Author Response to Anonymous Referee #1

General Comments

This study utilizes satellite passive microwave measurements to determine snow melt onset timing and duration across the Yukon River basin. Time series of these melt parameters are correlated with climate (solar flux; ENSO) and physiographic (latitude; elevation) variables in order to determine the primary influences on melt variability and trends. The paper is clearly organized and well written. The melt retrieval algorithm is de-scribed and validated in previous studies. While the work is novel, strong physical evidence is not provided for the statistical conclusions, likely due in part to the relatively short time series and small spatial domain. While the study is of interest to the remote sensing and northern hydrology communities, the lack of conclusive statements on the physical controls on melt timing limit the impact of this paper.

The melt timing trend variability for the Yukon River Basin is governed by multiple factors but dominantly by solar flux and elevation. The physical control for melt is solar radiation. Importantly, the overall pattern is toward longer melt duration for the spring snowmelt transition period which has significant implications for snowmelt runoff and associated flooding, as well as green-up and first leaf dates. Also of significance is highlighting the importance of choice of time period for analysis and the need for research studies to investigate varying time intervals in order to understand the dynamics and variability of trends. For all of these reasons, we feel that this study's impact is not inconsequential.

I hope the following comments constructively improve the manuscript.

Thank you, we appreciate your suggestions and have tried to incorporate the changes where appropriate and feasible.

1) Statements on the physical mechanisms or the variables controlling the melt trends/variability are inconclusive and speculative. Examples include: Page 716 line 13: "Moving interval trends suggest interannual variability within the time series. . ." Page 716 line 14: ". . .possibly related to El Nino- Southern Oscillation. . ." Page 724 line 17: "These alternations suggest a sub-trend cyclic pattern such as ENSO." Page 724 line 23: "(possibly related to ENSO)" Page 725 line 4: ". . .possibly related to ENSO and the solar cycle. . ." Related to this, the primary conclusions lack a clear mechanism to explain the statistical findings, with the interpretations remaining speculative. For example, page 726 lines 11-14: "The prevalence of snow in high elevations have a buffering effect on changes while lower elevation snow variability may suggest climate change susceptibility, both factors that can influence the timing trends presented here." In the absence of any snow measurements (which should be available for some locations) this is a purely speculative statement.

We are not trying to make conclusive attribution in this paper, rather our intent is to assess trends in melt timing and explore variability in the data. We faithfully present our data and acknowledge that we do make speculative statements in the discussion section of the paper as these are our interpretations. The nominal pixel size of this dataset is 25 km and scaling up from point measurements at a few locations does not dismiss the speculation in the conclusions; we are not comfortable making definitive conclusions about what is driving the trends we see in such a coarse spatial resolution and short temporal dataset because we recognize that there are sub-grid interactions and multiple processes at play.

Speculation should not degrade from the paper nor lessen its significance; rather it provides fodder for discussion and interpretation. We have not taken the reviewer's concerns lightly, and have decided to remove the power spectrum analysis and speculation on ENSO relation from the final paper. However, we would like to point out that many other studies have investigated solar activity and ENSO periodicities in natural processes from rainfall to streamflow and drought (see Fu et al. 2012 and references therein). We feel a study similar to Fu et al. 2012's streamflow analysis which would investigate the influence of solar activity and El Nino on snowmelt timing is worthwhile, but acknowledge that a much longer time series is necessary to more conclusively resolve solar activity and El Nino periodicities within the dataset.

To reflect this we added to and amended the second paragraph in the Discussion and Conclusions section as follows:
"Varying the time intervals for trend analysis enabled elucidation of inter-annual variability and sub-trends possibly related to circulation patterns; however, given the short data record we cannot conclude any causal relationship. Several studies have detected solar activity and El Nino periodicities in other natural processes from temperature to rainfall to streamflow and (Fu et al., 2012 and references therein). In particular, Fu et al. (2012) found 11 and 22 year periodicities corresponding to solar activity in streamflow records (longer than 90 years) from southern Canada, as well as shorter 3-4 year periodicities correlating to El Nino (2-7 year band). While a much longer dataset is needed, the results from this study suggest that a similar investigation of the influence of solar activity and El Nino on snowmelt timing is worthwhile for determining spatial and temporal patterns as well as the effects of climate change on cryospheric and hydrologic processes."

2) Multiple regression results are described on page 715 lines 8-11, and are reported as % variance explained (R2). This is followed by correlation results, which presumably are reported as r values (but this is not stated explicitly). There is a lack of clarity how the regression and correlation analysis were setup. While the reported correlations are significant, they are only moderate in strength (maximum r value of 0.44). I suspect the moderate statistical results are the cause of the numerous speculative statements throughout the paper (see previous comment).

We assume the reviewer means page 722 (715 is the title page). To better explain the trend and regression analyses we added the following sentences:

After the first sentence in the Trend Analysis sub-section of the Data and Methods:
"The percent of variance explained is also reported (R^2)."

After the last sentence in the Data and Methods section:
"For each dependent parameter (melt onset, end of melt-refreeze, and melt duration) multiple regression was calculated using five independent variables - average elevation, latitude, longitude, and composite (October to April for each year) anomalies for sea level pressure and air temperature at 850mb."

After the first sentence in the results section:
"Each approach is shown with trend direction depicted in color, followed by significance (from p-value) and R^2 for percent variance explained (Figures 3-5)."

The reviewer is correct that moderate statistical results lead our interpretations to be speculative. This provides further support that there are multiple processes influencing the melt dynamics with a few key factors being dominant.

3) The DAV melt retrieval technique is mature, well validated, and fully described in the literature. The nature of the algorithm however, means that only melt onset and end of melt/refreeze can be retrieved. Melt onset is a direct and useful retrieval, but the interpretation of the end of melt/refreeze variable is more problematic to me. This identifies a specific transition period in the melt process, but this is an ambiguous parameter not necessarily related to snow clearance date. The use of this variable requires justification, and an explanation of the climatological or hydrological significance.

The end of melt-refreeze relates to the timing of many hydrological and ecological processes, notably freshet, peak snowmelt runoff, and green-up which we feel is justification for its use (Figure A). The end of melt-refreeze is also positively correlated to the snow clearance date, but snow clearance depends on the amount of snow that must be melted at this transition (Figure A and B). More snow means a longer lag between end of melt-refreeze and snow free conditions, and less snow means a shorter lag (Figure B). Usually the lag is several days to a couple weeks depending on the amount of snow and melt intensity, but the active melting and depletion of snow is initiated at the end of melt-refreeze which is when snow saturation is reached and the snowpack has become isothermal.

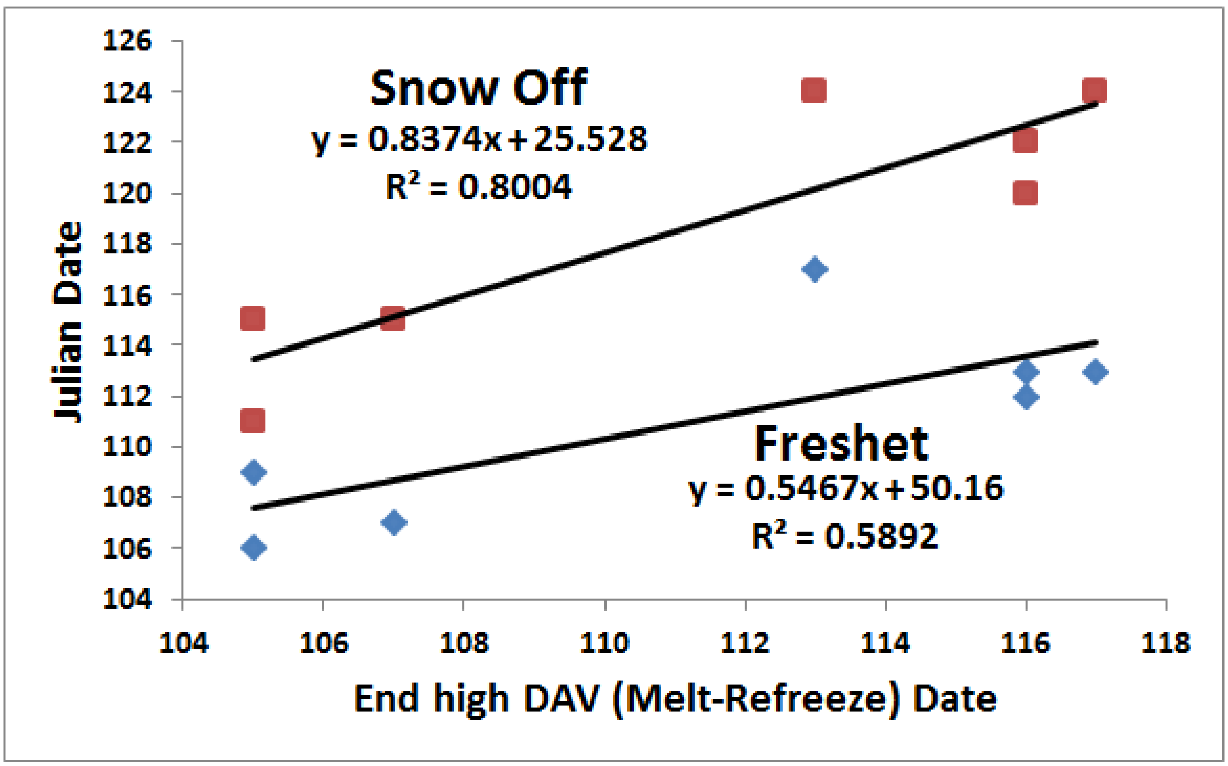

Figure A. Positive linear relationship between end of melt-refreeze (high DAV) and snow off date and freshet timing based on years 2003-2010 for a pixel encompassing Fairbanks, AK.

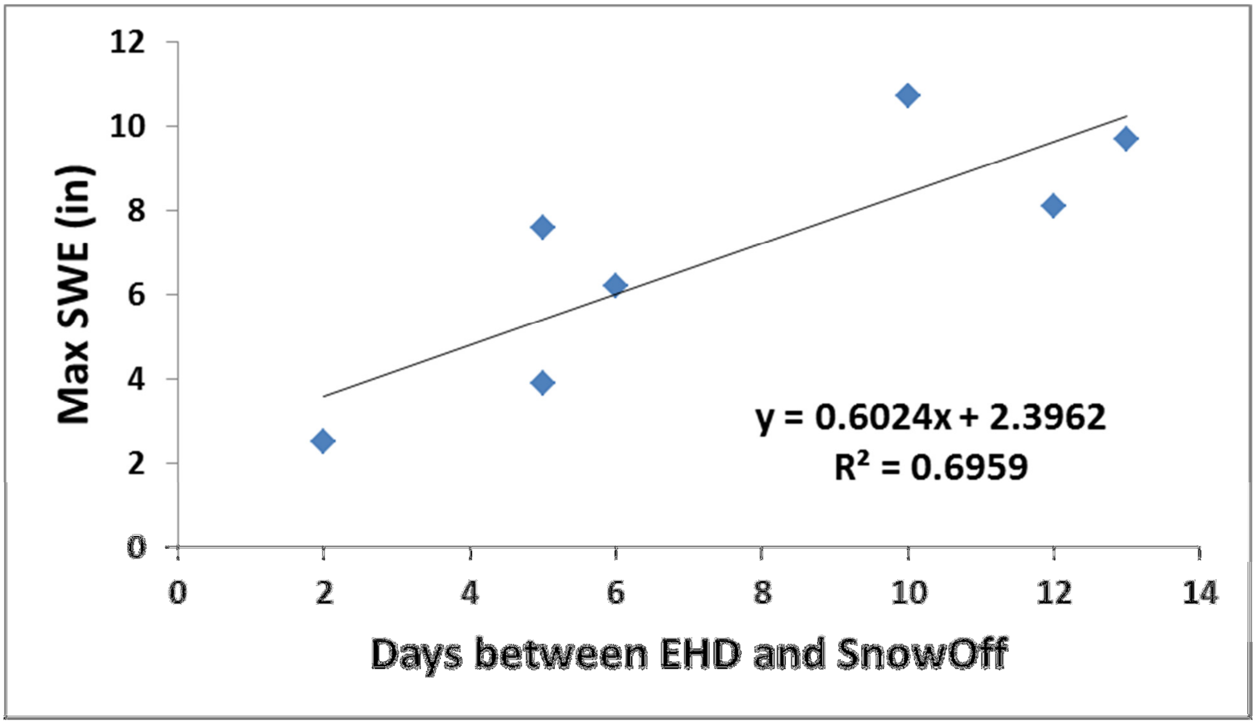

Figure B. Positive relationship between maximum SWE and the length of time between Snow Off date and the end of melt-refreeze (EHD). Snow Off date closely follows the EHD ranging from 2 to 13 days and more SWE correspond to a longer time between EHD and Snow Off. Data is for Coldfoot, AK which had SNOTEL data available to match the satellite record (data is from the National Water and Climate Center, Natural Resources Conservation Service, http://www.wcc.nrcs.usda.gov/nwcc/site?sitenum=958&state=ak).

To better explain and justify the use of the end of melt-refreeze parameter we added a new figure and several sentences as per the following:

In the middle of the third paragraph of the methods section after the sentence *"High DAV values, especially for 37 GHz sensitive to the top centimeter of snowpack, indicate when the snowpack is melting during the day and re-freezing at night (Ramage et al., 2006)."* We added:

"The end of this melt-refreeze period is of interest because its timing is closely followed by snow clearance, freshet, peak runoff, and other significant ecological processes such as green-up. This timing indicates that the snowpack is saturated and isothermal and melt occurs both day and night until the accumulated snowpack is gone, thus it is not the end of melt but rather a transition point when melt moves from intermittent to active. When the DAV is high there is a large contrast between the day and night, whereas a low value indicates less fluctuation (it is either always wet or always dry). Figure 2 illustrates how the timing of the melt-refreeze period relates to other significant events (i.e. snow clearance, discharge, and green-up)."

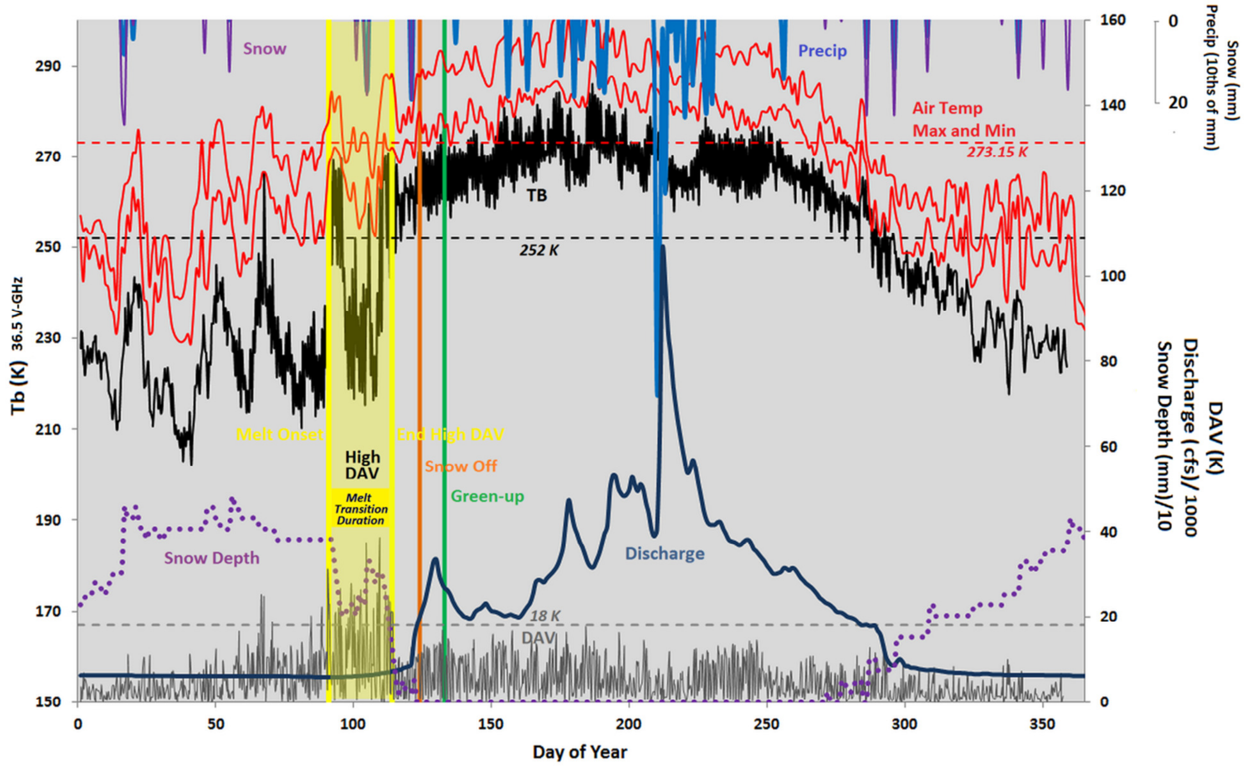

Figure 2. Illustration of the relation of melt timing variables and processes. Brightness temperatures (T_b) and diurnal amplitude variation (DAV)(from AMSR-E 36.5 V-GHz) in 2008 for the Fairbanks pixel (see label F in overview map Figure 1) in the Tanana River sub-basin of the Yukon River. T_b and diurnal amplitude variation (DAV) thresholds (set as T_b>252K and |DAV|>18K (Apgar et al. 2007)) determine dates of melt onset and end melt-refreeze (end of high DAV) which are defined as when the thresholds are met for more than three of five consecutive days. Analysis of SSM/I (data used in this study) is the same but with slightly different thresholds (246K and 10K, respectively). The end high DAV is followed shortly by snow off (10 days later), freshet (6 days later), snowmelt runoff peak (16 days later), and green-up (19 days later). Discharge data is from Tanana River at Fairbanks USGS 15485500 National Water Information System. Green-up data is from Bonanza Creek Long Term Ecological Research database. Precipitation, snow, snow depth, and air temperature are from the Global Historical Climatology Network (GHCND) from Fairbanks International Airport (64.81667 N, 147.86667 W).

4) The statement on page 717 lines 13-16 is problematic to me: ". . .with early melt, the snowmelt period may be longer, snow gradually depleted, and runoff spread out, but with late melt, the snowmelt is rapid, synchronous, and peak runoff high." It's not clear to me why early snow melt would occur over a longer period and the snowpack is gradually depleted and vice versa for late melt onset. The rate of snow melt is controlled by the intensity of the melt– early melt can still be short if temperature departures remain strongly positive.

The reviewer is correct that if temperatures remain positive then melt duration may be short even with earlier melt onset, however, with earlier melt, warm temperatures typically don't persist, but rather fluctuate. The statement comes from a synopsis of the work cited

in the literature by Woo and Thorne 2006. To address the comment and refer to the strong temperature dependency mentioned we changed the sentence in question to read as: "*Melt timing has a critical influence on the annual hydrological cycle: depending on the prevailing temperature patterns, the snowmelt period may be longer, snow gradually depleted, and runoff spread out with earlier melt, or snowmelt may be rapid, synchronous, and peak runoff high with delayed melt onset (Woo and Thorne, 2006).*"

5) It is difficult to envision how the peak periods for melt onset (Fig 2b) could differ so differently from the end of melt/refreeze (Fig 2c). The time lag between melt onset and end of melt/refreeze must only be a couple of weeks at most, and both variables are driven by temperature. But ENSO is a low-frequency phenomenon, so conceptually I find it difficult to meaningfully interpret how ENSO could influence those variables differently.

The data shows that the peaks are different and we faithfully report those data findings. While our conclusions may be too speculative for the reviewer they are reflective of the fact that there are many interdependent processes influencing the melt duration. In contrast melt onset is dominantly controlled by solar flux (as well as elevation). The end of melt-refreeze is more sensitive to a variety of climatic forcings, notably precipitation, temperature, and local weather patterns which may be influenced by the prevailing ENSO phase. However, given the brevity of the time series we have decided to remove the power spectrum analysis component from the final paper.

Editorial Comments

Page 719 line 2: what is meant by 'diminished snow cover'? This is a vague term that can be interpreted as lower snow depth or earlier snow melt.

This was changed to *"diminished snow cover extent".*

Lines 123/124: . . ."a measure of the dynamism of the snowpack. . ." This might be a little picky, but the DAV is actually a measure of the dynamism of the brightness temperature, which can be interpreted as a proxy of the dynamic response of the snowpack emissivity to changing liquid water content.

The quoted line referenced by the commenter is not in this paper. Page 721, line 2 states *"DAV, which is a proxy of the dynamism of the snowpack as liquid water content changes".* To clarify, we amended the sentence as *"DAV, which is interpreted as a proxy of the dynamism of the snowpack as the liquid water content changes."* We feel that this adequately describes DAV as an interpretation.

<u>**References**</u>

Apgar, J.D., Ramage, J.M., McKenney, R.A., and Maltais, P.: Preliminary AMSR-E Algorithm for Snowmelt Onset Detection in Subarctic Heterogeneous Terrain, Hydrological Processes, 21, 1587-1596, 2007.

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