmer et al., 2018; Overland and Wang 2018**), recent studies highlighted the state of the Northern Hemispheric cryosphere as a useful predictor for the boreal wintertime (DJF) NAO (**Cohen et al., 2007; Cohen et al., 2014; Vihma 2014; Garcia-Serrano et al., 2015; Cohen 2016, Orsolini et al., 2016; Crasemann et al., 2017; Warner 2018**). Although both systems seem to be connected (**Cohen et al., 2014; Furtado et al., 2016; Gastineau et al., 2017**), the emerging main hypothesis connects reduced autumn Barents-Kara sea ice concentration and increased Siberian snow cover with a negative NAO state in the following winter months (**Cohen et al., 2014**).

Deleted: et al. …017; , …ohen et al., et al. …018; , Kretschmer et al., et al. …018; , …verland and Wang 2018), recent studies highlighted the state of the Northern Hemispheric cryosphere as a useful predictor for the boreal wintertime (DJF) NAO (**Cohen et al., 2007et al. 2007… , Cohen et al., et al. …014; , …ihma 2014; , …arcia-Serrano et al., et al. …015; , …ohen 2016, Orsolini et al., al. …016; , …rasemann et al., et al. …017; , …arner 2018**). Although both systems seem to be connected (**Cohen et al., et al. …014; , …urtado et al., et al. …016; , Gastineau et al., et al. …017**), the emerging main hypothesis hypothesis connects reduced autumn Barents-Kara sea ice concentration and increased Siberian snow cover with a negative NAO state in the following winter months (**Cohen et al., et al.** ... [2]

The proposed mechanism behind this hypothesis is a multi-step process, starting with autumn sea ice loss for the European Arctic, followed by altered tropospheric circulation due to elevated Rossby wave numbers, vertical propagation of said Rossby waves upward into the stratosphere and consequently a weakening of the polar vortex (see **Cohen et al., 2014** for an in depth discussion). With the weakening (or the reversal) of the polar vortex, a stratospheric warming signal manifests. This signal propagates slowly back into the troposphere, where it manifests itself as a negative NAO, connected to the concurrent cold winters for Eurasia (**Kretschmer et al., 2018**).

Deleted: et al. …014 for an in depth discussion). With the weakening (or the reversal) of the polar vortex, a stratospheric warming signal manifests. This signal propagates slowly back into the troposphere, where it is expressed…anifests itself as a negative NAO, connected to the concurrent cold winters for Eurasia (**Kretschmer et al., et al. …** ... [3]

In recent years, many components of this pathway were investigated, especially concerning the increased frequency of cold winters over Europe and the emergence of the counter-intuitive "Warm Arctic – cold continent" (WACC) pattern over Eurasia (**Petoukhov and Semenov**

2010; Vihma 2014). However, there remains substantial uncertainty about the impact of Arctic sea ice in terms of location (**Zhang et al., 2016; Luo et al., 2017; Screen 2017; Kelleher and Screen 2018**), timing (**Honda et al., 2009; Overland et al., 2011; Inoue et al., 2012; Suo et al., 2016; Sorokina et al., 2016; King et al., 2016; Screen 2017; Wegmann et al., 2018a; Blackport and Screen 2019**) or if sea ice can be used as a predictor/forcing at all based on the contrasting result of model studies (**McCusker et al., 2016; Collow et al., 2016; Pedersen et al., 2016; Boland et al., 2017; Crasemann et al., 2017; Ruggieri et al., 2017; Garcia-Serrano et al., 2017; Francis 2017; Screen et al., 2018; Mori et al., 2019; Hoshi et al., 2019; Blackport et al., 2019; Romanowksy et al., 2019**).

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The interplay between Arctic sea ice and Siberian snow is much less explored. **Ghatak et al. (2010)** showed that reduced autumn polar sea ice leads to the emergence of increased Siberian winter snow cover, especially so in the eastern part of Eurasia. This dipole signal was amplified in coupled climate model runs for the 21st century, where sea ice is substantially diminished. In an observational study, **Yeo et al. (2016)** point out that the moisture influx from the open Arctic ocean into the Eurasian continent contributes to the increase of snow cover, a mechanism described by **Wegmann et al. (2015)**. **Gastineau et al. (2017)** found that reduced sea ice is connected to a distinct November snow dipole over Eurasia, both in reanalysis and model data. They further state that the snow component is a statistically more powerful predictor for the atmosphere in the following winter. This relationship was also found in a range of climate models, albeit with weaker links. **Xu et al. (2019)** found the same correlation in observational and model data, however looking at winter climate only. Based on their analysis, the authors state that the enhanced snow cover in winter is a product of the negative NAO rather than a precursor. **Sun et al. (2019)** highlight the importance of elevated North Atlantic sea surface temperatures for the development of a Eurasian snow dipole in autumn. This warming of the North Atlantic favors reduced sea ice cover for the European part of the Arctic, which triggers a high pressure anomaly over the Northern Ural Mountains via increased ocean to atmosphere heat fluxes, transporting cold air masses towards the south of its eastern flank.

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The possible impact of the Siberian snow on the stratosphere and eventually on the NAO is well discussed in **Henderson et al. (2018)**. Although observational NAO prediction studies with Siberian snow showed great success in the past (**Cohen and Entekhabi 1999; Saito et al., 2001; Cohen et al., 2007; Cohen et al., 2014; Han and Sun 2018**), links between snow and the stratosphere still seems to be missing or too weak in model studies (**Furtado et al., 2015; Handorf et al., 2015; Tyrrell et al., 2018; Gastineau et al., 2017; Peings et al., 2017**),

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whereas nudging realistic snow changes to high resolution models seems to improve the prediction skill (**Orsolini and Kvamsto 2009; Orsolini et al., 2016; Tyrrell et al., 2019**). Moreover, even though the stratosphere–surface connection is now reasonably well established (**Kretschmer et al., 2018**), the timing and location of the snow cover used for the prediction is, as with sea ice, still debated (**Yeo et al., 2016; Gastineau et al., 2017**). As an additional caveat, **Peings et al. (2013)** and more recently **Douville et al. (2017)**, showed that the proposed autumn snow-to-winter NAO relationship is non-stationary for the 20th century. A possible modulator for that relationship might be the phase of the Quasi Biennial Oscillation (QBO) (**Tyrrell et al., 2018; Peings et al., 2017; Douville et al., 2017**). **Peings (2019)** argues that neither snow nor sea ice anomalies trigger the stratospheric conditions needed to produce winter extremes and that instead high tropospheric blocking frequency over Northern Europe leads to the cryosphere anomalies.

Here, we follow up on the definition of a November Eurasian snow cover dipole (**Ye and Wu 2017; Gastineau et al., 2017; Han and Sun 2018**) which was identified to provide predictive power for the following winter months at the end of the 20th century. It is however unclear if this prediction skill is stable for time periods further back than 30 years and how it evolves in periods of high Arctic sea ice cover. In this study we address the question of a) nonstationarity of the Eurasian now cover to winter European surface climate relationship in the 20th century, b) importance of snow versus sea ice as predictor and c) possible precursors/modulators of the sea ice–snow–stratosphere chain. With this we aim to contribute to the understanding of impacts of cryosphere variability on midlatitude circulation (**Francis 2017; Henderson et al., 2018; Cohen et al; 2019**). To this end, we utilize centennial reanalyses and reconstruction data, where we focus on the transition from October to November to DJF to facilitate the idea of seasonal prediction.

This paper is organized as follows: Section 2 describes the data and methods used. In section 3, we introduce the snow cover indices and their interannual prediction value. Section 4 investigates interdecadal shifts in the correlation between snow cover and NAO as well as possible determining factors. The results are discussed in section 5 and finally summarized in section 6.

2. Data and Methods

a. Atmospheric reanalyses

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To evaluate long-term reanalyses, we use snow cover, snow depth and atmospheric properties from the MERRA2 reanalysis (**Gelaro et al., 2017**). MERRA2 has a dedicated land surface module and was found to reproduce local in-situ snow conditions over Russia very well (**Wegmann et al., 2018b**). For a detailed description of how MERRA2 computes snow properties see e.g. **Orsolini et al., (2019)**.

To cover the 20th century and beyond, we include two long-term reanalyses in this study, namely the NOAA-CIRES 20th century reanalysis Version 2c (20CRv2c) (**Cram et al., 2015**) as well as the Centre for Medium-Range Weather Forecasts (ECMWF) product ERA-20C (**Poli et al., 2016).** From the ERA-20C product we use snow depth, whereas from 20CRv2c we investigate snow depth and snow cover. Both reanalyses were found to represent interannual snow variations over Eurasia remarkably well. For an in-depth discussion of their performance and their technical details concerning snow computation see **Wegmann et al., (2017)**. We also performed the same analysis using the coupled ECMWF reanalysis CERA-20C (**Laloyaux et al., 2018**), but found no added knowledge gain over ERA-20C. Thus, we do not include CERA-20C in any further analysis.

We use detrended anomalies of these three reanalysis products to extend the October and November index proposed by **Han and Sun (2018)** into the past, where the November index is in essence the snow dipole described by **Gastineau et al. (2017)** using maximum covariance analysis (Figure 1). Where the October index is just calculated as field average snow cover, the November index is computed as difference between the eastern and the western field average. It should be noted, that **Han and Sun (2018)** found the November index to be linked to a negative NAO and colder Eurasian near-surface temperatures, whereas the October index was correlated with warmer-than-usual temperatures over Eurasia and a southward-shifted jet. However, since many studies focus on Northern Eurasian October snow cover as the predictor for winter climate, we will include it nonetheless. MERRA2 and 20CRv2c offer snow cover as well as snow depth as a post-process output, however ERA-20C only offers snow depth. We refrain from converting it to snow cover ourselves, but found the index based on snow depth to be extremely similar (also see Supplementary Figure 1) to the same index using snow cover. Moreover, comparing snow indices from reanalyses with snow indices using the NOAA Climate Data record of Northern Hemisphere Snow Cover extent (**Robinson et al. 2012**), which incorporates satellite data, does not highlight any meaningful differences (Supplementary Figure 2). All snow indices are normalized and linearly detrended with respect to their overall

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time period. Generally, we found the long term reanalyses to be of comparable quality of MERRA2 during the overlapping periods.

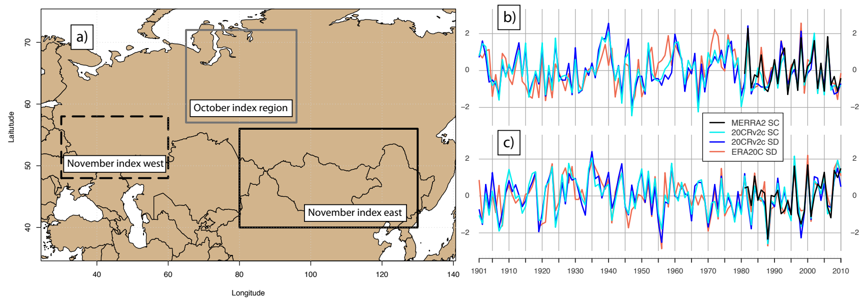

Figure 1: a) Regions for October and November snow index used in this study. b) Linearly detrended and standardized October snow index comparison for the 20th century for snow cover (SC) and snow depth (SD) variables. c) same as b) but for the November snow dipole.

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Besides snow properties we use detrended atmospheric and near-surface anomaly fields from all three reanalyses. Moreover, as **Douville et al. (2017)**, we use the field averaged (60°–90° N) 10 hectopascal (hPa) geopotential height (GPH) anomalies in ERA-20C as a surrogate for polar vortex (PV) strength. Although ERA-20C only assimilates surface pressure, correlation between this stratospheric index in ERA-20C and MERRA2 during the overlapping time periods is higher than 0.9.

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The ERA20C 10 hPa November–December mean GPH shows remarkable interannual agreement with state-of-the-art reanalyses that assimilate upper air data for the period 1958–2010 (see Supplementary Figure 3). Moreover, MERRA2 and ERA20C 10 hPa GPH anomalies agree best over the northern polar regions with correlation coefficients of >0.9 for the period 1981–2010 (see Supplementary Figure 3). This fact supports the extended value of the ERA20C polar stratosphere. Before 1958, the quality of the ERA20C stratosphere is difficult to assess, but the comparison with reconstructions of 100 hPa GPH zonal means shows very good agreement for late autumn and winter months (see Supplementary Figure 4). As the 20CRv2c ensemble mean dilutes the interannual variability signal back in time with increased variability within the ensemble members, we use the deterministic run of ERA20C for the following stratosphere analyses.

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We use 6-hourly 500 hPa GPH fields (GPH500) to calculate monthly blocking frequencies according to **Rohrer et al. (2018)**. Blockings are computed according to the approach introduced by **Tibaldi and Molteni (1990)** and are defined as reversals of the meridional GPH500 gradient. In accordance to **Scherrer et al. (2006)** the one-dimensional **Tibaldi and Molteni (1990)** algorithm is extended to the two dimensions by varying the latitude between 35° and 75° instead of a fixed latitude:

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i) GPH500 gradient towards pole: $$GPH500G_P = \frac{GPH500_{\varphi+d\varphi} - GPH500_{\varphi}}{d\varphi} < -10\ \frac{m}{°lat} \qquad (1)$$

ii) GPH500 gradient towards equator: $$GPH500G_E = \frac{GPH500_{\varphi} - GPH500_{\varphi-d\varphi}}{d\varphi} > 0\ \frac{m}{°lat} \qquad (2)$$

Blocks by definition are persistent and quasi-stationary high-pressure systems that divert or severely slow down the usually prevailing westerly winds in the mid-latitudes. They influence regional temperature and precipitation patterns for an extended period. Therefore, not all blocks that fulfill the two above-mentioned two conditions are retained. We only include blocks that have a minimum required lifetime of 5 days and a minimum overlap of the blocked area of 70% ($A_{t+1} \cap A_t > 0.7 * A_t$) in our blocking catalog. This largely follows the criteria defined by **Schwierz et al. (2004)**.

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b) Climate reconstructions

To be as independent as possible with regards to the reanalyses we use a wide array of climate index reconstructions for the 20th century:

- Atlantic Multidecadal Oscillation (AMO): For the AMO index we take October values based on the **Enfield et al. (2003)** study. We choose October to allow for a certain feedback lag with the atmosphere and to have decent prediction value for the upcoming snow and NAO indices.
- El Niño – Southern Oscillation (ENSO): We chose the ENSO3.4 reconstruction based on the HadISSTv1 **Rayner et al. (2003)** SSTs. As with the AMO, we select October values to allow for a reaction time in the teleconnections.
- North Atlantic Oscillation (NAO): We use the extended **Jones et al. (1997)** NAO index for DJF from the Climate Research Unit (CRU).
- Sea Ice: We use the monthly sea ice reconstruction by **Walsh et al. (2017)** which covers the period 1850–2013 to create a Barents-Kara (65–85°N, 30–90°E) sea ice index for November.

We checked for autocorrelation in the time series of the snow indices, stratospheric index, BKS sea ice index (Supplementary Figure 5), AMO index and ENSO index and only found significant autocorrelation in the BKS sea ice and AMO time series. We assess the significance of a regression coefficient in a regression model by dividing the estimated coefficient over the standard deviation of this estimate. For statistical significance we expect the absolute value of the t-ratio to be greater than 2 or the P-value to be less than the significance level ($\alpha=0.05$). The df are determined as (n-k) where as k we have the parameters of the estimated model and as n the number of observations.

3. Results

a. Interannual links

In the following paragraphs we investigate the year-to-year relationship between the snow indices and the following winter SLP fields. For this we use MERRA2 for a 35-year-long period ranging from 1981–2015, ERA20C for a 110-year-long window ranging from 1901–2010 and 20CRv2c for a 160-year-long window ranging from 1851–2010.

Figure 2 shows the linear regression fields of DJF SLP anomalies projected onto the respective snow indices in October and November. For October, we find no NAO-like pressure anomaly appears to be significantly correlated with the snow index in eacb of the three reanalysis products and respective time windows (Figure 2a,b,c). Instead, negative SLP anomalies dominate Northern Eurasia in MERRA2, with high pressure anomalies towards the Himalayan Plateau. The 110-year-long regression in ERA20C shows significant negative anomalies over the Asian part of Russia, reaching as far south as Beijing. A second significant negative SLP pattern appears along the Pacific coast of Canada. Finally, SLP anomalies in 20CRv2c support the main SLP patterns shown by ERA20C, but reduce the extent of negative anomalies over Eurasia and increase the extent of the negative anomalies over the North Pacific.

The DJF SLP anomaly patterns change substantially when projected onto the November snow index (Figure 2d,e,f). All three reanalysis products show negative NAO-like pressure anomalies with significantly positive anomalies over Iceland and the northern North Atlantic and significantly negative anomalies south of ca. 45° N, including Portugal and the Azores. As

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expected, MERRA2 shows the strongest anomalies due to the shorter regression period, however interestingly ERA20C, with the 110-year long analysis period, shows less large-scale significance for positive anomalies in high latitudes compared to the 150-year-long investigation period in 20CRv2c (even though non-significant anomalies cover roughly the same area as in 20CRv2c (not shown)). This hints towards decadal variations in the strength of the regression, but could also be due to biases in the reanalyses.

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To check for such biases we compared all reanalyses with the SLP reconstruction dataset HadSLP2r (**Allen and Ansell 2006)**, and found that for the regression analysis using the time period 1901–2010, 20CRv2c overestimates the polar sea level pressure response, whereas ERA20C is much closer to HadSLP2r (See Supplement Figure 6). This would indeed support the notion of decadal variations in the strength of the relationship between predictor and predictand. However, it is worth highlighting that this overestimation for 20CRv2c is not visible for the 1851–2010 period, where the regression anomalies resemble HadSLP2r much closer.

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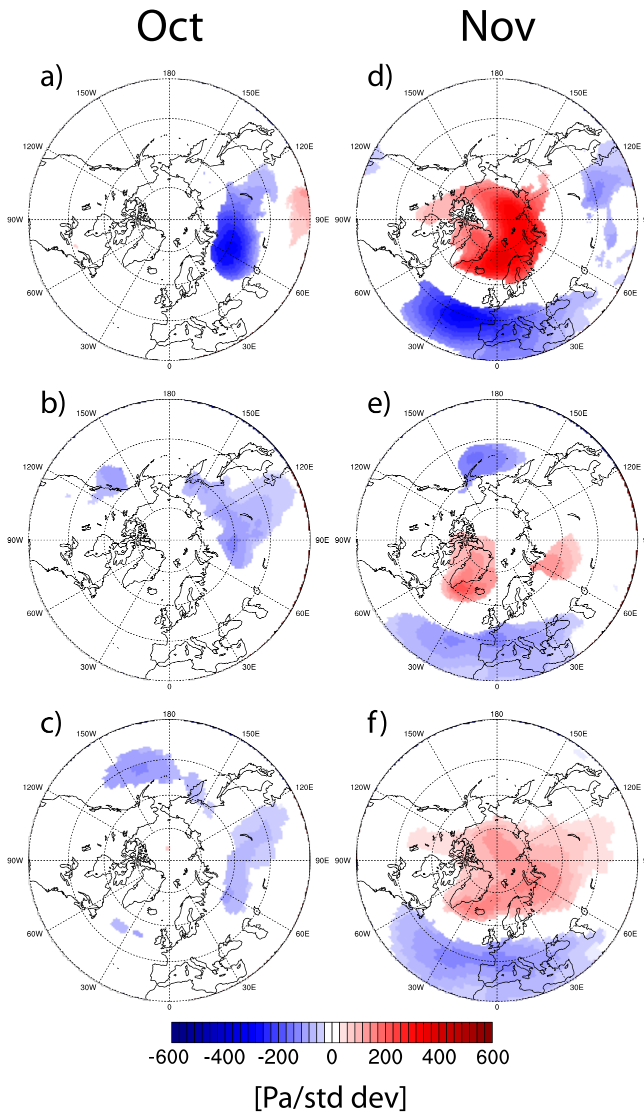

Figure 2: DJF sea level pressure [Pa/std dev] anomalies projected onto snow indices (see Figure 1) for October (left) and November (right) for a and d) MERRA2 covering 1981–2015, b and e) ERA20C covering 1901–2010 and c and f) 20CRv2c covering 1851–2010. Only anomalies >95% significance level are shown.

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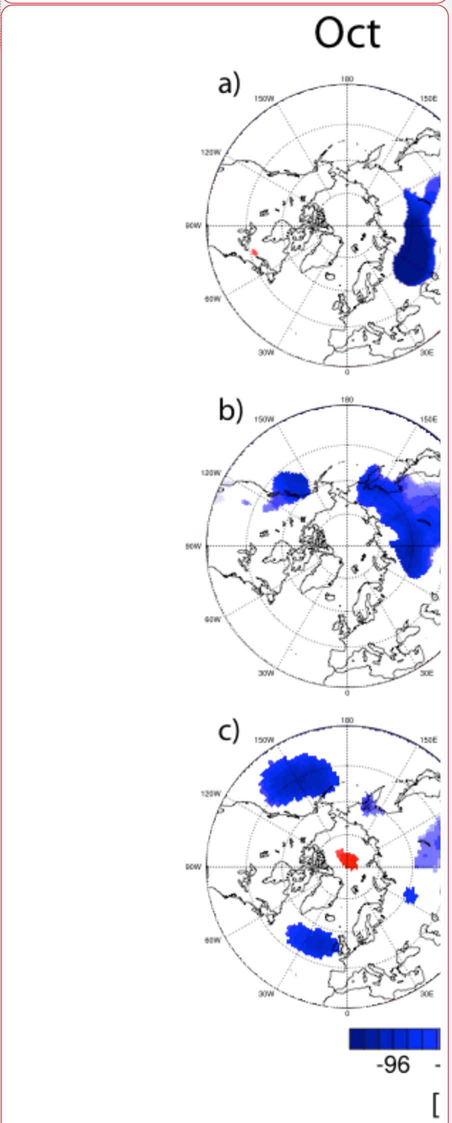

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We investigate other possible predictors for wintertime NAO via regressed anomalies onto the November Barents-Kara-Sea (BKS) ice concentration, November–December mean polar GPH at 10 hPa, October AMO and October ENSO indices (Figure 3). The periods for MERRA2 and ERA20C are identical as for Figure 2, whereas the anomaly plots for 20CRv2c are using the maximum period covered in the reconstructions, namely 1851–2010 in the sea ice reconstruction, 1856–2010 in the AMO reconstruction, 1901–2010 for the polar 10 hPa GPH index taken from ERA20C, and 1870–2010 for the ENSO reconstruction.

As can be seen from Figure 3, the 35-year-long analysis in MERRA2 shows November sea ice concentration and early winter stratospheric heights to regress a similar SLP pattern than the November snow index. Positive SLP anomalies over Iceland and Greenland combined with negative anomalies over Southern Europe and the adjacent North Atlantic shape a negative NAO-like pattern in DJF (Figure 3a). On the other hand, the interannual signals in the October AMO and ENSO indices do not point towards such a pressure distribution. The small interannual changes and low frequency of the AMO combined with the short sample period prohibit most of the significance, only Southern Eurasia shows regions with elevated SLP. Anomalies regressed on the ENSO index show, as expected, significance mostly for the North Pacific and North American region.

Looking at the regression patterns in the centennial reanalyses, the NAO-like pattern in the SLP anomalies regressed onto sea ice and stratospheric GPH can still be seen, however the extent and strength is substantially reduced compared to MERRA2 as well as compared to the regression using November snow as predictor. Again, ERA20C shows a decrease in the significant anomalies regressed onto sea ice compared to 20CRv2c, with possible reasons already discussed above. Elevated geopotential heights at 10 hPa consistently increase polar sea level pressure in the following winter months, however the impact over the European and North Atlantic domain severely decreases in the centennial reanalyses.

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SLP anomalies regressed onto the AMO index show significant positive SLP regions for large parts of Eurasia as well as positive anomalies over the North Atlantic west of Great Britain. Interesting to note in 20CRv2c is the very strong high-pressure anomaly reaching from the BKS to the southern part of the Ural mountains, a prominent feature often found for years with positive AMO and negative sea ice concentration, frequently linked to a high frequency of Ural blockings (UBs). SLP distribution after El Niño events does not change considerably irrespective of the dataset and time period used. A strong Pacific signal shows the northern part of the Pacific-North American pattern (PNA) with negative SLP anomalies over the eastern

North Pacific. Given the autocorrelation in the AMO and BKS sea ice index, the significance in Figure 2abc as well as Figure 2ghi might be severely lower due to the reduced amount of degrees of freedom.

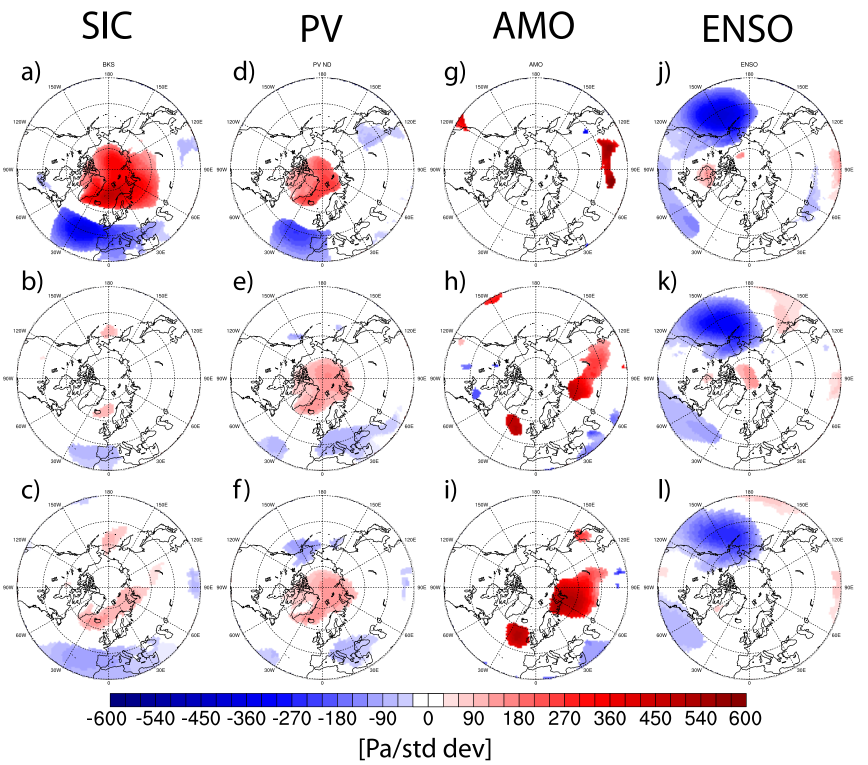
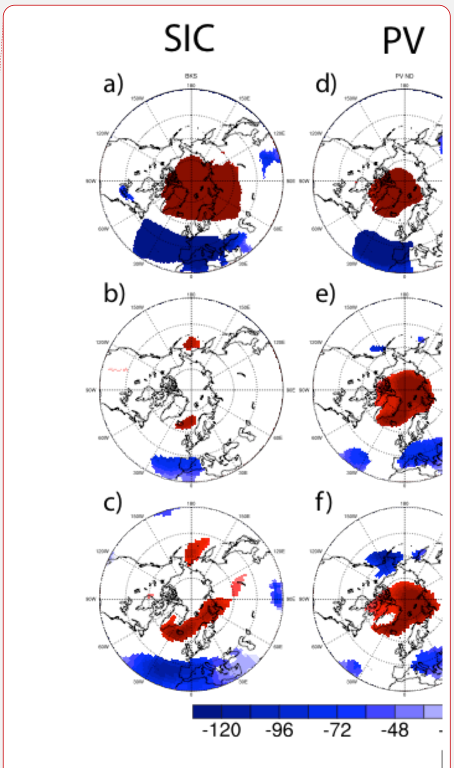


Figure 3: DJF sea level pressure [Pa/std dev] anomalies projected onto BKS ice concentration in November (far left), polar 10 hPa GPH November December mean (left), October AMO (right) and October ENSO indices (far right) for adgj) MERRA2 covering 1981–2015, behk) ERA20C covering 1901–2010 and cfil) 20CRv2c covering 1851–2010. Regression values for BKS ice concentrations were multiplied by minus one to aid comparability. Only anomalies >95% significance level are shown.

To investigate the vertical development of climate anomalies connected with the November snow dipole, Figure 4 shows the zonal mean anomalies of zonal wind and temperature in ERA20C projected onto the ERA20C November snow index (for an evaluation with an upper-air climate reconstruction see Supplementary Figure 7). The temporal evolution of the anomalies ranging from October to February shows that stratospheric warming occurs



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simultaneously within the same month as a positive snow cover dipole, with no stratospheric warming leading that development. Instead, significant lower troposphere warming is shown between 60°–90°N for October. The warming signal then dominates the stratosphere and upper troposphere in December, after which the strongest anomalies subside into the lower stratosphere and tropopause in January and February. This development of atmospheric temperatures is mirrored in the evolution of the polar vortex, where a reduction of the polar vortex and strengthening of the subtropical jet is seen together with the emergence of the November snow dipole, after which the region of strongest anomalies migrates from the upper stratosphere to the upper troposphere.

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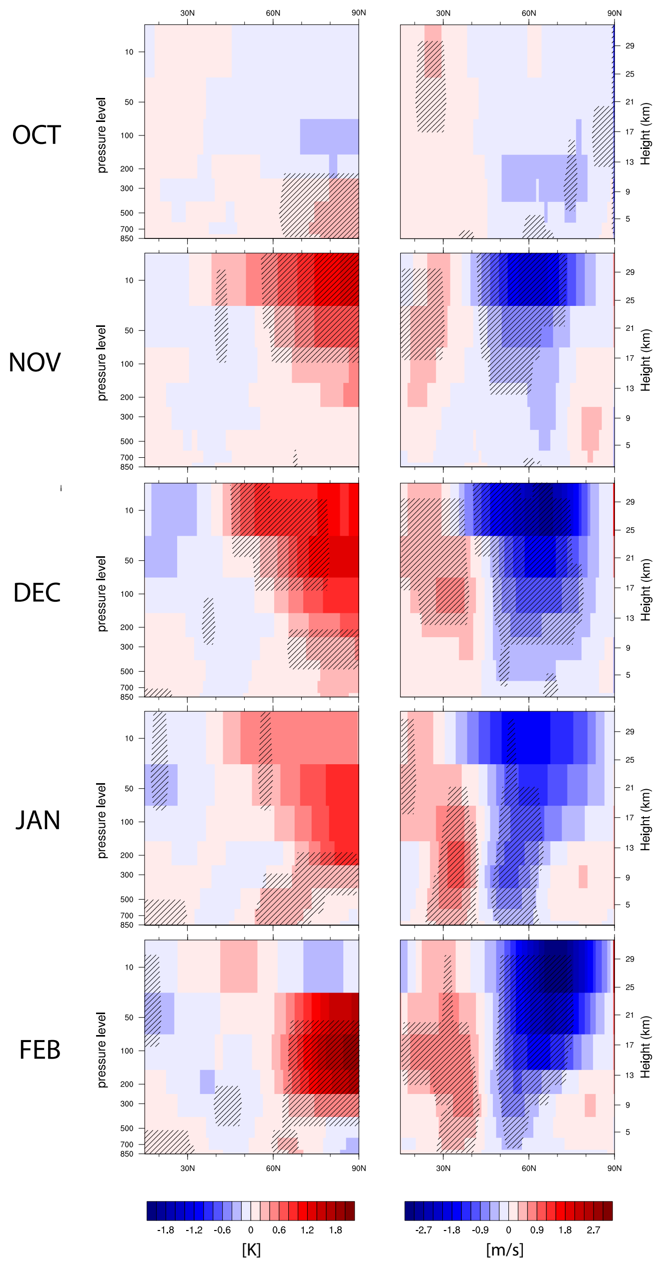

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601 *Figure 4: Zonal mean (180°E–180°W, 15°N–90°N) left) temperature anomalies and right) zonal mean zonal wind anomalies*
602 *projected onto snow indices in November for ERA20C covering 1901–2010. Shading indicates 95% significance level.*

To address the physical reasons as to how the low sea ice and high snow indices are connected, climate anomalies are regressed onto BKS ice concentrations for November (Figure 5). Compared to factors such as AMO and ENSO, BKS sea ice shows a distinct snow cover dipole coinciding with a high-pressure anomaly over the BKS and the northern Ural mountains, which supports a regional atmospheric blocking and cold air advection on its eastern flank. This cold air anomaly supports increased snow cover over eastern Eurasia, while relatively warm temperatures reduce the snow cover over eastern Europe. It should be noted that October BKS ice concentration shows qualitatively the same pattern for November snow cover anomalies (not shown), however not statistically significant.

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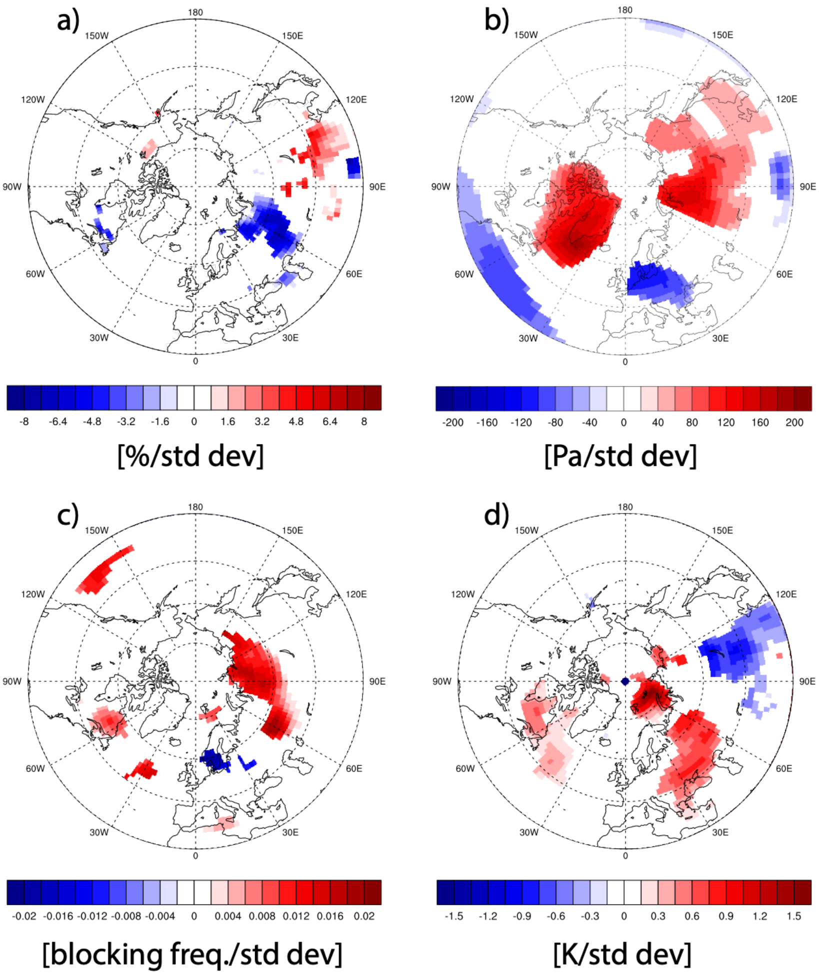

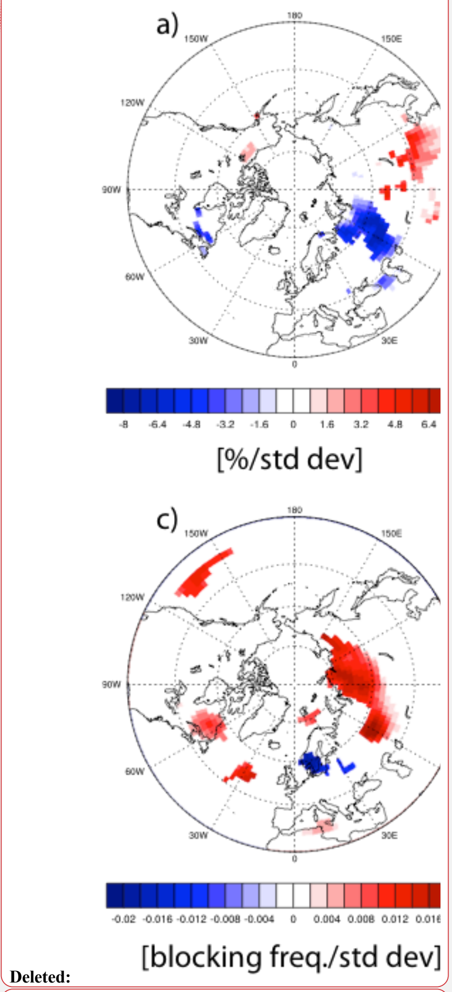

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Figure 5: 20CRv2c November anomalies projected onto BKS ice concentration in November covering 1851–2010. Regression values for BKS ice concentrations were multiplied by minus one to aid comparability. a) November snow cover [%/std dev] anomalies projected onto BKS ice concentration in November, b) November SLP [Pa/std dev] anomalies projected onto BKS ice concentration in November, c) November atmospheric blocking [blocking per season/std dev] anomalies projected onto BKS ice concentration in November and d) November 2m temperature [K/std dev] anomalies projected onto BKS ice concentration in November. Only anomalies >95% significance level are shown.

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b. Interdecadal links

The interdecadal evolution of the November snow index is shown in Figure 6. 21-year running means of the normalized time series of ENSO, AMO, BKS ice and snow hint towards a multidecadal frequency, similar in wave length to the AMO and BKS ice anomalies. Even though we refrain from correlating these time series due to the the 21-year filter (**Trenary and DelSole, 2016**), we find the possible mechanism behind the decadal co-occurrence of warm North Atlantic SSTs, reduced sea-ice and increased snow cover gradient to be physically plausible **(Luo et al. 2017)**. As **Luo et al. (2017)** point out, warm North Atlantic water reduces the BKS ice concentration, which decreases the meridional temperature gradient and strong westerly winds, which in turn supports high pressure over the Ural mountains and with that, cold air advection towards eastern Eurasia. It should be noted however, that the AMO and the November snow index are out-of-phase between 1880 and 1920, where uncertainties in both products are largest.

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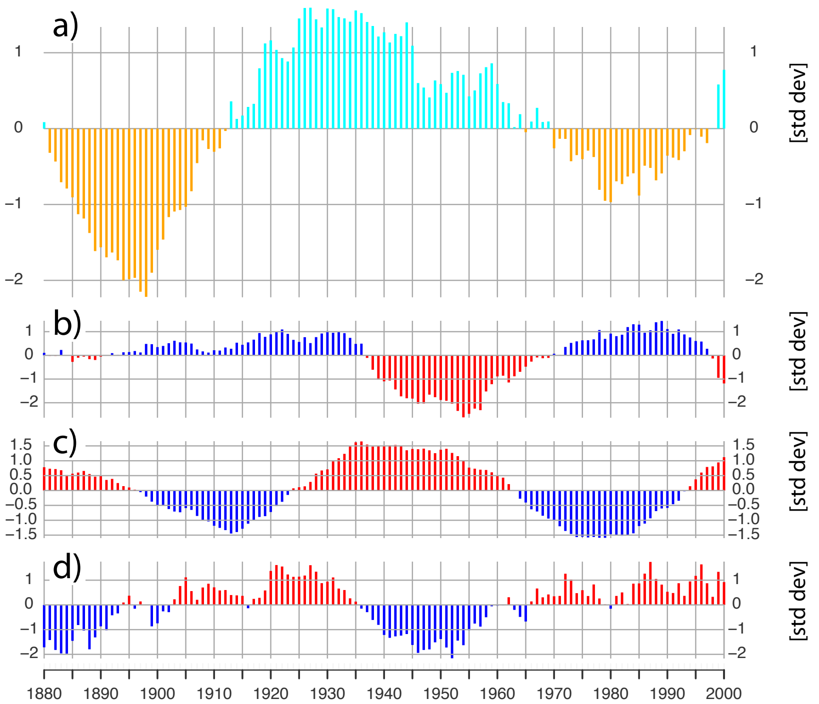

Figure 6: 21-year running means of a) November snow index from 20CRv2c, b) November BKS ice concentration, c) October AMO and d) October ENSO reconstruction.

The more critical question is the interdecadal evolution of the relationship between the predictor and the predictand. Similar to **Peings et al. (2013)** and **Douville et al. (2017)**, we apply a 21-year running correlation covering the period 1901–2010 to examine the stationarity of the relationship and differences between 20CRv2c and ERA20C.

Figure 7 summarizes the correlation over time for multiple pairs of climate variables. As Figure 7b points out, the sign of the November snow to winter NAO relationship in 20CRv2c is negative throughout the whole 20th century. Periods with negative correlations can be found at the beginning and the end of the century, with relatively weak correlation during the 1930s and 1970s. The periods of strong negative correlations overlap with commonly known Arctic warming periods, the early 20th-century Arctic warming (ETCAW) and the ongoing recent Arctic warming in context of anthropogenic global warming. In ERA20C, these periods are

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actually marked by positive correlations, indicating a non-stationary relationship between these two variables. Even stronger decadal variability can be seen for the running correlations between the October snow index and winter NAO-like impact (Figure 7a), with periods of pronounced negative correlations during the early 20th century Arctic warming and the 1980s. Emerging since the 1970s is a negative relationship shown in Figure 7e between BKS ice reduction (multiplied by minus one to aid comparability) and the formation of a negative NAO signal in the following winter, with very weak negative correlations for the ETCAW.

Together with the emergence of the sea ice to NAO relationship, negative correlations between BKS sea ice and November snow index (Figure 7d) as well as between stratospheric warming and winter NAO strengthen towards the end of the 20th century (Figure 7f). This strengthening is also found in ERA20C for the correlation between November snow and a following stratospheric warming, where 20CRv2c shows consistently positive correlation values throughout the 20th century (Figure 7c).

Overall, the 20CRv2c November snow index shows a more stationary relationship with tropospheric and stratospheric winter circulation than ERA20C. Possible explanations for this behavior will be discussed in the following section.

For all of the linear relationships shown in Figure 7 we performed a Durbin-Watson test to check for serial correlation between two variables and did not find any compelling indication for co-dependence in any case (see Supplementary Table 1). Moreover, we investigated different running correlation windows (11 years, 21 years, 25 years, and 31 years) and find that the main outcome of the analysis is not dependent on the choice of the correlation window (see Supplementary Figure 8).

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Figure 7: 21-year centered running correlation time series between a) October snow index and DJF NAO, b) November snow index and DJF NAO, c) November snow index and mean November December polar 10 hPa GPH index, d) November snow index and November BKS ice concentration, e) November BKS ice concentration multiplied by minus one to aid comparability and DJF NAO and f) mean November December polar 10 hPa GPH and DJF NAO index. Black dashed line indicating the 95% confidence level for a two-sided students T-test assuming independence and normal distribution.

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Based on the results from Figure 7 (and the overall significance of linear relationships, see Supplementary Figure 9) we investigate very basic linear multiple and simple regression

Formatted: Justified, Line spacing: 1,5 lines models to predict the upcoming DJF NAO index sign and assess the contributions to the prediction skill by November sea ice, November snow cover and November December mean stratospheric conditions. For the period 1901–2010 we investigate three different multiple regression models with

a) DJF NAO(t) = a1 × Nov. snow cover(t) + b1 × Nov. BKS sea ice(t) + c1 × ND 10hPa GPH(t)

b) DJF NAO (t) = a1 × Nov. snow cover(t) + b1 × Nov. BKS sea ice(t)

c) DJF NAO (t) = a1 × Nov. snow cover(t) + b1 × ND 10hPa GPH(t)

and one simple linear regression model

d) DJF NAO (t) = a1 × Nov. snow cover(t)

where DJF NAO is the standardized NAO index calculated by EOF analysis of 20CRv2c SLP data, Nov. snow cover is the November 20CRv2c snow cover index, Nov. BKS sea ice is the Walsh et al. November BKS sea ice index and ND 10hPa GPH is the ERA20C November December mean 10hPa GPH index with a1,b1,c1 being the constants determined by the least-squares calculations. Moreover, we perform b) and d) also for the period 1851–2010.

Figure 8 shows original and predicted normalized DJF NAO values together with the 21-year running correlation of both indices. Overall correlation values are low but significant for the 110-year time period (ranging from 0.41 to 0.38) but specific periods of high correlation emerge for both Arctic warm periods, the first one being centered around 1925 and the second one being centered around the year 2000 with both periods reaching correlation coefficients above 0.6. The multiple regression prediction model with three different predictors performs best, with a significant correlation to the original NAO variability of 0.41 for 110 years (Figure 8a). Nevertheless, November snow cover seems to add most of the prediction skill, since the decrease in correlation coefficient between the multiple regression model with three predictors and the simple linear regression model with just November snow cover as a predictor is 0.03. Moreover, periods of high correlation coefficients align with periods of strong negative relationships in Figure 7b.

For the same empirical prediction model using 160 years, the overall correlation coefficients decrease to around 0.3. As expected, the same periods of increased prediction skill emerge

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(Figure 8e&f) and the added prediction skill of sea ice is low. It should be noted however, that sea ice increases prediction skill during the current Arctic warming period, as well as the end of the 19th century with 2nd highest correlation coefficients centered around 1890 (not shown).

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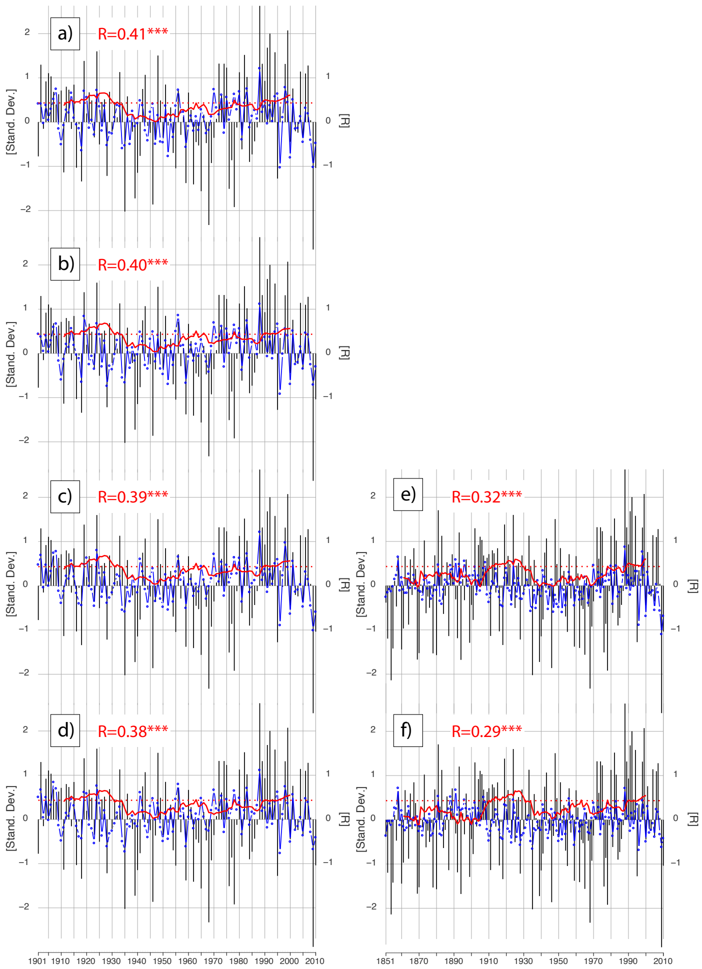

Figure 8: Comparison of 1901–2010 20CRv2c DJF standardized NAO values based on EOF analysis with predicted values from multiple and simple linear regression models showing a) multiple linear regression model with November snow cover index, November BKS sea ice index and ND 10hPa geopotential height index with an overall correlation of 0.41, b) multiple linear regression model with November snow cover index and ND 10hPa geopotential height index with an overall correlation of 0.4, c) multiple linear regression model with November snow cover index and November BKS sea ice index with an overall correlation of 0.39, d) simple linear regression model with November snow cover index and November BKS sea ice index with

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an overall correlation of 0.38. e) and f) same as c) and d) but for the period 1851–2010 respectively. Left Y-axis indicates standard deviation, right Y-axis indicates correlation coefficient. Red dashed line indicates 95% significance level for a 21-year period.

4. Discussion

We use a variety of reanalyses and reconstructions to address some of the open questions regarding the relationship between Eurasian snow cover and the state of the NAO in the following winter.

Given the highly discussed research topic of Northern Hemisphere sea ice cover and snow cover impact on mid-latitude circulation **(Cohen et al., 2019)**, as well as the highlighted need to investigate relationships over several decades (**Kolstad and Screen 2019**), we investigate a promising November west-east snow cover dipole over Eurasia (**Gastineau et al., (2017); Han and Sun (2018))** and its relationship to the DJF NAO state up to the middle of the 19th century to cover 150 years of internal and external climate forcings. Given the importance for seasonal prediction, we address the question of stationarity of said relationship as well as its context within other common Northern Hemispheric predictors.

Compared to **Gastineau et al. (2017) and Han and Sun (2018)**, we can extend the reanalysis study period from 35 to 150 years and highlighted the consistently negative sign of the snow-NAO relationship in the 20CRv2c dataset. Partial correlations for 110 years show that reduced BKS sea ice shows a similar response in DJF SLP anomalies, however its statistical importance, and therefore quality as being the prime predictor, is less than the November snow index (see Supplementary Table 2 for partial correlations). This is also found in simple multiple regression prediction models, where the November snow cover index was incorporating the major share of the prediction power. Extending the analysis of **Gastineau et al. (2017)** to 150 years further underlines the lack of snow–atmosphere feedback in most of the CMIP5 models and reduces the probability that the snow-NAO link is due to random internal variability at the end of the 20th century.

Moreover, given the monthly development of vertical temperature anomalies related to a high snow cover index supports the theoretical framework (**Cohen et al., 2014; Henderson et al. 2018**) for a Eurasian snow cover to stratosphere link in reanalyses for at least the 20th century and probably beyond. We find a cooling and snow cover expansion east of the sea ice anomaly,

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where cold air is advected on the eastern side of a Ural blocking anomaly (Figure 5). The increased geopotential heights and the related Rossby-Wave energy reach the stratosphere (Supplementary Figure 7), where a stratospheric warming and a slow down of the Polar Vortex manifests (Figure 4). These anomalies reach the troposphere in January and February where they express themselves as a negative NAO signal (Figure 2). It is noteworthy, that all of these features are significantly correlated with the November snow cover index for more than 100 years.

Peings et al. (2013) and the follow up study by **Douville et al. (2017)** found that the October and October–November mean snow cover over a broader region of Northern Eurasia, and its relationship to the wintertime NAO is indeed not stationary over time. We find a strong relationship between the reduced variance of the snow index time series with the reduction in correlation strength of snow cover and the wintertime NAO (Figure 9). The reduction of variance is even stronger in ERA20C than in 20CRv2c, which would explain the less stationary correlations in ERA20C. Furthermore, such periods of low snow variability coincide with a reduction of polar vortex variability, hinting even more so towards possible links between November snow and stratospheric temperatures in the following month. Together with the snow cover index, the November BKS sea ice index shows increased variability with strengthened negative correlation to DJF NAO during at the end of the 20th century (see Supplementary Figure 11).

These periods of increased variability in the November snow cover index co-occur arguably with the common Arctic warming periods of the 20th century, the ETCAW (**Wegmann et al., 2016; Hegerl et al., 2018**) and the recent ongoing Arctic warming with peak variance and correlation values centered around the years 1920 and 2000. Interestingly, October snow cover index and BKS sea ice index variability peaks slightly after the ETCAW around the year 1945. Analysing temperature anomalies (not shown) for all three periods reveals more continental warming over Russia for the period 1911-1930 whereas warming between 1936-1955 is located very much at the Kara Sea coast of Russia, where both the October snow index and the BKS sea ice index are impacted by. Generally, Arctic warming periods appear to increase variability of cryospheric predictors considerably and thus strengthen their impact in seasonal prediction frameworks. Given the importance of stratospheric variability for seasonal prediction and the apparent relationship between snow cover variability and stratospheric variability (Figure 9), it can be expected that the cryosphere-stratosphere pathway is also considerably stronger in

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The question remained, how stationary this relationship between Eurasian snow and the wintertime NAO is over time.

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Arctic warm periods than for cold periods. Moreover, in our statistical analysis, we found no indication for a stratospheric precursor of November snow cover anomalies.

In accordance to the shorter time frame analysis of **Sun et al. (2019)**, decadal variability of the November snow cover index seems mostly dominated by low-frequency variability in the AMO and subsequently reduced or increased polar sea ice concentration. This mechanism is also supported by the results of **Luo et al. (2017)**, who highlighted the decadal relationship between a positive AMO, reduced sea ice and increased Ural blocking for the second half of the 20th century. Looking at this mechanism on an interannual basis, we show a robust strengthening of the November snow dipole with decreasing BKS ice concentration, circulation changes over the BKS region and consequently cold air advection towards the eastern part of the snow dipole region for a period of 150 years. With this, our results support recent studies, which point out the counterintuitive mechanism of Arctic warming and increased continental snow cover via sea ice reduction and circulation changes (**Cohen** et al., **2014**; **Wegmann** et al., **2015**; **Yeo** et al., **2016**; **Gastineau** et al., **2017**).

Peings (2019) performed model experiments with nudged November Ural blocking fields, BKS ice and snow anomalies. The author found that UB events are not triggered by reduced sea ice, but in fact lead sea ice decrease. Moreover, more November snow alone did not lead to an increase in blocking frequency, nor to a stratospheric warming. The study highlights the UB events as primary predictor for a negative NAO and the Warm Arctic-cold Continents (WACC) pattern. On the other hand, **Luo et al. (2019)** established a causal chain via a stratospheric pathway from reduced sea ice to reduced potential vorticity gradient and increased blocking events leading to cold extremes over Eurasia. We computed the field average of blocking frequency within the domain of **Peings (2019)** (10°W-80°E, 45-80°N) and could find a strong correlation with the WACC pattern over time, however only for DJF blocking events (not shown).

We found a correlation of November UB events with wintertime NAO, which is however still weaker than the relationship with the November snow dipole, as well as our BKS ice index (see Supplementary Figure 10). Moreover, blockings within the domain of **Peings (2019)** (10°W-80°E, 45-80°N) are not related to a snow dipole whatsoever, neither in October nor in November (see Supplementary Figure 10). That said, we want to highlight the fact that the blocking pattern emerging in Figure 5 is mostly outside of the boundaries of this UB index (10°W-80°E, 45-80°N), and thus might not be caught by this recent study. Furthermore, **Peings (2019)** applies a very general snow cover increase in his nudging experiment, rather than a

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snow dipole with a west to east gradient. Finally, although we focus here on the connection to the NAO, we did not find strong significant correlations between autumn snow and winter WACC. As pointed out by **Peings (2019)**, the most important driver for the WACC signal is the Ural blocking, for which we find strong correlations throughout the 20th century (not shown).

Overall, we advocate the importance of the signal-to-noise ratio rather than mean states for the evolution of the November snow to winter NAO relationship. In our statistical analysis, we did not find any indication for a centennial relationship between the autumn ENSO or autumn QBO sign with the variability of the relationship between November snow cover and DJF NAO (not shown). As mentioned above, we found the strongest influence to be the increased variability of the system due to energy uptake.

That said, a source of uncertainty is the disagreement between ERA20C and 20CRv2c when it comes to the stationarity of the relationship. 20CRv2c shows negative correlation throughout the whole 20th century, whereas ERA20C flips the sign of the correlation in the late 1930s and late 1970s. The same relationship but using October snow shows high agreement between the two datasets, which is the same case for the correlations between snow and stratospheric GPH. We therefore conclude, that the information stored in the November snow cover in 20CRv2c is slightly different to the information stored in the ERA20C snow depth. **Wegmann et al. (2017)** found that Eurasian November snow depth shows much larger disagreement between 20CRv2c and ERA20C than the same snow depth in October. In the same study, the authors found decadal trends (although linear trend subtraction for all predictor time series was done for this study) in ERA20C snow depth which migh impact the running correlations. Finally, since snow depths are relatively low in October, differences between using snow cover and snow depth might be less important from an energy transfer point of view.

The disagreement between ERA20C and 20CRv2c may also be related to uncertainties and inhomogeneities in both reanalyses. Many studies showed that both ERA20C and 20CRv2c are not suitable for studies looking at trends (e.g. **Brönnimann et al., 2012; Krüger et al., 2013**) and may include radical shifts in atmospheric circulation, particularly over the Arctic (e.g. **Dell'Aquila et al., 2016; Rohrer et al., 2019**). However, **Rohrer et al. (2019)** showed that although trends in centennial reanalyses may be spurious, at least in the Northern Hemisphere year-to-year variability of mid-tropospheric circulation is in agreement even in the early 20th century.

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Kolstad and Screen 2019 highlighted the importance of non-stationarity regarding Arctic sea ice and mid-latitude climate variability. In our analysis, running correlations show interdecadal variations concerning the strengths of November snow as the predictor for wintertime NAO. Compared to the analysis of **Douville et al. (2017)**, we could strengthen the stationarity by facilitating the November dipole snow, especially using 20CRv2c snow cover data, but the question behind decadal peaks and valleys in the running correlation persist. To begin with, the October and November snow indices show very different, nearly anticorrelated, running correlation patterns. A high November snow index seems to be a strong predictor for a negative NAO state at the beginning and end of the 20th century, as well as around the 1950s and 60s. On the other hand, the October index, and related to that the results by **Douville et al. (2017)**, shows negative correlations during the 1940s and 1980s. ¶
We found the main reason for the reduction in correlation strength to be reduced variance of the snow index time series during said time period (Figure 8). The reduction of variance is even stronger in ERA20C than in 20CRv2c, which would explain the less stationary correlations in ERA20C. Furthermore, such periods of low snow variability coincide with a reduction of polar vortex variability, hinting even more so towards possible links between November snow and stratospheric temperatures in the following month. ¶

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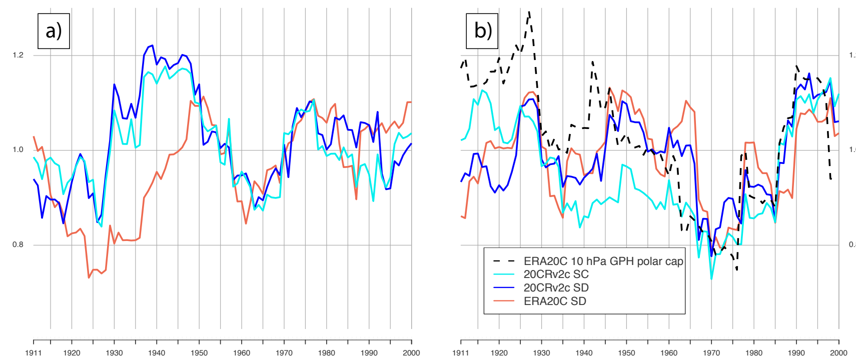

Figure 9: 21-year running standard deviation time series of a) October snow index and b) November snow index in ERA20C and 20CRv2c (snow cover and snow depth). Dashed black line shows running standard deviation of 10 hPa November December mean GPH over the polar regions.

5. Conclusion

Several reconstruction and reanalysis datasets were used to examine the link between autumn snow cover, ocean surface conditions and the NAO pattern in winter for the whole 20th century and into the 19th century. We found evidence for a manifestation of a negative NAO signal after November with a strong west-to-east snow cover gradient, with this relationship being significant for the last 150 years. Interdecadal variability for this relationship seems to be linked to Arctic warm periods which increase the variability of the cryospheric predictors considerably. As a result, increased variability in the predictors helps to generate a better seasonal prediction estimation.

Furthermore, our analysis of centennial time series supports studies pointing out the impact of autumn snow on stratospheric circulation as well as the connection between reduced BKS ice concentration and increased snow cover in eastern Eurasia. The latter mechanism is triggered via the development of an atmospheric high-pressure anomaly adjacent to the BKS sea ice anomaly, which transports moisture and cold air along its eastern flank into the continent. The interdecadal evolution of the November snow index also points towards a co-dependence with high North Atlantic SSTs subsequently reduced sea ice.

Extending the investigation period from 35 to 110 and up to 150 years increases the confidence in recently proposed physical mechanisms behind cryospheric drivers of atmospheric

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variability and decreases the probability of random co-variability between the Arctic cryosphere changes and mid-latitude climate.

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For future studies regarding seasonal prediction, we emphasize the use of the November snow dipole concerning a forecasting of the winter NAO state. Nevertheless, periods of weak correlation might occur again, especially since it is uncertain how the sea ice to snow relationship will change with stronger anthropogenic global warming, once the Arctic is ice free in summer or the local warming is strong enough to override the counterintuitive snow cover increase. Thus, further studies are needed to investigate the interplay between Arctic sea ice and continental snow distribution. Future experiments should take into account year-to-year variability and realistic distribution of snow cover if links to the stratosphere are to be examined.

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Acknowledgements

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Data Availability

The MERRA2 reanalysis data is publicly available at the NASA EARTHDATA repository (https://disc.gsfc.nasa.gov/daac-bin/FTPSubset2.pl). The ERA-20C reanalysis data is publicly available at the ECMWF data repository (https://apps.ecmwf.int/datasets/). The 20CRv2c reanalysis data is publicly available at the NOAA Earth System Research Laboratory repository (https://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2c.html). The blocking algorithm is publicly available at https://github.com/marco-rohrer/TM2D. The AMO reconstruction data is a publicly vailable at the NOAA Earth System Research Laboratory (https://www.esrl.noaa.gov/psd/data/timeseries/AMO/). The Niño 3.4 reconstruction is publicly available at the GCOS Working Group on Surface Pressure repository (https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Nino34/). The NAO reconstruction is

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publicly available at the Climate Research Unit repository (https://crudata.uea.ac.uk/cru/data/nao/). The Walsh et al. sea ice concentration reconstruction is publicly available at the National Snow and Ice Data Center repository (https://nsidc.org/data/g10010).

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Author Contribution

M.W. devised the study, the main conceptual ideas and the proof outline. M.R. assisted with data availability and performed the blocking algorithm. M.W. wrote the manuscript in consultation with M.S-O. and G.L., who aided in interpreting the results.

Competing interest

The authors declare that they have no conflict of interest.

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