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Biogeosciences Discussions

Interactive comment on "Pan-Arctic linkages between snow accumulation and growing season air temperature, soil moisture and vegetation" *by* K. A. Luus et al.

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On behalf of all co-authors, I would like to thank all three anonymous reviewers for providing detailed, informative and insightful revisions. The manuscript has been greatly improved thanks to the implementation of these many suggestions. The paper now begins with two clear examples illustrating the interpretation of ACE point pair output, and contains an honest assessment of all study limitations, as well as an improved discussion of ACE output in relation to previous *in situ* findings. Detailed responses to all referee comments are provided below. Many thanks! K.A. Luus

Anonymous Referee 1

1. A subsection on limitations has now been added to the methodology section, which includes a discussion of reasons why the R^2 values observed in this study tend to be weak.

2. Problems with the interpretation of previous studies have now been resolved, in accordance with the suggestions provided.

3. Section 3.3: Mentions of GloPEM NPP have now been removed from the paper, as its use was not central to the aims and objectives of this paper. The plot of pan-Arctic GloPEM has been removed from Figure 2.

4. Results and Discussion Section: The descriptions are now rephrased so as to describe the relative strength of these associations. The newly-added methodology subsection on limitations now also describes the impossibility of identifying specific environmental processes by applying a statistical technique to assess linkages in coarse resolution remote sensing observations. Instead, the mechanisms leading to these linkages can only be inferred in context of *in situ* findings.

5. Figures 3-5 and Table 3: The associations between all variables studied tend to be noisy and non-linear. The associations between variables cannot be determined from visual assessment. Even when the associations are linear, they cannot be determined from simple plots of x vs y (please refer to Example 2). It would therefore only complicate the issue to show many plots with no discernible associations. All of the R^2 values from the linear regressions of variables (before the ACE transformations) are already provided in Table 3. All R^2 values from the linear regressions are smaller than the R^2 values following ACE transformation. The differences in the x axis of [x,f(x)] plots are not due to differences in correlation strength, but due to the tendency of different vegetation classes to have slightly different ranges of vegetation transmissivity. The shape of the line

BGD
10, C1277–C1287, 2013

in figures 3-5 is not an indication of correlation strength, but of the shape of the association between point pairs [x,f(x)] and [y,g(y)]. The strength of these associations is shown in Table 5.

6. Section 4.1.2, last paragraph: Thank you for pointing this out. The description is now altered so that rapid snowmelt is described as occurring primarily due to low shading.
7. Section 4.2: When the associations between SWE and soil moisture are considered only for regions with SWE$<$90 mm and MV $<$0.17, the ACE transformed values have substantially greater R^2 values (0.08) than those found through linear regression (0.00). This is now mentioned in section 4.2.
8. Section 4.3.1. paragraph 1: The snow holding capacity of shrubs is now mentioned earlier in the text, with specific mention of their effect on limiting sublimation.
9. Paragraph 4: Thank you for this detailed identification of an error in the discussion of snow accumulation, topography and aboveground biomass. The text has been corrected, with reference to the articles mentioned.
10. This sentence has been removed from the manuscript, as suggested. The associations between SWE and vegetation transmissivity over shrublands and mixed forest regions are now discussed at the end of this subsection.
11. Yes, this is a very good point. The effects of trees and shrubs on snow accumulation are now better differentiated.
12. Section 5: Additional detail was added to these statement to clarify that they do not refer to shrub-dominated regions.

13. Appendix A: The methodology now includes a section on limitations of this study, where a description of uncertainties in datasets are discussed in context of the approach used to limit their influence on findings.
14. Minor comments: p3, sentence 2: This sentence has been rephrased and split into two to allow improved clarity in the description of how shrubs influence snow accumulation.
15. p3: Mentions of FMI now refer instead the FMI-led consortium.
16. p4: Aims are now written up with a series of bullet points
17. Section 3.2, last paragraph: Mentions of NPP have been removed from this paper, as they were not crucial to the aims and objectives.
18. Section 3.4: Yes, thanks for noticing this error in phrasing. The time period over which snowmelt occurs is not considered in this study, only SWE immediately before snowmelt and land surface properties following the end of snowmelt.
19. Section 4.1.2, last sentence: This sentence has been removed.
20. Table 1: The GRMTD class includes the CAVM's “graminoid, prostrate dwarf-shrub, forb tundra”; the SRBTD class contains the CAVM's ”prostrate dwarf-shrub, herb tundra”. These two classes are distinct, and are separated by the CAVM into two distinct categories: graminoid tundra (GRMTD), and prostrate-shrub tundras (SRBTD). The vegetation categorizations are made accordingly, with semicolons separating different classes and commas included within the names of classes according to the CAVM standards.
21. Figures 1 and 3-5: Figures 1 and 3-5 are now bigger.
22. References have been added where required.

BGD

10, C1277–C1287, 2013

Anonymous Referee 2

1. Two improved examples are now provided to allow readers to better understand the ACE technique from the outset.

2. In the methodology section, the limitations of this study are now discussed. Specifically, since the ACE technique is applied to a coarse resolution, aggregated remote sensing dataset, it is impossible to make specific conclusions about the exact mechanisms guiding these interactions. Discussion of results in terms of the latest findings from in situ studies is therefore crucial to provide insight into which processes are being observed. However, it is beyond the scope of this study to conduct a reanalysis of in situ processes using the ACE technique. This could provide an interesting direction for future research.

3. This is now discussed in Limitations (subsection 3.6): "The relationships observed through the ACE analysis could be applied to generate estimates of variables within the 2003-2008 time period; however, since these ecological linkages may be altered under changing climate regimes, the ACE derived empirical relationships cannot be used to predict future behavior. The ACE technique could, however, be applied to monitor the strength and directionality of these ecological linkages in order to shed light on the response of northern environments to changes in snow and growing season conditions."

4. Levene's test was applied to examine inter-annual variability in all variables, including SWE. When each year was considered separately, results indicated that none of the variables displayed substantial inter-annual heterogeneity ($0.5 < p\text{-value} < 0.99$): Therefore, although there can be large inter-annual variability in snow metrics, Levene's test indicated that the inter-annual variances in all mean values of snow and growing season values were not statistically significant. All analysis of mean values was therefore conducted over averaged (2003-2008)

BGD

10, C1277–C1287, 2013

Interactive Comment

	2003	2004	2005	2006	2007	2008	F statistic	p value
Air temperature	9.5559	9.6780	0.95355	9.4232	8.3694	8.3990	0.1757	0.9717
Soil moisture	0.0015	0.0016	0.0015	0.0015	0.0017	0.0016	0.8714	0.4992
Veg. opacity	0.0165	0.0158	0.0167	0.0163	0.0163	0.0158	0.1325	0.9850
SWE	1323.7	1587.5	1515.1	1619.3	1841.9	1838.4	0.3612	0.8753

Table 1. Results from Levene's test indicating the heterogeneity of variances across years for all parameters

values.

5. Thank you for pointing out the need for an additional example to illustrate the application of ACE. One example now shows the application of the ACE technique to a situation where the associations can be clearly seen in a x vs. y scatterplot, and another shows the application of ACE to a dataset where the association cannot be visually assessed from time series of x, time series of y, or scatterplots of x vs. y. The associations examined in this study cannot be clearly seen from scatterplots of x vs. y, so the second example provides a more realistic idea of the challenges involved in the assessment of non-linear associations without ACE.

6. Although $<$15 mm estimates of SWE are considered unreliable, this represents a very small portion of the range of SWE. No sharp changes in shape of the ACE derived associations are observed near the 15 mm SWE threshold. The influence of uncertainties in SWE at very low values therefore appears to have very little, if any, effect on the ACE derived associations.

7. Chang et al. (1987) calculate snow depths (SD) up to 100 cm as a linear function of brightness temperatures at 18 GHz (T_{18}) and 37 GHz (T_{37}): SD = 1.59*(T_{18}-T_{37}). GlobSnow SWE offers a substantial improvement on this approach, as SWE is estimated using a combination of ground-based observations and output from a microwave snow emission model. Hancock et al. (2013) conducted an ex-

tensive evaluation of SWE from SSM/I, AMSR-E and GlobSnow against ground meteorological and snow depth observations. Findings from this study indicated that other SWE products can saturate over 80-150 mm SWE snowpacks; however, GlobSnow SWE was not found to have this problem. Similarly, over Finnish sites and over the INTAS-SCCONE snow course sites (Russia and Former Soviet Union), GlobSnow sensitivity appears to continue above 150 mm to about 175 mm (see Takala et al., 2011). Therefore, we are confident that the associations observed in the analysis are not an artefact of any reduced sensitivity at 100 mm but reflect the nature of the relationships as presented.

8. There certainly exist associations between the NTSG growing season variables both because they are extracted from the same passive microwave observations, and because of the influences of wetter soils and warmer growing season conditions on encouraging plant growth at high-latitude sites. The associations between air temperature and vegetation transmissivity have already been described in section 3.3, with references to literature. However, in the multivariate ACE analysis, the ACE transformed values from all three growing season variables had a highly statistically significant (p-value<0.01) influence in the multivariate regression of ACE transformed values of SWE. It is therefore clear that despite the inherent associations between variables, all three contribute substantially to the regression, and their transformed values must be considered non-collinear. The associations between SWE and vegetation, and those between SWE and growing season air temperature, will of course bear similarity due to the temperature dependence of high-latitude vegetation, but the lack of collinearity in the transformed values makes clear that this is still a worthwhile question to explore. The description in section 3.4 has been improved in the text so that it is clearer that it is the **transformed** values of growing season variables that are not collinear.

9. Placing results within the context of the current scientific understanding of *in situ* processes is informative, even when the statistical strength of the associations

BGD

10, C1277–C1287, 2013

uncovered by ACE is weak. Certainly, the paper could be shortened if literature on processes was not discussed, but this would not necessarily be beneficial.

10. The findings from the preliminary analysis (sections 3.2, 3.3 & 3.4) are now no longer mentioned at the start of section 3. They are instead discussed in the sections on preliminary analysis.

11. This reference is included in the paper.

12. Yes, the influence of vegetation on trapping windblown snow is likely to influence snow distribution patterns, even at the 25 km scale. For example, Liston and Sturm (2002) modeled snow distribution patterns according to vegetation and blowing snow across 20,000 km^2 of Arctic Alaska.

13. The newer versions of GlobSnow have better accuracy due to the inclusion of historical weather data and better cloud/snow differentiation, among other improvements. However, the associations between mean snow and growing season land surface conditions appear to remain relatively unchanged.

14. Figures 1,3,4 and 5 are now bigger.

15. Section 3.1 now states: "Terrestrial regions with $>50\%$ fractional cover of open water according to the AMSR-E growing season dataset were masked out of analysis."

16. All mentions of high or low SWE have now been changed to say higher or lower SWE.

17. These references have been added.

BGD
10, C1277–C1287, 2013

Anonymous Referee 3

1. Yes, this is a good point. It is now discussed in the limitations of this approach, and in the appendix description of GlobSnow SWE. This point is also mentioned as a potential influence on the positive association between vegetation transmissivity and SWE over dense evergreen forests.
2. Uncertainties in SWE are now better described in the appendix, as well as in a new section of Methodology on Limitations.
3. The wording has now been changed so as to refer to relative strengths.
4. The main advantage of the ACE technique isn't the slight improvement of R^2 values, but the ability to gain insights into the shapes and thresholds of non-linear associations between two or more variables. The results sections have been reworded to focus less on the R^2 values, and more on the shapes of the associations.
5. Mean SWE over three distinct time periods was examined rather than maximum SWE over these time periods because the primary motivation of this paper was to examine spatial associations between growing season and snow season influences on carbon cycling. When considering the very long Arctic snow season, mean SWE has a much greater influence on soil temperature and rates of sub-nivean respiration than maximum annual SWE.
6. The start of the snow season refers to the first 30 days following the first snowfall each autumn, as defined independently for each pixel, and for each year. The end of the snow season refers to the last 30 days for which snow is on the ground, also defined independently for each pixel, and for each year. Please refer to the description provided in section 3.1 (Methodology: Data Preparation).

BGD

10, C1277–C1287, 2013

Interactive Comment

7. Two more thorough examples [Figures 1 & 2] are now provided at the beginning to better demonstrate how the shape of ACE point pairs can be interpreted. It is hoped that these examples will assist readers in interpreting Figures 3–5.

8. Thirty days was selected as the period over which land surface characteristics were averaged as this represents a period of time that fully captures landscape transitions. Over thirty days, both snow depletion (100% to 0% fractional snow cover) and snow accumulation (0% to 100% fractional snow cover) tend to occur even over forested sites. Similarly, both vegetation senescence and green-up can usually occur within thirty day time periods at the start and end of the growing season. It was important that the time period over which conditions are averaged at the start and end of the snow season was not dependant on the specific site, but rather, set to the same value across the pan-Arctic region. Otherwise, the time period selected for each individual site would act as a confounding factor, and would complicate efforts to understand, for example, whether snow accumulation is hindered in regions with warm air temperatures at the end of the growing season.

9. The limitations of the study, and the need for the statistical findings to be interpreted cautiously in relation to well-understood field processes, are now discussed in the Methodology section of this paper. Definite conclusions regarding the exact processes responsible for each characteristic cannot be made when a statistical approach is employed over a coarse resolution satellite derived dataset. It is especially important that caution be exercised when the output is discussed in relation to field scale processes in situations where the input data has uncertainties, the associations derived are weak, and the scaling of associations remains relatively poorly understood. Therefore, although it is interesting when the ACE derived associations agree with the current scientific understanding of field scale processes, it is better to remain cautious in the interpretation of these associations.

BGD

10, C1277–C1287, 2013

Interactive Comment

10. Thank you for suggesting the idea of applying the ACE technique to examine temporal analysis over a small, defined area over which ground measurements have been acquired. Two simple examples are now provided at the start of the paper which focus on using the ACE analysis to analyze temporal associations in meteorological data collected at a single site. The first example examines a well-understood relationship that can easily be detected without application of the ACE technique. The second example provides an example of a well-known, approximately linear association that is difficult to detect in temporal plots of x over time, y over time or x vs. y. However, when the ACE technique is applied, the resulting point pair output produces output that is consistent with the scientific understanding of the associations between these variables. It is hoped that, by providing two simple examples of temporal analysis using the ACE technique, that readers may be more readily eased into the remaining analysis without feeling that there is too much too soon.

11. This reference is included in the paper.

Interactive comment on Biogeosciences Discuss., 10, 1747, 2013.

BGD

10, C1277–C1287, 2013

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