Norrköping, 2012-08-20

Response to Reviewer #1

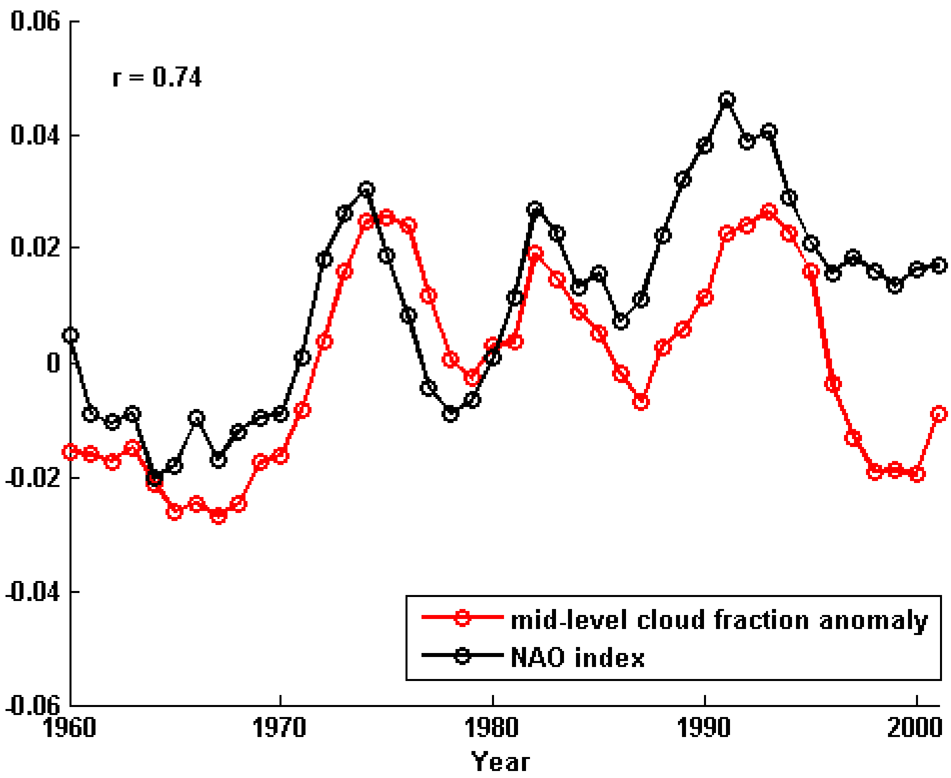
This is a nice, concise paper that investigates the how the vertical distribution of clouds in the cold season in the polar/extra-tropical region depends on the phase of the Arctic Oscillation. The cloud data come from three satellite borne instruments and the paper is a nice example of how such data can be used. I find that the paper is interesting and generally well written. However, I have a couple of major issues that the authors should consider before I can suggest that the paper is accepted.

- We would like to thank the reviewer for her/his constructive remarks given below. Please find point-by-point reply to your comments. Please note that, since we included three new figures, the figure numbers in the revised manuscript have changed.

Major comments:
a) The influence of the AO is studied by stratifying cloud data into different phases of the AO index. However, the period under consideration is brief and, unfortunately, the statistical significance of the results is not considered at all in the paper. Without indications of the significance we can not be sure that the patterns found are not just chance occurrences. When calculating the statistical significance the authors should take into account possible serial correlations in the data. Such serial correlations are present at least in the AO index and might also be present in the cloud data.

- Following the suggestion by both reviewers, we carried out statistical significance test on the AIRS data since AIRS has longer data record compared to other sensors used in the study. A new figure is added in the revised manuscript based on this result. We believe that the Greenland Cloud Dipole Anomaly (GCDA) structure is statistically significant and robust due to following reasons.
1) For each longitude-height bin, we correlated AO index with cloud fraction anomalies (please refer Fig. 12 in the revised version). These anomalies were computed by subtracting climatological mean for the study period (NDJFM 2002-2011). Interestingly, a dipole structure similar to shown in Fig. 4 is visible in correlations as well and the correlations over the dipole feature are statistically significant at 95% confidence level.
2) The dipole structure is visible irrespective of the length of data record, suggesting robustness of this feature. For example, we used satellite data for five years (CloudSat and CALIPSO; 2006-2011) and nine years (AIRS-Aqua; 2003-2011), and found the existence of dipole structure.
3) The anomalies of cloud fraction for the dipole feature based on the nine years AIRS data exceed at least one standard deviation. This is now shown in the revised Fig. 4 (old Fig. 3).
4) To check the consistency of observed correlations in the middle troposphere further at multi-decadal scales, we analyzed mid-level cloud cover estimates from the ERA-40 Reanalysis data set for 42 year period (1960-2001) over an area eastward of Greenland (15W-90E; 67N-82N), where the dipole feature is most prominent. We investigated the correlation of cloud fraction anomalies (w.r.t. climatological mean during 1960-2001, 5-

year running mean of DJF values) with the NAO index (a regional expression of AO over northeast Atlantic) and found statistically significant (at 95% confidence level) co-variation with correlation coefficient of 0.74 (as shown below). Note that the NAO index is scaled to fit into same y-axis in the plot. The NAO index is defined as: nao=(-msl(28W,64N)+msl(9W,38N))/3.e+4, msl is mean sea level pressure at the chosen geographical coordinates. 3.e+4 is the scale factor used to fit NAO index on the same y-axis.



b) I also miss some indication of how much of the cloud cover the AO "explains". To indicate this the authors could show a plot of the climatological mean cloud cover.

- A plot of climatological cloud cover is now provided in the revised version (new Fig. 3).

c) Finally, I find that the authors overestimate the similarities between the patterns found with the different data sets. To me it is not clear that Fig. 3 and Fig. 4 show the same patterns.

- There are certainly differences in these figures, especially, in the lower troposphere and in the enhanced AO case. However, please note that both of these figures show dipole feature in the middle and upper troposphere around Greenland. Considering their very different sensitivities, retrieval algorithms and the study period, we believe that the observed agreement is quite encouraging.

Minor comments:
p10307, l6: "strongest pattern" -> "most important mode".

- corrected.

p1307, l24: I don't think it is true that there is a general trend in the AO index. It might have looked so at the time of Thompson et al. 2000, but it seems to have been a premature conclusion. The AO index shows a lot of low-frequency variability. See e.g. Cohen and Barlow, J.Clim., 18, 4498-4513, 2005.

- corrected. Please see below our response to the second reviewer on similar comment.
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p10313, l14: "is observed" should be deleted.

- corrected.

p10313 and 10314: It is not clear to me what the difference is between Fig. 4 and 5. From the text (p10313, l19 and p10314, l6) it seems that both figures show ice clouds. Figures: In some of the figures the altitude is measured in hPa and in other figures in km. Perhaps a consistent choice could be made.

- (old) Fig. 4 shows anomalies for all clouds, while (old) Fig. 5 only for ice clouds. There are actually large differences between the two in the lowermost troposphere. However, since the dipole feature is so dominant in ice phase clouds, which are prevalent in the middle and upper troposphere, that these two figures look similar. This is due to the fact that the most of the contribution to total cloud anomalies at the mid- and upper atmospheric levels in Fig. 4 is coming from Fig. 5.

Response to Reviewer #2

General comments:
The authors use A-Train data to analyze the spatial distribution of clouds during positive and negative polarity of AO, and report a cloud dipole pattern around Greenland. The paper is generally well-written and provides an updated view of cloud spatial distributions.

- We would like to thank the reviewer for the constructive remarks and for pointing out a number of useful references. Please find below point-by-point reply to your comments. Please note that three new figures are included and therefore the figure numbers in the revised manuscript have changed.

My specific comments focus on the statistical significance of the results and the novelty of the principal finding.
Specific comments:
1. The statistical significance of the results needs to be assessed because the number of years available for analysis is limited. Tests will be performed at many spatial points, so issues of multiplicity necessitate establishment of field significance as discussed in the following paper and references therein:
DelSole, T. & Yang, X. (2011) Field Significance of Regression Patterns. J. Climate, Journal of Climate, American Meteorological Society, 24, 5094-5107.

- Please refer to the response given above for Reviewer #1, who raises similar question on the statistical significance of the results.

2. The manuscript seems to suggest it is the first to analyze the spatial distribution of clouds in the context of the AO or NAO (e.g., "for the first time"; line 20, page 10308). This may be the first study to use this suite of satellite data for this purpose, but much is known about the distribution of clouds under the AO or NAO, including what the authors refer to as the "Greenland cloud dipole anomaly". This result should be presented in the context of its appearance in various forms based on other data in the following and references therein:
Hurrell, J. W.; Kushnir, Y.; Ottersen, G. & Visbeck, M. (Eds.) (2003) The North Atlantic Oscillation: Climate Significance and Environmental Impact. Amer. Geophys. Union Geophysical Monograph Series (134), 279 PP. ISSN: 0065-8448; ISBN: 0-87590-994-9
Park, S., and C. B. Leovy (2000), Winter North Atlantic low cloud anomalies associated with the northern hemisphere annular mode, Geophys. Res. Lett., 27(20), 3357–3360, doi:10.1029/2000GL011609.
Previdi, M., and D. E. Veron (2007), North Atlantic cloud cover response to the North Atlantic oscillation and relationship to surface temperature changes, J. Geophys. Res., 112, D07104, doi:10.1029/2006JD007516.

Trigo, R. M., T. J. Osborn, and J. M. Corte-Real (2002), The North Atlantic Oscillation influence on Europe: Climate impacts and associated physical mechanisms, Clim. Res., 20, 9–17.
Wang, X. and JR Key (2003). Recent Trends in Arctic Surface, Cloud, and Radiation Properties from Space. Science, 299 (5613), 1725-1728. [DOI:10.1126/science.1078065]

- We would like to thank the reviewer for pointing out these useful references. Indeed, few of these studies discuss the AO or NAO variability and clouds. Below, we clarify why the present study is original.
a) None of the studies so far have shown the zonal dipole structure existing in the vertical. This is something unique about the A-Train data sets. Therefore the novel aspect here is that we have shown how the dipole structure in cloudiness manifests itself in 3D. We could precisely locate vertical and spatial extent of the dipole structure and we were able to show out-of-phase relationship between low and medium level clouds in the vertical.
b) Previous studies do not sufficiently cover the core Arctic region (Park and Leovy, 2000). They are either limited to the North Atlantic or the southern edges of the Arctic Ocean or cover only few points in the Arctic.
c) These studies are based mostly on modeling (Previdi and Veron, 2007) or reanalysis data (trigo et al, 2002) or total cloud fraction from satellite observations (2D) (Previdi and Veron, 2007).

While we are quite encouraged to find discussions from these modeling/reanalysis studies, our study using 3D cloud and thermodynamics data provides a solid observational basis for those earlier studies.

We have fully acknowledged these studies in the revised manuscript and have clarified our value addition.

3. The manuscript states that "there is no consensus on what forces the oscillations in the AO" (line 27, page 10307). Several studies published during the past decade convincingly agree that the AO and NAO arise from the dynamics of potential vorticity overturning (i.e., Rossby wave breaking and blocking). This should be noted with references to:
Benedict, J. J.; Lee, S. & Feldstein, S. B. (2004) Synoptic view of the North Atlantic Oscillation. J. Atmos. Sci., 61, 121-144.
Strong C, G Magnusdottir, 2008: Tropospheric Rossby Wave Breaking and the NAO/NAM. J. Atmos. Sci., 65, 2861–2876. doi: http://dx.doi.org/10.1175/2008JAS2632.1
Woollings T, B Hoskins, M Blackburn, P Berrisford, 2008: A New Rossby Wave–Breaking Interpretation of the North Atlantic Oscillation. J. Atmos. Sci., 65, 609–626. doi: http://dx.doi.org/10.1175/2007JAS2347.1

- This line is removed and based on the references above a paragraph is added in the revised manuscript. Few studies during the last decade attempted to provide plausible mechanisms for that bi-phasic coupled atmospheric process. Life-cycles of about two weeks of these oscillations were explained as anticyclonic (cyclonic) breaking of low frequency synoptic-scale waves, their remnants forming the positive (negative) NAO phases by Benedict et al, (2004). Further studies by Strong and Magnusdottir (2008) showed a similar result, adding that at lower latitudes the cyclonicity of waves breaking changes for the two NAO phases, while Woolings et al (2007) explain the same life cycle's two phases as a basic (positive phase) and perturbed (negative) one by variations in upper level Rossby waves breaking.

4. The text refers to the "trend in the AO" (line 23, page 10307) citing a paper from 2000. Since 2000, it has become clear that the observational record (1958-present) no longer evidences a trend in the AO, and this should be clarified in the text:
Cohen, Judah, Mathew Barlow, 2005: The NAO, the AO, and Global Warming: How Closely Related?. J. Climate, 18, 4498–4513. doi: http://dx.doi.org/10.1175/JCLI3530.1
Semenov, V. A., M. Latif, J. H. Jungclaus, and W. Park (2008), Is the observed NAO variability during the instrumental record unusual?, Geophys. Res. Lett., 35, L11701, doi:10.1029/2008GL033273.

- The text is now revised citing the above-mentioned references. Cohen and Barlow (2005) examined NAO and AO trends over the period 1958-2004 showing that, there is weak to non-existent trend over that period in spite of winter warming trend, showing the latter being unrelated to the NAO/AO. A similar result was found by Semenov et al (2008) who also showed that trends, e.g. similar to those observed in 1965-1995, can be reproduced by the model and so generated by internal variability.

5. The conclusions refer to differences in "energy and moisture transport" (line 5, page 10317), but no calculations were presented for "transport" per se.

- We agree that we do not explicitly provide calculations of energy and moisture transport per se. We believe that the combination of information, based on wind patterns from ERA-Interim, zonal temperature and water vapour anomalies from AIRS, and the height at which dipole feature is observed, makes it obvious that the energy and moisture advection is enhanced in the Northeast Atlantic during positive phases. Moreover, the latter is also independently shown in many previous studies in different contexts.

6. The CPC's AO index in Fig. 1 has already been normalized by the standard deviation of the monthly index (1979-2000 base period) as detailed here:
http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/history/method.shtml
Zero and +/- one on this index therefore have intrinsic meaning related to the mean and

standard deviation of the AO index as defined by CPC. Basing the submitted analysis on defining an additional mean and standard deviation of the already normalized index (blue lines, Fig. 1) therefore appears awkward and unnecessary. This convention should be discussed and justified above and beyond the fact that the analysis period and AO base period differ.

- We, in principle, agree with the reviewer. However, please note that we use only a subset of this time series, i.e. daily index for NDJFM months, since the AO influence is strongest during these months. Therefore, the subset was treated (from purely statistical point of view) independently for selecting only enhanced AO index values. Alternatively, one could use a fixed threshold to select enhanced values, but it is equally difficult to provide a proper physical basis for such threshold. It is important to note that, irrespective of which metric is used to define “enhanced AO index”, the scientific conclusion is least likely to change.

7. It would be helpful to include a map view of the cloud differences (vertically integrated
or sliced at a vertical level) for comparison to Fig. 8. Otherwise, the meridional averaging onto longitude-height axes limits spatial understanding of results.

- Following the reviewer’s suggestion, a spatial plot of cloud anomalies from AIRS data at 400 hPa are shown in the new Fig. 9 for the EP and EN cases. This figure clearly shows a 2D manifestation of the dipole structure, wherein positive anomalies are visible eastward of Greenland and negative westwards. The Central Siberian and Northeast Asian regions also show anomalies of opposite nature during the EP and EN phases; however, their spatial extent is not as large as over the dipole feature region in the North Atlantic.

Technical comments:
1. Vertical axes on the figures should be consistently km or hPa to facilitate comparisons.
2. The phrase "zonal vertical distribution" is not clearly defined (Abstract line 10; line 27, page 10316).

- Clarified in the revised manuscript.