Response to reviewer comments

We thank all reviewers for their helpful comments. Please find below our responses in blue.

Response to Reviewer #1

Passive microwave satellite data are frequently used to identify changes of snow properties, especially timing of melt. Mostly spring snowmelt timing is addressed in non- glaciated areas and melt days are extracted over glaciers and ice sheets. This study seeks to detect melt days over non-glaciated snow covered areas as well as investigates options for detection of snow cover (winter) start and end. A range of weak- nesses of the approach are revealed by comparison to in situ measurements. An interpretation of trends and patterns are provided but usefulness questionable (see comment below). Mid-winter patterns have been described before, as well as snow duration analyses. Kim et al. 2011 have also used SSMI to detect surface status. It is stated in the introduction that little is known about the spatial and temporal variability of winter melt events at Pan-Arctic scale (line 44). There are however a number of re-analyses studies available on this topic (e.g. Liston and Hiemstra 2011, Rennert 2009) and also from active microwave satellite data (Bartsch 2010). The observed patterns found in the presented study agree with the above studies, what is not addressed in the discussion.

We thank the reviewer for the comments but what the reviewer interprets as weaknesses in our methodology, we see as inherent limitations of the PMW sensor that are clearly noted and discussed in the paper.

We have removed Line44, and added Bartsch 2010 in the introduction and discussion. The other references are already cited in the paper. The Kim et al [2011] study was carried out for landscape Freeze/Thaw (FT) detection and they did not differentiate the FT signal coming from snow-covered versus snow-free surfaces. Their results are therefore not comparable with this study, which focuses only on snow-covered regions for winter-snowmelt detection.

There are inconsistencies regarding terminology. The title and abstract refer to 'events', the text/method to melt days. Events might be of several days of duration. In addition, only afternoon data are used. The paper thus presents an account of melt 'afternoons'. The title and abstract should be revised and adjusted to reflect this.

The algorithm does detect winter melt events, but we summarized the results as the number of melt days to avoid the issue of event splitting that can occur with the algorithm. We have now explicitly explained this strategy in Lines 190-192.

The usefulness of the trend analyses of late afternoon melts is questionable. The authors should also include the morning measurements in order to increase the detection capability. Mid-winter melt events are not bound to diurnal-variations. This would still miss out events, but increase the number of samples. Previous studies have actually chosen the characteristic refreeze-pattern instead of melt detection (e.g. Bartsch et al. 2010). Detection of refreeze allows the inclusion of very short melt events which cannot be detected themselves due to the satellite data sampling intervals.

Good point. We have included melt detection from the morning orbits and updated all the results. This has indeed increased the number of melt days in some temperate climate regions (e.g., southern Alaska and northern Europe). However, it has not resulted in much change in either the spatial distribution patterns or the trend analyses.

The abstract includes the information that results are compared to in situ measurements, but not the outcome. Especially short events from ROS are not detected, which are of major interest for wild live and climate change studies. The failure in such cases demonstrates the shortcoming of the approach to use melt only.

We have modified the abstract to include the validation results.

Bartsch et al. 2010 used the increase of backscatter to detect refreeze events from QuikSCAT. However, the record of QuikSCAT is too short for trend analyses. The increase in the spectral gradient of 19 and 37 GHz from the SSM/I data (T_BD) has been widely used for snow water equivalent retrievals [e.g., Chang et al., 1987], which is also used to determine the main snow onset date in the fall in this study. Although all the melt/refreeze events during the winter are associated with a decrease followed by an increase in T_BD (Fig. 2), not all increases in T_BD can be attributed to refreeze events (some are due to snow accumulation). Similar ambiguities apply for refreeze events detection from QuikSCAT data [Bartsch et al., 2010].

This study focuses on winter melt detection, which occurs more often than ROS [Bartsch et al., 2010; Cohen et al., 2015]. With regard to ROS, we have re-examined all events included in Table 2, and added the following to Section 3.1 (Lines 296-301):

"Out of all twelve melt events investigated, six events coincided with observed ROS. Of the six ROS events, half were associated with successful satellite detection. Those ROS events that were successfully detected were followed by a continued warming of air temperatures that likely delayed the re-freezing of the liquid water in the snow. Those ROS events that were not detected fall under the category of a short duration melt event and thus are not detectable, as described above."

How does the performance compare to melt day detection performance commonly used over ice sheets and glaciers?

Melt over ice sheets and glaciers usually occur during the spring/summer melt season (e.g., Tedesco, 2007) which is the time of year we exclude for detecting winter melt events. Thus it is not appropriate to compare the performance of winter melt detection over seasonal snow to those on ice sheets and glaciers. See also Lines 202-204.

How does the approach of melt detection compare to results from Kim et al. 2011 (SSMI) or Naeimi et al. 2012 (ASCAT)? Kim et al 2011 showed that a dynamic threshold is needed.

Kim et al [2011] used a seasonal threshold approach and optimized the threshold values using reanalysis air temperatures. In this sense, the remote sensing retrievals are 'calibrated' using air temperature information. As mentioned earlier, Kim et al [2011] carried out landscape FT detection at a global scale, and did not differentiate the FT signal from snow-covered vs snow-free surfaces. Naeimi et al. 2012 (ASCAT) only showed surface state flags of frozen/unfrozen or snowmelt, they did not show the number of melt days over the winter. Thus the results from the two studies are not comparable with winter melt day results in the current study. Our method also uses dynamic pixel-dependent thresholds to determine the main snow onset, the main melt onset, and the winter melt days. We have clarified this in Section 2.2.

Kim et al. 2012 also analyze passive microwave trend analyses for snow cover. How do patterns compare?

Kim et al [2012] used a similar approach as in Kim et al [2011] and thus did not differentiate the FT signal from snow-covered vs snow-free surfaces. Furthermore, Kim et al [2012] only showed trends for the non-frozen period (as indicated in the title), which is not comparable with the winter melt day trends from this study.

Other comments

Line 48: Semmens et al. 2013 also demonstrated the importance of fog

A reference to fog by Semmens et al [2013] is included in the revised manuscript in line 52.

Line 60: add e.g. before the list of references as there are many more studies published on this Topic
Done

Line 63: Semmens et al. 2013 also used passive microwave data. Grennfell and Putkonen also used passive microwave data

We have modified the sentence and included Grennfell and Putkonen, 2008.

Section 3.2. – results agree with Bartsch 2010

We have added this in the discussion Section.

Additional references

Kim Y, Kimball J S, Zhang K and McDonald K C 2012 Satellite detection of increasing northern hemisphere non-frozen seasons from 1979 to 2008: implications for regional vegetation growth Remote Sens. Environ.121472–87

Bartsch, A. (2010): Ten Years of SeaWinds on QuikSCAT for Snow Applications. Remote Sens. 2010, 2(4), 1142-1156; doi:10.3390/rs2041142;

Naeimi, V., Paulik, C., Bartsch, A., Wagner, W., Kidd, R., Boike, J. and K. Elger (2012): ASCAT Surface State Flag (SSF): ASCAT Surface State Flag (SSF): Extracting Infor- mation on Surface Freeze/Thaw Conditions From Backscatter Data Using an Empirical Threshold-Analysis Algorithm. IEEE Transactions on Geoscience and Remote Sens- ing. DOI: 10.1109/TGRS.2011.2177667.

Response to reviewer #2

The manuscript describes a climatology of snow melt days across the Arctic or land regions poleward of 50N using passive microwave observations. They also validate their results against reanalysis datasets and from station data/snowpit surveys. They find that snowmelt days are relatively rare (a week or less) over the winter period. They do find that snowmelt days are positively correlated with length of the winter season (defined as the period of a stable snowpack) and that there are only weak trends in snowmelt days.

This is a strong team of topic experts, a well-written manuscript and the analysis was expertly executed. The topic is of interest and the manuscript a worthy contribution to the cryosphere community and has relevance to climate change as well. I have very few comments to add to improve the manuscript. My few minor comments are listed below.

I did see that another reviewer found inconsistencies in the definition of melt events. I was not bothered by potential inconsistencies though it is probably best for the authors to clarify their definitions.

We thank the reviewer for the positive comments. We have added some additional explanation in Lines 190-192 to clarify the melt event/day issue.

I recommended that the manuscript be accepted pending minor revisions.

Minor comments: 1. Line 110 – the authors state that they filled data gaps through linear interpolation form adjacent days. However the authors mentioned above the technique for detecting water is robust because there are large variations in TB depending on the presence of water. Therefore simply linear interpolating would be problematic near dates of snowmelt?

Good point. Filling data gaps through linear interpolation from adjacent days will certainly bring some uncertainties to the detection results. However, this should have been somewhat mitigated by using both T_BD and T_B37V for melt detection (see section 2.2 Lines 156-158). In addition, the large differences of T_BD and T_B37V for days with melt and freeze conditions (Fig. 2) would limit false detection for days filled by linear interpolation.

The Kim et al. [2011] study was for freeze/thaw detection from the SSM/I data globally (thus they had more data gaps than this study). They also used linear interpolation from adjacent days for gap filling as in this study.

2. Figure 5 – in panels 5a and 5b why not show MSOD and NMOD as day of year rather than as month?

We show MSOD and MMOD as month in Fig. 5 so that it is easier to understand the spatial distribution patterns of monthly mean number of melt days described in Section 3.2 and shown in Fig. 7. In addition we describe the spatial distribution of MSOD and MMOD by months in Section 3.2.

3. Is it possible that the reanalysis products (especially ERA-Interim) in general have more snowmelt days because they are sampled four times daily and the PMW only once a day? This should be checked.

The reanalysis-based method that we employed, used the daily mean temperature to estimate melt events so the potential impact of the more frequent sub-daily sampling is dampened. We also now use both morning and afternoon overpass to detect winter melt from the satellite data, making the satellite results more comparable to those of the daily reanalysis data. Using both the morning and afternoon satellite passes results in some increase in melt days from the satellite mainly in temperate climate regions, such as southern Alaska and northern Europe (Fig. 6), however, the increases are too small to fully resolve the different melt days from the satellite and reanalysis (especially ERA-I).

4. Figure 8 – why use a temperature climatology of 1961-1990 which is colder than the period of the passive microwave data set of 1988-2013? Preferably an overlapping period should be used for the temperature climatology or even 1981-2010.

This figure was removed from the paper as it was not considered essential and the climatology can be readily generated from existing gridded observational or reanalysis datasets.

5. Figure 12 – the results presented in the figure where temperatures are warming in the fall and spring but not winter across the Northern Hemisphere landmasses is not a new result but is very similar to seasonal temperature trends shown in Cohen et al. 2012.

Reference: Cohen, J., J. Furtado, M. Barlow, V. Alexeev and J. Cherry 2012: Asymmetric seasonal temperature trends. Geophys. Res. Lett., 39, L04705, doi:10.1029/2011GL050582.

Thank you for noting. We have cited the reference in the paper.

Response to Reviewer #3

Summary: In this paper, the authors undertake an analysis of mid-winter snow melt events across land areas of the pan-Arctic domain above 50°N using microwave remote sensing. An algorithm is developed to infer liquid water in snowpacks using variations in surface brightness temperatures from SSM/I and SSMIS over 1988-2013. Mid-winter melt events are relatively rare with ≤7 occurrences (days) each year across most areas under study, with higher frequencies in temperate regions. The spatial patterns in winter snow melt events inferred from air temperature obtained from reanalysis products concur with those detected by the microwave remote sensing data. Further analyses reveal few statistically significant trends in winter melt events with the notable exception of northern Europe.

This is an interesting paper with novel results and it should be suitable for publication in *The Cryosphere* following some moderate revisions. My report provides guidance on how the paper should be revised prior to publication:

We thank the reviewer for the positive feedback.

General Comments:

1) In-text references do not follow the format used by *The Cryosphere*, i.e. round rather than square brackets should be used for references.

Square brackets are allowed according to instructions on TC website: http://www.the-cryosphere.net/for_authors/manuscript_preparation.html

2) Has validation of the proposed algorithm been performed in regions other than Canada and Finland, such as Russia and Alaska?

Yes – The algorithm was developed/validated with observations at the WMO weather stations across the pan-Arctic as shown in Figure 5b. Note the validation results using the weather station data are presented in the Data and Method Section (Lines 160-169). However, the in situ field measurements (snow survey and surface-based radiometer data) were only collected by the authors in Canada.

3) At times snow melt events occur just below the surface of the snowpack – is the proposed methodology able to detect such events?

This is probably not common during the winter. The melt detection algorithm is based on the sensitivity of microwave signal to the appearance of liquid water in the snowpack (surface or subsurface) - there is a sharp decrease in T_BD from dry to wet snow transition. Thus it should be able to detect subsurface melt events as well. However, detection of sub-surface melting is similar to a mixed-pixel effect (presumably dry/frozen surface and wet melted sub-surface), and thus would be hard to quantify at the satellite scale. Figure 4 provides some evidence that the F/T signal from uneven surface and sub-surface re-freeze likely becomes muted relative to the initial onset of melt. See the Results section on lines 281-283. We have also added the following sentence in the Discussion and Conclusions Section (Lines 378-379).

"The algorithm should also be able to detect subsurface melt events although this aspect was not evaluated in this paper."

4) The results presented in this paper focus on terrestrial snowpacks – can the methodology also be applied to snow on sea ice?

Good question. Similar channel difference approaches have also been used for snowmelt onset detection over the Arctic sea ice [e.g., Drobot and Anderson, 2001]. However, the emissivities of first-year sea ice are different than that of multiyear sea ice, and the emissivities over multiyear sea ice can have a large range due to the varied histories of the ice floes. These complicate the detection of snowmelt over sea ice, so we do not recommend the use of the algorithm developed in this study for melt detection over sea ice. A multiple indicators approach was developed in Markus et al [2009] for melt/refreeze detection over the Arctic sea ice. We have added the above to the Discussion and Conclusion section (Lines 379-386).

Drobot, S. D., and Anderson, M. R.: An improved method for determining snowmelt onset dates over Arctic sea ice using scanning multichannel microwave radiometer and Special Sensor Microwave/ Imager data, J. Geophys. Res., 106, 24,033 – 24,049, doi:10.1029/2000JD000171, 2001.

5) How reliable is the algorithm when applied to complex terrain such as the western Cordillera of North America?

Good point. The algorithm is based on the large difference of T_BD for dry snow versus wet snow (~30K), however, the range of T_BD can be much smaller (~10K) in areas with deep snow and complex terrain [Tong et al., 2010]. In-addition, changes in elevation and terrain aspect can have profound influence on air temperatures at the local scale, resulting in dramatic temperature differences over very short distances. Therefore the use of coarse resolution passive microwave satellites to detect melt events in complex terrain is not recommended. The performance of the algorithm in these areas may have a relatively large uncertainty that needs to be further evaluated. This can be an area of future work. We have added this in Section 4.

6) If only the afternoon overpasses are used to infer snow melt events across the pan- Arctic, how are melt events during other times of the day accounted for?

Good point. We have now included snow melt events from the morning overpasses as well.

7) Probability values should be reported for all correlation coefficients presented in the paper.
Done

8) The findings of recent rising air temperatures during fall (SON) with no trends in winter (DJF) and spring (MAM) across the Northern Hemisphere seem to contradict results from other studies (see Figure 12). These results should be placed into context (time period and area of interest). Why are temperature trends not reported only for the domain of study (i.e. pan-Arctic land areas above 50°N) for comparison with the snow melt analyses? Why are the seasonal air temperature trends not inferred from the Mann-Kendall test instead of linear regressions? Probability values for these trends should also be reported.

To be consistent, we have computed the seasonal air temperature trends using the Mann-Kendall test from CRUTem4 data and included the results in the text. The results are very similar to those from linear regressions. We have provided a trend map for the winter season (Figure 11).

9) Further to this, how reliable are trend analyses for a rather short (25 years, 1988-2013) period of study? Are the reported trends greater than the variability experienced over the period of study, i.e. is the signal greater than the noise in the data?

Good point. We now explicitly acknowledge this in Lines 405-408. The question of signal/noise is taken account of in the test for trend statistical significance.

10) The authors should consider suggestions for future work in the final paragraph of Section 4.

We have added a couple of sentences at the end of the final paragraph for future work.

Specific Comments:

1) P. 1, line 12: Insert “GHz” after “19”.
Done

2) P. 1, line 19: Replace “7” with “seven”.
We have replaced 7 with one week

3) P. 1, line 22: “ERA” and “MERRA” are not defined.
These are very common names, for briefness we do not define them in the abstract.

4) P. 2, line 34: Insert a comma after “events”.
Done

5) P. 5, line 104: Define “EASE”.
Done

6) P. 6, line 126: Insert “GHz” after “19” and insert a space in the second “37 GHz”.
Done

7) P. 7, line 151: Add a comma after “e.g.”
Done

8) P. 8, line 170: Change to “one week”.
Done

9) P. 8, line 195: Insert a comma after “disappearance”.
Done

10) P. 9, lines 197/198: Delete “degree” and define acronyms used here.
Done

11) P. 9, line 203: Why are 30-day moving averages of daily mean air temperatures used here for analysis?

This is to define the start and end of winter period similar as in the satellite approach. We have modified the sentence to clarify this point.

12) P. 10, line 224: Insert a space in “Table 2”.
Done

13) P. 11, line 246: Delete the space in “0°C”.

The space is required by the journal.

14) P. 11, line 248: Should this be “1 cm” instead of “-1 cm”? Replace the contraction “didn’t” with “did not” and delete the space in “0°C”.

The snow temperature is for 1 cm below the surface, so it is -1 cm. We have replaced “didn’t” with “did not”.

15) P. 11, line 250: Delete the space in “0°C”.
See above.

16) P. 12, lines 269/270: More information in the Methods must be provided on the selection of Daring Lake and La Grande IV as areas to test the algorithm to detect snow melt events. Provide for instance the province/territory where these locations are found and a brief description of their environment (vegetation, physiography, etc.) What does “La Grande IV” mean?

The specific locations/provinces of the field sites are provided in Table 2. As indicated in Table 2, the Survey Sites are named after the closest weather station while the actual survey locations are provided in lat/lon. On Line 237 it is noted that the sites are a mix of boreal forest and tundra environments. We chose these locations because of the availability of snowpit survey data with melt/ice crusts recorded in field notes.

17) P. 13, line 285: Revise to “(Figure 5c). A pixel-wise”…
Done

18) P. 13, line 286: Delete the second “winter”.
Done

19) P. 14, line 301: Insert a comma after “e.g.”.
Done

20) P. 14, lines 316 to 318: Are any of these trends statistically-significant? It is difficult to interpret linear trends when associated probability values are not provided. Figure captions for trend analyses do report a statistical significance of 90% and as such the Methods section must discuss use of this level as definition of statistically-significant trends.
We have added a sentence in the Methods Section to indicate the use of 90% level as definition of statistically-significant trends.

21) P. 14, line 319: Delete “are shown in” and insert brackets in “(Figure 9).”
We have modified the sentence to include information about the significance level.

22) P. 15, line 321: Avoid tentative language such as “tends”.
We have modified the sentence.

23) P. 15, line 323: Delete “period”.
We prefer to keep the “period” because we’re referring to the winter period duration defined in this study, which is different than the commonly used winter season (i.e. DJF).

24) P. 15, line 327: Again avoid the use of tentative language.
Done

25) P. 15, line 334: What is the probability value for the correlation coefficient reported here?

$p < 0.001$, we have added this in the text.

26) P. 15, line 336: Replace “are” with “is”.
Done

27) P. 16, line 348: Revise to “lasts”.
Done

28) P. 16, line 363: Change to “northern”.
Done

29) P. 17, line 370: Replace “which” with “that”.
Done

30) P. 17, line 383: Replace “which tend to” by “that produce”.
Done

31) P. 17, line 386: Delete “which revealed”.
We have modified the sentence.

32) P. 18, line 404: Should this be “pan-Arctic”?
We have removed this sentence.

33) P. 18, line 405: Any thoughts on possible future work that could be added here?
We have added a couple of sentences for future work at the end of the paragraph.

34) P. 18, line 409: Replace “which” by “that”.
Done

35) P. 28, Table 1: How does the change in SSM/I orbital overpass from descending (July 1988 to December 1991) to ascending affect the results presented in this study?

Note F-08 descending (July 1988 to December 1991) is for afternoon overpass, which is different than other satellites. We have modified Table 1 to include both the morning and afternoon overpass.

36) P. 31, Figure 2: Are snow pit data available for this site in Finland, as presented in Figure 3 for Manitoba?
No, we choose this site for its multiple melt/refreeze events.

37) P. 32, Figure 3: If possible, this figure should have the same format (two panels) as shown in Figure 2 for consistency between them. Are Tmin and Tmax not available for this site?

Note this figure shows hourly air temperature, so it is impossible to make it the same as in Figure 2, which shows daily air temperature.

38) P. 33, Figure 4: The caption should specify the location where these time series results apply.
Done

39) P. 34, Figure 5: How do these results compare to those presented by Choi et al. (2010)?

Choi et al. [2010] only presented time series of the average snow season duration over the Northern Hemisphere during 1972-2007, not the spatial distribution. Since both the study area and the time period are different between Choi et al. [2010] and this study, it is impossible to compare the results.

40) P. 35, Figure 6: The color scale should be identified as “Days”.
Done

41) P. 36, Figure 7: Why are results for June not presented here? Please define the color scale here as well.

Good point. Results for June are now included, color scale defined.

42) P. 37, Figure 8: What are the units for the color scale? Why are these results presented and how relevant are they to those on the detection of snow melt events from microwave remote sensing?

This figure was removed from the paper as it was not considered essential and the climatology can be readily generated from existing gridded observational or reanalysis datasets.

43) PP. 38/39, Figures 9 and 10: The text must specify what level of significance trends are reported at. Insert “Days” for the color scales here too.
Done

44) P. 40, Figure 11: What are the probability values for the correlation coefficients presented here?
We have included the significant level in the caption and text.

45) P. 41, Figure 12: This figure could be improved by using a program other than Excel for plotting. The y-axis lacks a title and units.
We have modified this figure (now figure 11).

References:

Choi, G., Robinson, D. A., and Kang, S.: Changing Northern Hemisphere snow seasons, J. Climate, 23, 5305-5310, 2010.

Frequency and distribution of winter melt events from passive microwave satellite data in the pan-Arctic, 1988-2013

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Abstract

This study presents an algorithm for detecting winter melt events in seasonal snow cover based on temporal variations in the brightness temperature difference between 19 GHz and 37 GHz from satellite passive microwave measurements. An advantage of the passive microwave approach is that it is based on the physical presence of liquid water in the snowpack, which may not be the case with melt events inferred from surface air temperature data. The algorithm is validated using in situ observations from weather stations, snow pit measurements, and a surface-based passive microwave radiometer. The validation results indicate the algorithm has a high success rate for melt durations lasting -multiple hours/days and where the melt event is preceded by warm air temperatures. The algorithm does not reliably identify short duration events or events that occur immediately after or before periods with extremely cold air temperatures due to the thermal inertia of the snowpack and/or overpass and resolution limitations of the satellite data. The results of running the algorithm over the pan-Arctic region

(north of 50º N) for the 1988-2013 period show that winter melt events~~days~~ are relatively rare totaling~~averaging~~ less than one week ~~7 melt days~~ per winter over most areas, with higher numbers of melt days (around two weeks per winter) occurring in more temperate regions of the Arctic (e.g., central Quebec and Labrador, southern Alaska, and Scandinavia). The observed spatial pattern is~~was~~ similar to winter melt events inferred with surface air temperatures from the ERA-interim and MERRA reanalysis datasets. There was little evidence of trends in winter melt event frequency over 1988-2013 with the exception of negative trends ~~decreases~~ over northern Europe attributed to a shortening of the duration of the winter period. The frequency of winter melt events is shown to be strongly correlated to the duration of winter period. This must be taken into account when analyzing trends to avoid generating false positive~~increasing~~ trends from shifts in the timing of the snow cover season.

1. Introduction

Snow cover is important in Arctic climate and ecological systems and has decreased in areal extent and duration especially during the spring period in response to rapid Arctic warming in recent decades [Brown and Robinson, 2011; Callaghan et al. 2012; Derksen and Brown, 2012]. The conventional wisdom is that Arctic warming will result in an increase in the frequency and duration of winter melt events, which may also include rain-on-snow (ROS) events. These winter melt/refreeze events modify the physical properties of snow (albedo, density, grain size, thermal conductivity), generate winter runoff [Bulygina et al., 2010; Johansson et al., 2011] and can result in potentially significant impacts on the surface energy budget, hydrology and soil thermal regime [Boon et al., 2003; Hay and McCabe, 2010; Rennert et al., 2009]. The refreezing of melt water can also create ice layers that adversely impact the ability of ungulate travel and foraging [Hansen et al., 2011; Grenfell and Putkonen, 2008], and exert uncertainties in snow mass retrieval from passive microwave satellite data [Derksen et al., 2014; Rees et al., 2010]. Winter warming and melt events may also damage shrub species and tree roots, affecting plant phenology and reproduction in the Arctic [AMAP, 2011; Bokhorst et al., 2009]. ~~However, little is known about the spatial and temporal variability of winter melt events at the pan-Arctic scale.~~

Winter melt events are rare extreme events over most of the Arctic and are sporadic in time and space [Pedersen et al., 2015]. These events are linked to intrusion of warm air from southerly or southwesterly flow, may be associated with fog [Semmens et al. 2013], rain and/or freezing rain, and typically last for several days. Previous studies [Cohen et al. 2015; Rennert et al 2009] have shown that the synoptic conditions associated with these events are closely related to larger modes of atmospheric circulation.

Microwave remote sensing measurements are very sensitive to the presence of liquid water in snow. Dry snow is a mixture of air and ice. Because the permittivity of water is much higher than air and ice at microwave frequencies, the introduction of even a small amount of liquid water (0.5 %) in snow can increase the permittivity of snow by over an order of magnitude [Ulaby et al., 1986]. This increases absorption and reduces the penetration depth, which in turn results in a large increase in brightness temperature (T_B) and decrease in radar backscatter. Satellite active and passive microwave measurements have been widely used for snow melt detection over various components of the Arctic cryosphere during the spring melt period [e.g., Kim et al., 2011; Markus et al., 2009; Tedesco, 2007; Wang et al., 2011]. Only a few satellite studies have focused on winter melt or ROS detection, and are mainly for specific regions or limited time periods ~~based on active microwave satellite data~~ [Bartsch, 2010; Bartsch et al., 2010; Doland et al., 2016; Grenfell and Putkonen, 2008; Semmens et al., 2013; Wilson et al., 2012]~~ for specific regions and limited time periods~~. Here we develop an algorithm to detect winter melt from satellite passive microwave (PMW) data over pan-Arctic snow-covered land areas north of 50º N for the period 1988-2013.

Winter melt and ROS events can also be inferred from surface weather observations [Groisman et al., 2003; McBean et al., 2005; Pedersen et al., 2015], reanalyses [Cohen et al. 2015; Rennert et al., 2009], or reanalysis-driven snowpack models [Liston and Hiemstra, 2010]. In most of these studies, winter melt events are assumed to occur when the daily surface air temperature exceeds a certain threshold. For example, Groisman et al. [2003] defined a thaw day as a day with snow on the ground when the daily mean surface air temperature is above -2º C. Inferring thaw events from surface air temperatures in this way does not consider the energy balance of the snowpack. In addition, reanalysis datasets can contain important biases and inhomogeneities over the Arctic [e.g. Rapaic et al. 2015] that will impact the spatial and temporal frequency of the inferred winter thaw events. The advantage of the passive microwave approach described above is that melt events are directly linked to the appearance of liquid water in snow which drives changes in snowpack properties relevant to Arctic ecosystems. The brightness temperature time series is also considered to be consistent over the 1988-2013 period as it is derived from near identical spaceborne sensors.

Previous studies have linked field observations of ice layer formation from ROS events with satellite measurements [Bartsch et al., 2010; Grenfell and Putkonen, 2008], but few studies have showed links between satellite measurements and in situ observations of changes in snow properties from melt/refreeze events [Langlois et al., 2012; Nghiem et al., 2014]. Passive microwave satellite data have two important limitations for detecting melt/refreeze events: the relatively coarse resolution (10-25 km) and the twice daily overpasses. Thus melt events of short duration or limited spatial distribution may not be detectable. The objectives of this study are to (1) develop an algorithm for winter melt detection from PMW data, and (2) to characterize winter melt events detectable by PMW at the satellite scale using weather station observations, surface–based PMW radiometer measurements, and snowpit surveys observed during multiple field campaigns. These PMW results are compared to winter melt detection results inferred from near surface air temperature fields from two commonly used reanalysis datasets. Trends in PMW-derived winter melt frequency over the period 1988-2013 are presented along with a demonstration of the impact on trend results of using a fixed winter period for defining the snow season.

2. Data and Methods

2.1. Satellite passive microwave data

This study uses T_B data from the Special Sensor Microwave/Imager (SSM/I, 1987–2008), and the Special Sensor Microwave Imager/Sounder (SSMIS, 2009 to present) re-projected to 25 km equal-area scalable earth-grid (EASE-Grid) available from the National Snow and Ice Data

Center in Boulder, Colorado [Armstrong et al., 1994]. These sensors provide a continuous time series of T_B since 1987 (Table 1). We do not perform sensor cross calibration given that only small differences were found between sensors [Abdalati et al., 1995; Cavalieri et al., 2012; Stroeve et al., 1998]. Since our melt detection algorithm (described below) only uses the relative change in the temporal variations in T_B, slight offsets in absolute T_B between sensors should not affect algorithm performance. The gaps in the data are filled by linear interpolation from adjacent days. Vertically polarized T_B from both morning and afternoon overpasses are utilized to increase the likelihood of observing melt events~~, rather than morning overpasses~~. Due to large temporal gaps in the early SSM/I record, the time series used begin in the fall of 1988 and extend to 2014 (Table 1). Although horizontal polarized measurements are more sensitive to ice lenses within the snowpack [Derksen et al., 2009; Rees et al., 2010], there is not much difference between the two polarizations for melt detection and we use vertically polarized measurements to be consistent with Wang et al. [2013].

2.2. Winter melt detection method for PMW

As the purpose of this study is to detect winter melt events, the winter period duration (WPD) is defined as occurring between the main snow onset date (MSOD) in the fall (beginning of continuous dry snow cover on the ground) and the main melt onset date (MMOD) in the spring (i.e. the beginning of the period with frequent melt/freeze diurnal cycles) at each pixel. Figure 1 illustrates the steps involved in detecting melt events for the WPD, based on the temporal variations in the difference of the brightness temperature (T_BD) between 19 GHz and 37 GHz and a 37 GHz T_B threshold. For dry snow conditions, as snow accumulates T_BD increases due to the larger scattering effect of the microwave signal by snow grains at 37 GHz versus 19 GHz [Chang et al., 1987]. Upon the appearance of liquid water in snow, T_B increases at both frequencies and results in a sharp drop in T_BD, to similar magnitudes seen in snow free conditions, but will quickly revert back to dry snow T_BD levels once the snow refreezes allowing for the detection of melt/refreeze events (Figure 2).

The purpose of determining MSOD is to capture the earliest start date of the continuous dry snowpack. The MSOD is determined as the first date when (1) $T_BD \geq Tsn$ (a threshold = mean July T_BD + 3.5 K) for 7 out of 10 days and (2) $T_B37v < 253$ K for 10 out of 11 days (Figure 1). The thresholds and conditions were optimized by comparing the PMW determined MSOD to daily snow depth observations from the Global Surface Summary of the Day dataset archived at the National Climate Data Center (http://www.ncdc.noaa.gov). The T_B criterion in (2) is applied to exclude periods with T_BD fluctuations related to early season freeze/thaw cycles rather than winter melt events (see below for its derivation).

MMOD is determined following Wang et al. [2013]. Their algorithm was based on temporal variations in T_BD relative to the previous 3-day average T_BD (referred as M hereafter). Melt onset was detected if the difference in M and daily T_BD was greater than a threshold (TH_{old}= 0.35*M) for four or more consecutive days. Based on trial and error, the MMOD detection algorithm in Wang et al [2013] is modified here to detect mid-winter melt events that are typically of shorter duration. Firstly, the threshold is modified slightly from TH_{old} = 0.35*M to TH_{new} = 0.4* M (pixel-dependent) since the goal is to detect melt events with one or more days of duration (instead of four or more days as in the previous study), and secondly, a T_B37v

threshold condition is added following Semmens et al. [2013] to mitigate false detection due to $T_B D$ changes not related to melt (e.g.,, from noise or artifacts from data gap filling). The resulting expression for winter melt event conditions is (M-$T_B D$) > TH_{new} and $T_B 37v \geq 253$ K for one day (Figure 1), referred as the winter $T_B D$ algorithm hereafter). The $T_B 37v \geqslant 253$ K condition was obtained by evaluating a range of $T_B 37v$ values from 250-255 K, at 1 K increments to identify the threshold most sensitive to the presence/absence of liquid water in snow. This was inferred from histograms of daily maximum (Tmax), mean (Tm), and minimum (Tmin) air temperatures for days detected as melting at all available weather stations during 2000-2007 (see locations in Figure 5b, ~5100 observations in total). The results show that for $T_B 37v = 253$ K, Tmax is ⩾ 0º C for nearly 96% of cases, Tmin is < 0º C for 94%, and Tm is ⩾ 0º C for 80%. This suggests that the PMW-detected winter melt events are consistent with diurnal positive air temperature events, while most of the events (80%) probably last multiple hours thus corresponding to days with Tm⩾ 0º C. If a melt event is detected within 10 days from the MMOD, then it is not considered a mid-winter melt event, but rather a preliminary melt event to the MMOD and is excluded from the analysis.

An example of the performance of the winter $T_B D$ algorithm is shown in Figure 2 for a case at Pudasjarvi, Finland (65.4º N, 26.97º E) during the 2013- 2014 winter. At Pudasjarvi station, the snow depth first became greater than 0 cm on day of year (DOY) 291 of 2013. The snow depth was mostly less than 10 cm for days 291 to 332, with two periods of no snow on the ground while Tmax fluctuated around 0º C. The PMW detected MSOD was on DOY332, corresponding within 1 one week of the date of continuous snow cover above 10 cm observed at the station (Figure 2b). MMOD was detected on DOY64 of 2014, however, there was still snow on the ground until DOY108, typical of high latitude snow cover where melt onset is followed by the spring thaw, which is a sustained period with high diurnal air temperature variation where the snowpack is melting during the day and refreezing at night. At the end of this melt–refreeze period, the snowpack may be actively melting both day and night until snow disappearance, which can take several weeks [Semmens et al., 2013]. During winter 2013-2014, 20 melt days in total were detected at Pudasjarvi, all corresponding to days with Tmax$\geqslant 0^{o}$ C. However, not all days with Tmax$\geqslant 0^{o}$ C are detected by PMW as melting, for example DOY351-352, for reasons which will be explained further in the validation section.

The winter T_BD algorithm is applied to time series of T_B for each winter over the period 1988-2013. Melt events may last from one to several days and in some cases the algorithm may split events. For this reason we use the annual number of melt days (rather than number of events) in presenting and analyzing the results. The WPD varies at each pixel and is determined by MSOD and MMOD as described above. This approach is referred to as "PMW-varying" in the following analysis. Since we focus on melt events during the winter period, the T_BD algorithm is only applied to pixels with MSOD detected before the end of December and with MMOD later than March 1st, i.e. with WPD > 60 days. The PMW-varying approach is internally consistent in that it takes account of annual variations in winter temperature and snow cover. This is not the case for analysis using a fixed "winter" window where spurious trends can be created from changing seasonality (i.e. earlier snow melt). To highlight this, a fixed window approach is also applied ("PMW-fixed") where the T_BD algorithm is applied to time series of T_B from November to April. The results presented in the following sections are from the PMW-varying method unless explicitly indicated otherwise. Since the microwave response of melt on permanent snow and ice is different from seasonal terrestrial snow cover, we mask out the Greenland Ice sheet and glaciers in our analyses.

2.3. Winter melt detection for reanalysis datasets

Winter melt event information from the 0.75º x 0.75º degree latitude/longitude European Centre for Medium-Range Weather Forecasts Re-Analysis Interim (ERA-I) [Dee et al., 2011] and the 1/2º latitude by 2/3º longitude Modern Era-Retrospective Analysis for Research and Applications (MERRA) [Rienecker et al 2011] reanalyses were used to evaluate the melt event climatology generated by the PMW method. Melt events in the reanalyses are inferred from 6-hourly air temperatures over the same period as the satellite data. For the comparison, a winter thaw event is defined as a period of above-freezing daily mean air temperature occurring during the winter period dominated by below-freezing air temperatures. (Here the winter period is defined by 0° C crossing dates (between fall and spring) obtained with a centered 30-day moving average of daily mean air temperature)., Thiswhich is analogous to the “PMW-varying” method described above. An additional condition is imposed of a surface snow cover of at least 10 cm snow depth for ERA-I and 4 mm SWE for MERRA to obtain results comparable to the PMW method of detection over snow covered ground. The mean daily air temperature is the average of the 00, 06, 12 and 18 UTC values. Snow depths for ERA-I are taken from the daily snow depth reconstruction described in Brown and Derksen [2013] to avoid various inconsistencies with the snow depths in the reanalysis.

2.4. In situ field observations and methods

The satellite-based winter T_BD algorithm is validated with surface–based PMW radiometer measurements along with near surface air/snow temperature observations recorded on April 12th-13th, 2010 during a field campaign near Churchill, Manitoba, Canada [Derksen et al., 2012]. A modified version of the winter T_BD algorithm is applied to the surface-based radiometer measurements due to the continuous nature of the data. We simply used the average T_B values from the stable pre-melt period as our reference frozen T_BD value instead of previous 3-day average.

Furthermore, we try to characterize winter melt events detectable by the winter T_BD algorithm using snowpit surveys recorded during multiple PMW snow measurement campaigns conducted between 2005 and 2010 in both the boreal forest and tundra environments of Canada (Table 2). The number of satellite detected melt events for the specific EASE-Grid pixels surrounding the snow pit locations are compared to the number of melt forms/ice formations identified within the snowpack. A melt feature identified lower (closer to the ground) is consider an early winter event, while those melt features identified closer to the surface of the snow are considered more recent events. An example of the coincident satellite, air temperature and snow pit information for a survey site near Thompson, Manitoba is shown in Figure 3. Hourly air temperatures from weather stations in the vicinity of the snow pits (within 70 km), are examined to identify if and when a melt event occurred in the region, how long the melt event lasted, what the average temperature was for the duration of the event and what the minimum, maximum and average 36 hour air temperatures were preceding the melt event. Results of the field evaluation are presented in Section 3.1

2.5. Other data and analysis methods

Gridded (5º x 5º) monthly surface air temperature over land areas during the study period are obtained from the Climatic Research Unit (University of East Anglia) CRUTem4 dataset [Jones et al., 2012]. Seasonal air temperature trends for the fall (September – November), winter (December – February), and spring (March – May) periods are computed to assist the interpretation of trends in winter melt events. The Mann-Kendall method is used for trend analysis taking into account serial correlation following Zhang et al. [2000]. Trends are only computed at grid cells with melt events detected in at least 12 winters, and grid cells with trends statistically significant at 90% level are shown. Correlations between the winter melt related variables are computed using the Pearson's correlation -method with significance levels determined from the two-tailed Student's *t* test.

3. Results

3.1. Field evaluation of the winter T_BD~~melt~~ algorithm

Figure 4 illustrates the time series of the surface-based radiometer T_B and air/snow temperature measurements recorded during the April 12th-13th ~~Churchill~~ melt event near Churchill. The area shaded in green highlights the period for which the modified T_BD algorithm identified the melt event. As the near surface air temperatures approached 0º C, T_B increased rapidly at both the 19 and 37 GHz. The detected melt onset occurred ~ 40 minutes after the 11 cm and 7 cm air temperatures crossed the 0° C threshold and 25 minutes before the 2 m air temperature exceeded

0° C, likely due to radiant heating from the sun to the snow surface and the boundary layer air temperature probe. The -1 cm snow temperature did not~~n't~~ reach 0° C until three hours after the detected melt onset, suggesting that the rapid increases in T_B here were responses to the appearance of liquid water in the snow surface. The influence of radiant heating ~~becomes obvious~~is evident during the late afternoon/early evening as the incoming solar radiation lessens as the sun begins to set~~, upon sunset~~ (~1900 h local), at which point the snowpack and boundary layer air temperatures all drop below 0° C, coinciding with a decrease in T_B ~~closely followed by a gradual drop in the T_B signal~~ even while the 2 m air temperatures are still positive. Compared to the rapid increase in T_B during the melt onset, the more gradual decrease in T_B is likely due to the mixed effects of uneven re-freezing of the snow surface and delayed freezing of sub-surface liquid water.

The validation results from the seven snowpit survey sites and twelve melt events ~~using snowpit data~~ are summarized in Table 2. The performance of the winter T_BD algorithm is highlighted in bold~~green~~ for a successful melt detection and in italic~~red~~ for a failed detection. The results suggest that a successful detection is likely when the melt duration lasts for periods longer than six hours and/or the melt event has been preceded by warm air temperatures that have warmed the snowpack to near melting conditions (previous day's Tmax > -3° C). In these situations, it is common for melt features to form within the snowpack. The algorithm does not reliably identify short duration melt events or events that occur immediately after extremely cold air/snowpack temperatures (previous 36 hour minimum air temperature < -13° C). In these instances, the snowpack likely has enough thermal inertia to remain within a frozen state for the whole duration of the melt event, or very quickly return to a frozen state and thus liquid water is not detectable with satellite T_B. Out of all twelve melt events investigated, six events coincided with observed ROS. Of the six ROS events, half were associated with a successful satellite melt detection. Those ROS events that were successfully detected were followed by a continued warming of air temperatures that likely delayed the re-freezing of the liquid water in the snow. Those ROS events that were not detected fall under the category of a short duration melt event as described above.

~~The winter T_BD algorithm is also not well suited to detect ROS events and the subsequent development of ice layers within the snowpack. The Daring Lake [Rees et al., 2010] and LaGrande IV melt events presented in Table 2 were coincident with ROS, but were both quickly followed by cold air temperatures leading to the re-freezing of the liquid water and were thus not detected.~~ The winter T_BD algorithm is very sensitive to liquid water within the snow, but does not necessarily capture all events that can create melt features within the snowpack, largely due to the fact that liquid water from both melt and ROS events tends to re-freeze quickly during the winter months and unless these events occur very close to the timing of the satellite overpass (ascending ~ 1830 h and descending 0630 h local time), they may remain undetected. In addition, wide-spread, spatially expansive melt or ROS events are rare [Bartsch, 2010; Cohen et al., 2015], and as such may be missed by the coarse resolution (25 km) PMW data. These limitations are common to other melt detection techniques that utilize current spaceborne passive microwave sensors.

3.2. The spatial distribution of winter melt events

Figure 5 shows the PMW-derived MSOD, MMOD, and WPD during the 1988-2013 period. On average, continuous snow cover starts in the Canadian Arctic islands and high elevation regions of the Arctic in September and progresses to the open tundra in October (Figure 5a). By November, most of the areas north of 50º N are covered by snow except for some temperate maritime and lower latitude regions where continuous snow cover sets in December. The spring main melt onset starts at lower latitudes in March, progresses to the boreal forests and tundra in April/May, and reaches the high Arctic in June (Figure 5b), giving rise to spatial variability in the duration of the winter period from one to seven months on average (Figure 5c). A pixel-wise definition of winter period for ~~winter~~ melt detection is required to account for this spatial variability as well as the temporal variability from year-to-year fluctuations in snow cover.

During the 26 winters covered by this study, melt occurred at least once everywhere north of 50º N using the PMW-varying window method (Figure 6a). However, the average cumulative number of melt days is less than one week per winter for most areas, with more melt days (around two weeks per winter) occurring in areas with a relatively long snow season and more temperate winter climates (e.g., central Quebec and Labrador, southern Alaska, and Scandinavia). The spatial distribution patterns of NMD from ERA-I (Figure 6c) and MERRA (Figure 6d) generally agree with that from PMW. However, ERA-I detects about one week more melt days on average in most areas , while MERRA detects less melt days in Quebec and central Canada relative to PMW. Both ERA-I and MERRA detect more melt days in southern Alaska and western North America (NA). These are relatively deep snowpack regions where melt may not occur in short periods of freezing air temperatures due to the thermal inertia of the snowpack. Compared to the PMW-varying window method (Figure 6a), there are many more melt days detected using the PMW-fixed window method (Figure 6b), especially in the relatively temperate climate regions (e.g., northern Europe and lower latitudes of NA and Russia) where the WPD is relatively short and thus limits the possible number of melt days to be detected.

Figure 7 shows the monthly mean NMD from October to June~~May~~ during the period 1988-2013. Winter melt events mainly occur in the fall (October-November) and spring (April-June~~May~~) months at high latitudes (>60º N) where continuous snow starts early and melts late (Figure 5). During November to March for the period 1988-2013, no winter melt events are detected across large areas of Siberia and the Canadian and the Alaskan tundra where the monthly surface air temperature ~~(SAT, from the Climatic Research Unit (University of East Anglia) CRUTem4 dataset [Jones et al., 2012])~~ is usually lower than -20º C (not shown~~Figure 8~~). On average, April has the maximum extent and duration of winter melt events (Figure 7).

3.3. Changes in snow cover and winter melt events

~~The Mann-Kendall method is used for trend analysis taking into account serial correlation following Zhang et al. [2000]. Trends are only computed at grid cells with melt events detected in at least 12 winters.~~ The PMW-derived estimates of changes in snow cover (MSOD, MMOD, and WPD) over the 1983-2013 period are shown in Figure ~~9~~8. Large regions ~~Most~~ of the Arctic exhibit~~s~~ trends to later snow onset ~~trends~~, particularly over northern Scandinavia, western Russia, Alaska, and Quebec ~~and most coastal areas~~ (Figures ~~9~~8a and 8d~~a~~). The timing of the spring main melt onset date exhibits~~tends to be~~ trends to earlier melt over most of the Arctic except for northern Europe and western NA (Figures ~~9~~8b and 8~~,~~e). The net effect is ~~As a result, there are~~

significant negative trends in winter duration period that exceed -10 days/decade over large regions of the Arctic (Figures 98c and 8,f).

Over the study period, there are few significant trends in NMD over the Arctic (Figures 109a and 9c), and where there are significant trends, these tend to beare dominated by decreases over northern Europe. The spatial distribution patterns of NMD trends contrast markedly between the PMW-varying and the PMW-fixed results (Figures 109b and 9d). Trends from PMW-fixed are dominated by increasing trends in NMD over most of the Arctic except for northern Europe. Corresponding tTrends from the reanalyses are not shown because the annual winter thaw frequency series from ERA-I and MERRA are not always consistent over the 1988-2013 period in some regions. For example over northern Quebec (not shown) the two series are well correlated over the period from 1980-2001 (r=0.75, $p < 0.001$) but diverge markedly after 2001 when numerous changes in data assimilation streams occurred in both reanalysis datasets [Rapaic et al. 2015]. This underscores the advantage of the PMW melt detection approach which is based on where a consistent T_B time series. of T_B isare obtained from near identical sensors.

4. Discussion and conclusions

An algorithm for detecting terrestrial winter melt events using satellite PMW measurements is developed and evaluated using in situ observations at weather stations and field surveys. The use of the high resolution (both spatially and temporally) surface-based radiometers and temperature profile data highlight the fact that passive microwave radiometers are particularly sensitive to minute amounts of liquid water present at the snow surface as is evident by the dramatic change in the radiometric signal observed even when the recorded snow temperature are still below 0° C. The winter T_BD algorithm is able to successfully detect winter melt events lasting for more than six hours in different environments but is less successful for short duration melt and ROS events due to the thermal inertia of the snowpack and/or the overpass and resolution limitation of the PMW data. The algorithm should also be able to detect subsurface melt events although this aspect was not evaluated in this paper. Similar channel difference approaches have also been used for melt onset detection over the Arctic sea ice [e.g., Drobot and Anderson, 2001]. However, the emissivities of first-year sea ice are different than that of multiyear sea ice, and the emissivities over multiyear sea ice can have a large range due to the varied histories of the ice floes. These complicate the detection of melt over sea ice, so we do not recommend the use of the algorithm developed in this study for melt detection over sea ice. A multiple indicators approach was developed in Markus et al. [2009] for melt/refreeze detection over the Arctic sea ice.

During the period 1988-2013, winter melt occurred at least once everywhere north of 50º N. The average cumulative melt days totaled less than one week per winter for most Arctic areas, with more melt days (approximately two weeks per winter) occurring in areas with relatively long snow season and temperate climate. Winter melt events are not detected in some areas of Siberia and the Canadian and the Alaskan tundra where the monthly SAT is usually lower than -20º C. The spatial distribution patterns of NMD are in general consistent with results inferred from surface air temperature data in the reanalysis datasets (ERA-I and MERRA) and PMW., while the detected NMDs are different probably due to biases in the reanalysis datasets and the different methodology used to infer melt events. and also with tThe spatial distribution patterns of NMD are similar to those of refreeze events derived from QuikSCAT for north of 60° N [Bartsch, 2010; Bartsch et al., 2010].

Over the period 1988-2013, large regions most of the Arctic exhibit trends to later snow onset in fall and, earlier melt onset in spring, resulting in significant negative trends in and thus decreasing winter period duration of winter period. The number of melt days was observed to be significantly positively correlated with the duration of winter period over most of the Arctic, particularly in regions where interannual variability in snow cover is higher (Figure 10). However, tThere are few areas of the Arctic with locally no significant trends in NMD over most of the Arctic except for northern Europe, where there is evidence of significant are negativedecreasing NMD trends consistent with the positive correlations between WPD and NMD over this area (as shown in Figure 10). The lack of significant trends in winter melt events observed in this study is considered to be related to the relatively short period of data available for analysis and the dynamic mechanisms generating winter melt and ROS -events thatwhich tend to produce more random and chaotic environmental response patterns [Trenberth et al. 2015; Cohen et al. 2015]. This is underscored by trend analysis of annual numbers of winter melt events in ERA-I and MERRA over a longer 1980-2014 period (not shown) where locally significant increasing trends were only observed at 1% of snow covered land points in MERRA and 2% in ERA-I. Cohen et al [2015] also found that the frequency of ROS events was correlated to large-scale modes of atmospheric circulation thatwhich contributes to regional-scale variability in ROS trends. The absence of positive winter melt trends observed in this study may also be linked to Another contributing factor to the lack of increasing winter melt trends is the seasonal pattern of warming over Arctic land areas during 1988-2013, which is dominated by warming in the snow cover onset fall period (~~September - November~~ trend=0.67°C/decade, $p<0.001$) with comparatively little warming in the winter (~~December - February~~ trend=-0,15°C/decade, $p=0.47$) and spring (~~March - May~~ trend=0.20°C/decade, $p=0.22$) period. The spatial character of winter warming over the period (Fig. 11) also shows little warming or cooling over the regions experiencing the largest NMD frequencies. This conclusion is consistent with the findings of Cohen et al. [2012].

There is field evidence of changes in snowpack density and ice layers from a number of locations in the Arctic that is supported by an increased frequency of winter thaw events [Chen et al., 2013; Groisman et al., 2003; McBean et al., 2005; Johansson et al., 2011]. However, winter thaw events in some of these studies were inferred from air temperature observations [Groisman et al., 2003; McBean et al., 2005], which are different from results detected by PMW measurements. As previously pointed out in Figure ~~10b~~9b, the frequency of winter melt events is strongly influenced by the method used to define WPD. A spatially and temporally varying definition of WPD is required as the use of a fixed window generates artificial NMD trends from changes in the timing of the snow cover season. This is further demonstrated in Figure 1~~3~~2 where monthly NMD trends are computed using a fixed WPD of November-April. The results clearly demonstrate that increases in NMD are being driven by trends during the snow cover shoulder seasons of November-December and March-April and not the main winter period. A number of studies reporting increasing NMD trends used fixed winter periods in their analyses [e.g. Groisman et al., 2003; McBean et al., 2005].

The major advantage of the PMW winter melt event method presented here is that it is based on physical processes in the snowpack (melt/freeze), unlike thaw events inferred from air temperature observations that may or may not be associated with snowpack melt processes depending on the thermal inertia of the snowpack. The PMW series is also consistent over time unlike some reanalysis datasets. Several studies have focused on the development of ROS detection methods using PMW data and encouraging results were obtained at some field sites [e.g., Doland et al., 2016; Grenfell and Putkonen, 2008; Langlois et al., 2016]. Future work will focus on the detection of pan-Arctic ice lenses (from both melt/refreeze and ROS events) by integrating PMW techniques. Additional work is also needed to evaluate the -performance of the winter melt algorithm in areas with deep snow and complex terrain where the range in T_BD for dry snow versus wet snow is likely to be much smaller [Tong et al., 2010].

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