“Northern Hemisphere spring snow cover variability and change over 1922–2010 including an assessment of uncertainty” by R. D. Brown and D. A. Robinson

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Interactive comment: M. Pelto, mauri.pelto@nichols.edu

Brown and Robinson (2010) provide a thorough description of the development of a snow cover data set for March and April in the Northern Hemisphere. The resulting snow cover extent data set with the detailed confidence limits established provides a valuable data set for identifying changes in snow cover extent and the associated errors. I will confine my comments to two minor and one key point in this well written paper.

1) An important and potentially valuable further output from the data set that should be included here is the change in SCA from March to April each year. The net loss from March to April each year of SCA would be more specific to early spring melting and hence temperature and less influenced by the snowfall conditions that preceded spring. Particularly in Figure 9 a plot of temperature versus the change in SCA from March to April should be more valuable than simply a plot of SCA versus the temperature of that month. The data set evaluated for March-April=SCA Change, yields a bit of a positive trend for NA since 1970, more SCA lost, and a negative trend for EA, less SCA lost. I would look forward to the authors potentially gleaning some further useful interpretation out of a comparison of the differences in SCA between March and April.

2) Figure 2: Why did the confidence interval in April for EA increase significantly for the 1990-2000 interval?

3) Abstract and Conclusion: “The rate of decrease in March and April NH SCE over the 1970–2010 period is ~7–8million km 2 per 100 years which corresponds to an 8–11% decrease in NH March and April SCE respectively from pre-1970 values. “ Given that this is a 40 year long record the rate of change should be per decade.

Authors Response:

1) The authors appreciate the comment but do not agree that an analysis of the change in snow cover extent (SCE) between March and April (henceforth referred to as dSCE) should be included in the paper. The commenter states that dSCE would be more tightly linked to temperature but this ends-up not being the case because dSCE includes errors from both March and April and the r-squared value for the correlation between dSCE and dTemp (the change in temperature between March and April) is only 0.2 compared to about 0.5 for the corresponding monthly values. The only way to increase the correlation is to average the monthly SCE and temperature series (r-squared = 0.56) which reduces some of the noise.

The dSCE time series for the NH is essentially constant from 1940-on (see Figure below) so there is not much to comment on in terms of seasonal shifts.

In response to the request that we do some further interpretation of the differences in SCE between March and April we have added some text and a new key reference (highlighted bold red) explaining the higher temperature sensitivity in April compared to March.

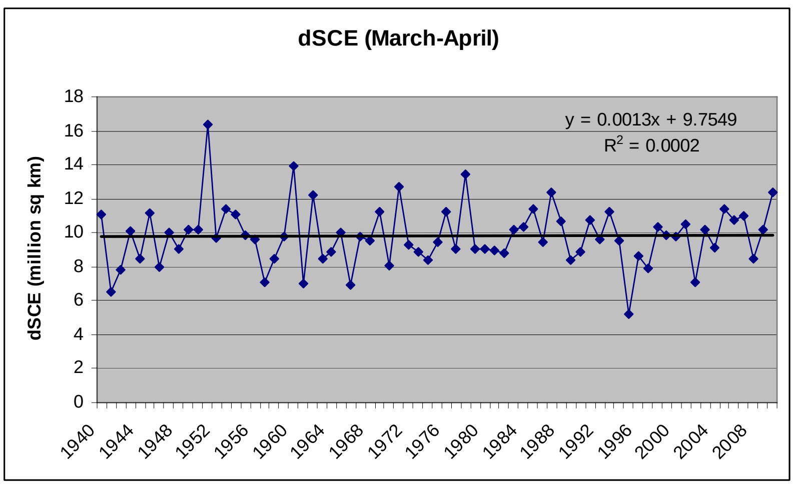
P2485, lines 2-6 “Reliable information on spatial and temporal variability in continental and hemispheric snow cover extent (SCE) is important for climate monitoring (e.g. Arndt et al., 2010), climate model evaluation (e.g. Foster et al., 1999; Frei et al., 2005; Roesch, 2006; Brown and Frei, 2007) and

cryosphere-climate feedback studies (e.g. Hall and Qu, 2006; Fernandes et al., 2009; **Flanner et al., 2011**)."

P2494, lines 4-9 "A least-squares regression method was used that included the annual estimates of observational errors in SCE. The results obtained with the updated NH series with annual error estimates included are -1.44 x 10^6 km^2 °C^{-1} (r^2 = 0.50) and -2.00 x 10^6 km^2 °C^{-1} (r^2 = 0.49) for March and April respectively which are similar to the values published in Brown (2000) except that temperature explains a larger fraction of the variance with the updated series. **The larger temperature sensitivity in April is consistent with the findings of Flanner et al. (2010) that NH terrestrial snow cover feedbacks are strongest in the April-May period.**"

Additional reference:

Flanner, M. G., Shell, K. M., Barlage, M., Perovich, D. K. and Tschudi, M. A.: Radiative forcing and albedo feedback from the Northern Hemisphere cryosphere between 1979 and 2008, Nature Geoscience, doi:10.1038/ngeo1062, 2011.



Annual variability in the change in NH SCE between March and April.

2) The increase in the confidence interval is partly related to low agreement between datasets in a few years (reasons indicated in the paper) that end up affecting the filtered average, and the use of regression analysis to estimate the confidence interval in the 2003-2010 period (yields a wider confidence interval on average than estimates derived from multiple datasets).

3) You have a point. We changed the units to per decade in the text but left the units unchanged in Table 3 for comparison purposes.

Thanks for the feedback!

Anonymous Referee #1
Received and published: 9 December 2010

The manuscript is well written and clear in its presentation. This work adequately covers many of the shortcomings of previous efforts to describe snow extent trends by way of, for example, employing multiple data sets and applying appropriate statistical tests. It is unfortunate that the assessment is limited to two calendar months, and I was not entirely clear on why, but the authors do note that they were forced to limit the work to this time period - although fortuitous that March and April are primary melt months for the seasonal snow cover in most locations.

On page 2494, beginning on about line 13, the authors do note that snow cover extent is only part of the total snow cover story, with volume or mass being the elusive parameter that continues to be difficult to impossible to evaluate over large areas with any high accuracy. They note that although there is the obvious and direct connection between snow extent and air temperature at this time of year, snow mass is certainly playing a role in the rate at which the snow disappears in March and April. With respect stream flow volume, It might be good to acknowledge that the trend for an earlier disappearance of snow in April may be an indication of change in the timing of maximum runoff, but without correlation with snow depth or water equivalent it doesn't tell the whole story in terms of hydrology. Perhaps this is in the category of "suggestions for future work". In summary, this paper represents an important and practical contribution to the overall understanding of the response of the Northern Hemisphere seasonal snow cover to a changing climate. I do not have any technical corrections for this paper.

Authors Response:

1) The reviewer is correct that this is not evident at the outset. We have inserted some text in the introduction to clarify this point.

P2485, lines 18-21 "Brown (2000) presented estimates of historical variability in NH March and April snow cover extent (SCE) over the 1922-1997 period that were subsequently updated and included in the 4th IPCC assessment (Lemke et al., 2007; Figures SPM.3, TS.12 and 4.2). **The hemispheric reconstruction was restricted to only these two months due to limitations in the spatial coverage of historical snow depth observations**."

2) Good point. We added a note that further work was needed to investigate the difference in winter snow accumulation between the two continents and included a note that the SCE trends were consistent with widespread trends to earlier snowmelt runoff.

P2493 lines 27-29 "The rates of decrease are much higher when computed over the period of satellite coverage as the data start during a period when hemispheric snow cover was relatively high, and include the period of recent rapid warming. **The observed trends in SCE are consistent with widespread warming (see Table 3) as well as with evidence of earlier snowmelt and a shift in hydrologic regimes over NH land areas (e.g. Yang et al., 2002; Stewart et al. 2005; Aziz and Burn, 2006; Tan et al., 2011).**

P2494 lines 19-22 "Everything being equal, shallower snowpacks will respond more quickly to temperature anomalies so the difference in recent winter snow accumulation trends between the two continents may be playing a role. **Further work is required to investigate the difference in snow accumulation trends between the two continents**."

References added to text:

Aziz, O. I. A., Burn, D. H.: Trends and variability in the hydrological regime of the Mackenzie River Basin, J, Hydrol., 319, 282-294, doi: 10.1016/j.jhydrol.2005.06.039, 2006.

Stewart, I. T., Cayan, D. R., and Dettinger, M. D.: Changes toward earlier streamflow timing across western North America, J. Clim., 18, 1136–1155, 2005.

Tan, A., Adam, J. C., and Lettenmaier, D.P.: Change in spring snowmelt timing in Eurasian Arctic rivers, J. Geophys. Res., 116, D03101, 12 pp., doi:10.1029/2010JD014337, 2011

Yang, D., Kane, D. L., Hinzman, L. D., Zhang, X., Zhang, T., Ye, H., and Yang, D.: Siberian Lena River hydrologic regime and recent change. J. Geophys. Res., 107, 4694, doi:10.1029/2002JD002542, 2002.

Thanks for the feedback!

Anonymous Referee #2
Received and published: 19 January 2011

Overall, the manuscript is well written and provides a clear and logical flow of arguments I think that it is an important extension of previous work and well suited for publication in TC. I have a few suggestions on content to strengthen the interpretations, but do not see these as major issues.

Content suggestions:

1) On page 2487 the authors mention that it is not possible to correct for "technological bias" in the data sets. Given that the authors go to great lengths to calculate other errors, I think it is appropriate to add a sentence here explaining that this bias is expected to be significantly lower than other forms and why this should be the case (as is assumed for further calculations to produce significant findings but not stated in the text directly).

2) On page 2491 the authors discuss Figure 1 and provide various reasons for the high standard deviations amongst data sets. It might be useful to similarly calculate the geographic distribution of differences in elevations in the individual data sets. The maximum standard deviations appear in the higher topography regions and in locations of narrow coastal mountains, which suggest that the scaling differences between data sources could be a major reason for this disparity (as discussed in the text). I think such a calculation would help quantify the discussion of this point.

3) I suggest adding corresponding temperature trends to Table 3.

4) I think that Figure 9's relationships and that of Table 4 could be enhanced by correlating March temperature (or averaged March to April temperature given the SCE is not a discrete 1 March to 1 April value) with March to April snow cover change. Given that snow cover is a result of integrated snowfall (and snowmelt, although likely relatively smaller than spatial accumulation until March) during the winter, the given correlations are likely reduced by existing snowcover responding to temperature anomalies in previous months. This calculation should improve correlations.

Technical Correction: On pg 2492 there is a space missing between "around1980" in the second to last line.

Authors Response:

1) Agreed. The following text was added:

P 2486, line 17: "However, these errors are expected to be small compared to the seasonal and interannual fluctuations in continental snow cover extent, and comparison of NOAA SCE over NA and EUR with a multi-dataset average (section 4.1) showed that the difference series did not contain any trend which provides some evidence that these errors are not affecting the homogeneity of the data series for continental-scale variations in SCE in March and April."

2) The reviewer is correct that differences in the resolution in datasets were affecting the results. The authors have addressed this problem by redoing the analysis with the monthly snow cover anomaly series from each dataset which provides results that are more consistent with the area where snow cover is varying and removed anomalies such as the coastal "noise" in Arctic regions. A revised Figure 1 and revised text have been added. The revised analysis showed that the differences between datasets were largest over northern Europe contrary to the results using raw data values. This also required corrections to the abstract and conclusions section.

Revised text: (revised figure below)

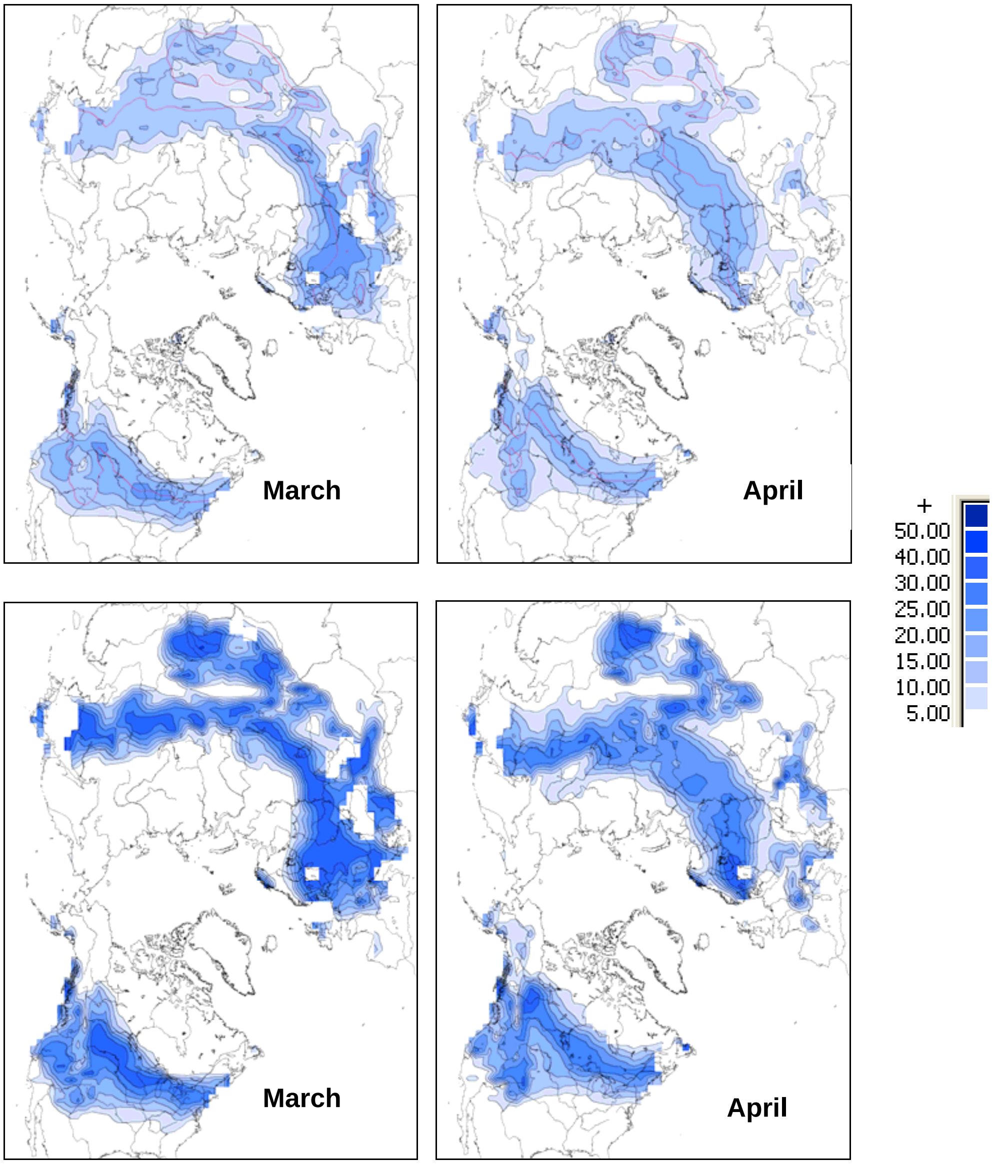
P 2490, lines 1-14“To gain further insight into the spatial pattern of between dataset variability the data, were interpolated to a common 190.5 polar stereographic grid and the standard deviation contoured (Fig. 1, top panels). The analysis was carried out with the monthly snow cover anomaly series to reduce the impact of topographic influences on the interpolation process and remove systematic differences in how each dataset “sees” snow cover. The PMW dataset was excluded from the analysis as the spatial pattern of snow cover deviated significantly from the other datasets in mountainous areas and around the southern boundary of the snow line. Not surprisingly the main zone of dataset variability follows the snow line position in each month, as shown by the 50% mean snow cover contour for the multi-dataset average, with the largest dataset variability in March over northern Europe and north-central Russia. In NA the zones of maximum variability were much smaller and located in the lee of the Rockies and the U.S. mid-west. The dataset variability was lower in April with the Eurasian zone of maximum dataset variability remaining over the western part of the continent while the variability was more-or-less evenly spread along the mean position of the snow-line in NA. In general, the spatial pattern and relative magnitude of the results follow the interannual variability in snow cover (Fig. 1, bottom panels) with the exception of eastern Eurasia and the Tibetan plateau where the between dataset variability is lower.”

References Cui et al., Randall et al and Savoie et al were removed from the reference list as a result of this revision.

3) Done

4) To get a meaningful correlation you have to correlate the change in SCE with the corresponding change in temperature but this ends up yielding a lower correlation because the noise from each month is added into the analysis. Averaging the monthly SCE and temperature series increases the correlation with temperature (r-squared = 0.56) by reducing some of the noise. Please also see the response to the discussion comment where the same point was raised.

Thanks for the feedback!



Revised Figure 1: Top: spatial pattern of between dataset variability expressed as the average annual standard deviation in monthly snow cover anomalies over the 1979-2002 period for five datasets with data in the 1979-2002 overlap period (excluding PMW). The red line shows the mean position of the 50% snow cover contour. Bottom: spatial pattern of interannual variability in snow cover over the same period from the standard deviation in monthly snow cover fraction computed with the NOAA dataset. Units are % snow cover fraction.