Anonymous Referee #1
Received and published: 20 November 2016
Comment: This is a generally very good study of Greenland Ice Sheet accumulation based on Ice-Bridge data, that compares the results with several different regional climate models and a kriged map of ice-core data. Finally, an attempt is made to interpret recent accumulation variations (spatial and temporal) with reference to the Atlantic Multidecadal Oscillation and North Atlantic Oscillation changes, although Greenland Blocking should also be mentioned here. This latter section is less strong and can be supplemented with some extra material from recent studies (see below). I'm not convinced, from the results presented, that the AMO is necessarily the main driver of the Greenland accumulation increase seen since 1976, and would welcome a bit more analysis of this aspect. Overall the paper is important because it presents a major new dataset of Greenland accumulation and highlights some major regional differences between the RCMs and IceBridge data, that need to be reconciled in future work. It helps to identify key regions where Greenland accumulation data are relatively lacking and need to be collected.

Response: We have significantly modified the portion of the manuscript evaluating spatial and temporal variations in accumulation and their relationships with atmospheric and oceanic modes of variability. We expand the discussion of relationships with the NAO, AMO and GBI, and incorporate additional relevant references. These results are consistent with our original EOF analysis, but we think that our new discussion and figure based on correlations significantly improves the manuscript.

Comment: Specific comments:
Please use "GrIS" rather than "GIS" (Geographic Information Systems!) abbreviation for Greenland Ice Sheet.

Response: This acronym has been corrected to GrIS everywhere in the paper.

Comment: page 1, line 30: reference "Shepherd 2012" should be "Shepherd et al. 2012". I would add several further recent references here: Enderlin, E. M., I. M. Howat, S. Jeong,M.-J.Noh,J.H.vanAngelen,and M.R.van den Broeke (2014) An improved mass budget for the Greenland icesheet, Geophys. Res. Lett., 41,866–872,doi:10.1002/2013GL059010. Hanna, E., F.J. Navarro, F. Pattyn, C. Domingues, X. Fettweis, E. Ivins, R.J. Nicholls, C. Ritz, B. Smith, S. Tulaczyk, P. Whitehouse & J. Zwally (2013) Ice-sheet mass balance and climate change. Nature 498, 51-59, doi: 10.1038/nature12238. van den Broeke, M. R., Enderlin, E. M., Howat, I. M., Kuipers Munneke, P., Noël, B. P. Y., van de Berg, W. J., van Meijgaard, E., and Wouters, B.: On the recent contribution of the Greenland ice sheet to sea level change, The Cryosphere, 10, 1933-1946, doi:10.5194/tc-10-1933-2016, 2016.

Response: The reference has been corrected and additional references have been added.

Comment: p.2, l.3: supplement van den Broeke et al. (2009) reference with van den Broeke et al. (2016) (full details above).

Response: The reference has been added.

Comment: p.2, l.5 "due to complex relationships between accumulation variability and surface melt runoff" - add reference: Hanna, E., P. Huybrechts, I. Janssens, J. Cappelen, K. Steffen, and A. Stephens (2005), Runoff and mass balance of the Greenland ice sheet: 1958–2003, J. Geophys. Res., 110, D13108, doi:10.1029/2004JD005641.

Response: The reference has been added.

Comment: p.2, l.8: "preferred modes of climate variability like the NAO and AMO: add Greenland Blocking Index (GBI, Hanna et al. 2016) to these: Hanna, E., T. Cropper, R. Hall, J. Cappelen (2016) Greenland Blocking Index 1851-2015: a regional climate change signal. International Journal of Climatology, MS no. JOC-15-0742.R1, accepted/in press.

Response: This text and reference have been added.

Comment: p.2, l.13 Suggest add text in CAPS to the following: "but are too sparse to capture the full spatial variability of GIS accumulation, especially in the southeast," ALTHOUGH ATTEMPTS HAVE BEEN MADE TO INTERPOLATE ICE-CORE-BASED ACCUMULATION DATA - SUPPLEMENTED WITH COASTAL PRECIPITATION DATA - TO THE WHOLE-ICE-SHEET SCALE (BALES ET AL. 2009). HOWEVER, THIS APPROACH MAY POSSIBLY UNDERESTIMATE ACCUMULATION IN PARTS OF THE INTERIOR COASTAL MOUNTAINS OF SOUTH-EAST GREENLAND.

Response: The suggested changes have been made.

Comment: p.2, l.15 -> "more spatially distributed AND REPRESENTATIVE GIS accumulation dataset..."

Response: The suggested changes have been made.

Comment: p.3, l.6 (and throughout MS) - correct "principle component analysis" to "principal component analysis".

Response: The suggested changes have been made.

Comment: p.3, l.18: How are the IRHs related to spatial and/or temporal changes in accumulation?

Response: We have added the following text:
"We calculate accumulation between each pair of adjacent IRHs for every radar trace along the flight lines. Spatial changes in accumulation are evident from varying distances between IRHs along each flight line. Temporal changes in accumulation are evident from examining accumulation during different epochs at one location."

Comment: p.5, l.17, Equation 3: Is rho(z) the *mean* density of the respective layer?

Response: Yes, rho(z) is the mean density between IRHs. This has been clarified.

Comment: p.6, l.14: missing full stop at end of sentence.

Response: The suggested changes have been made.

Comment: p.8, l.21: "data set" -> "dataset".

Response: The suggested changes have been made.

Comment: p.9, l.29: ->"where ice cores were collected several decades ago".

Response: The suggested changes have been made.

Comment: p.9, l.31: "data poor regions" -> "data-poor regions".

Response: The suggested changes have been made.

Comment: p.10, l.10: you can’t really have a percentage of SMB as there is no absolute zero point, so I’m not sure this makes sense.

Response: These are accumulation percent differences calculated using (Model – IceBridge)/IceBridge, which we use extensively in Figure 8 and Table 2.

Comment: p.10, l.26 slightly reword to "These correlations indicate AN ASSOCIATION BETWEEN the AMO AND Greenland precipitation ALTHOUGH, DUE TO COLLINEARITY, ANY PHYSICAL RELATION COULD PARTLY BE ACTING THROUGH NAO CHANGES."

Response: The suggested changes have been made.

Comment: pp.10/11 overlap: Point out that the positive GrIS precipitation-AMO correlation, with warmer North Atlantic & Greenland temperatures, might also be due to associated storm-track or blocking changes (e.g. Hanna et al. 2013 IJOC, Hanna et al. 2016). Hanna, E., J.M. Jones, J. Cappelen, S.H. Mernild, L. Wood, K. Steffen & P. Huybrechts (2013) The influence of North Atlantic atmospheric and oceanic forcing effects on 1900–2010 Greenland summer climate and ice melt/runoff. Int. J. Climatol. 33, 862–880, doi: 10.1002/joc.3475.

Response: The suggested references to storm-tracks and the GBI have now been included in our revised section on accumulation relationships with climate modes.

Comment: p.11, l.7 "Negative correlations in the northern and western regions...are indicative of greater precipitation during NAO negative conditions..." - but there should be positive correlations for Greenland overall (Greenland precip more generally reduces under negative NAO) because negative NAO is usually linked with positive GBI (anticyclonic conditions over Greenland, which should overall suppress precipitation) - please clarify. Obviously there are well-documented regional variations of this relation.

Response: We respectfully disagree that there should be positive correlations between Greenland precipitation and the NAO overall. Box et al. (2013) found that the sign of this correlation reverses four times from 1880-2005. Hanna et al. (2011) found no significant correlation between the NAO and Greenland-wide precipitation from 1870-2009 and 1950-2009 (their Table 7). Our new figure using seasonal-annual correlations with the NAO, GBI and AMO clarifies their relationships with IB accumulation.

Our analysis of EOF2 in the context of the wintertime NAO is supported by the similar temporal variability of the wintertime NAO index and EOF2 time series (original figure 10d), and the similar spatial correlation patterns in the EOF2 vs. IB (original figure 10b) and wintertime NAO vs. IceBridge (Figure 1a below) correlation maps. A plot of the spatial correlation between IceBridge and annually averaged GBI (Figure 2 below; not in manuscript) strongly resembles the inverse of the spatial correlation between IceBridge and annually averaged NAO (Figure 1b below), which is to be expected given the strong negative correlation between the annual NAO and GBI time series (Hanna et al., 2016). In the summertime, when the NAO and GBI show their largest differences (Hanna et al., 2016), we find a weak positive correlation between IceBridge accumulation and summertime GBI (Figure 1c below) – i.e. slightly higher accumulation during summers without overall enhanced blocking. While this may seem counter-intuitive, this relationship is driven by enhanced meridional flow and moisture advection into Greenland under the weak zonal flow associated with GBI positive (NAO negative) conditions (Hanna et al., 2016). Hanna et al. (2016) similarly find enhanced precipitation in central-northern Greenland associated with positive GBI summers (their Figure 6g). They also show negative precipitation anomalies in southeast Greenland during positive GBI summers (their Figure 6g), but our IceBridge data has poor coverage in this region. Note, also, that whereas Hanna et al. (2016) compare summer precipitation to summer GBI, we are only able to correlate annual precipitation to summer GBI.

Comment: p.11, l.25 -> "used to validate THE study".

Response: The suggested changes have been made.

Comment: p.11, l.30 "we hypthesize that rising accumulation over most of the GIS interior since 1976 is related to an increasing AMO index" – rising accum. could equally well reflect changes in atmospheric circulation, e.g. a more meridional airflow on average - with more moisture laden south-westerly winds, affecting Greenland.

Response: We no longer discuss this recent accumulation rise because it is not statistically significant. The relevant figure (original Figure 11) has also been removed.

Comment: p.12, l.6: The Hanna et al. (2013) reference cited here should be for the IJOC paper referenced above, not the Nature paper - please amend.

Response: The suggested changes have been made.

Comment: p.13, l.6 : change "strongest" to "most strongly". References Box & Rinke 2003 paper has the authors' names repeated twice. Please add other author names (or et al.) of the Shepherd 2012 Science paper.

Response: The suggested changes have been made.

Comment: Table 1: add in the caption what the plus/minus figures represent.

Response: The suggested changes have been made.

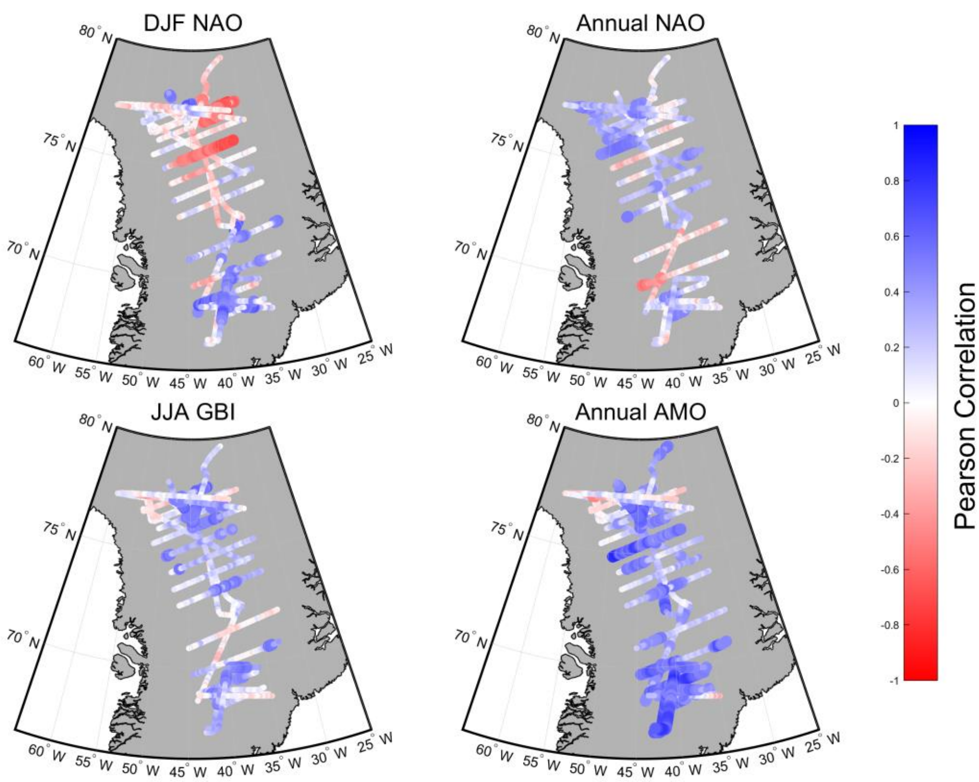

Figure 1: Pearson correlation map between 1899-2014 IceBridge accumulation and epoch-averaged climate indices. Statistically significant ($p < 0.05$) correlations are shown as larger data points. Maps show correlation of IceBridge data with a) Wintertime Jones (1997) NAO. b) Annual Jones (1997) NAO. c) Summer GBI. d) Annual AMO.

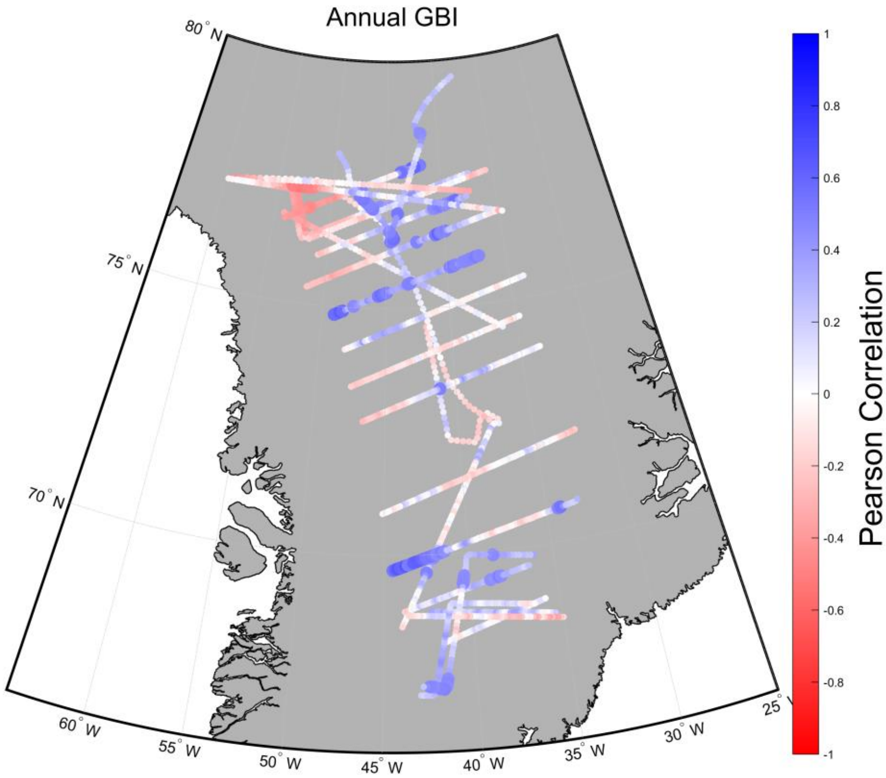

Figure 2: Pearson correlation map between 1899-2014 IceBridge accumulation and epoch-averaged GBI. Statistically significant ($p < 0.05$) correlations are shown as larger data points.