Author Response to Anonymous Referee #2

General comments:

The authors present an analysis of spatial and temporal trends in dates of melt onset and end of melt over the Yukon River Basin from SSM/I passive microwave brightness temperature data over the period 1988-2010. The literature has seen a number of papers exploring this theme in recent years (e.g. several papers by Takala and colleagues not referenced in this paper; Tedesco et al, 2009; Wang et al. 2011) so this reviewer was wondering what new insights this paper might possibly provide. In the introduction the authors' explanation of the uniqueness of the paper is that the focus on a river basin permitted "a more detailed investigation of trends and governing factors, especially elevation differences". The authors hypothesis, if I understand it correctly [lines 10-11, page 719], is that trends will differ based on elevation, and that documenting this is important for understanding the hydrological response of the region to warming (the latter connection is nicely summarized and presented in the Introduction).

Ok so now we have a glimmer of hope that this paper will do something more than just report trends over a short period of satellite data. However, there's a bit of a problem the authors divide the basin up into 200 m elevation classes but the satellite pixels are 25 km x 25 km. We then learn that the methodology employed [lines 19-25, page 721] assumes that the terrain is relatively homogeneous. The authors dismiss most of these problems as mainly pertaining to passive m/w estimates of snow water equivalent and happily continue without any attempt to ground-truth the ability of their method to function correctly over the study domain and resolve the elevation-dependencies they are looking for. At this point, further discussion of the paper is largely irrelevant because I now have serious questions about the credibility of the results.

I have added a few specific comments below, but you cannot expect to publish a paper focused on documenting elevation-dependencies in trends when there are known issues with the data in mountainous terrain, when your study resolution is two orders of magnitude smaller than the satellite, and where no attempt was made to ground truth the data.

We appreciate the concerns of the reviewer, but feel that the results are credible and of relevance. We have tried to address the majority of the comments below and have added many of the references suggested by the reviewer. With regard to the ground-truthing comment, the detection of melt with passive microwave (especially using 37 GHz vertical) has been well documented in previous studies (see Ramage et al. 2006, Tedesco et al. 2009). Additionally, the majority of the basin (72.6%) is lowlands/plains, not mountains. We also screened out pixels containing glaciers (which tend to be at higher elevations). With regard to the study resolution comment, we feel the reviewer has misunderstood the dimensionality of the study. Elevation is in the z range and its accuracy would depend on the resolution of the DEM. The entire study resolution is not two orders of magnitude smaller, rather the basis of the study is by sub-basin (Porcupine, Stewart, etc.) with areas much larger than the pixel size (encompassing hundreds of pixels), which remains the case even when separated into elevation class as we are averaging within a basin across the entire elevation band. This is not to say there is not uncertainty or a small degree of error in this methodology, but in our view this averaging across large spatial areas (much greater than the pixel size) and the fact that the melt signal is distinct and previously validated/ground-truthed should serve to alleviate the concerns brought forth.

Specific comments:

1) There is no evidence of any ground-truthing, a major oversight that you share with Yang et al (2009).

The melt onset and end DAV algorithms were ground-truthed in previous papers (Ramage et al. 2006, Apgar et al. 2007) albeit for a smaller area which may not be representative of the entire basin, however, it still provides some validation of the brightness temperature melt signal. Furthermore, only 27.4% of the Yukon River Basin is mountain range, the rest (72.6%) is wetland, plains and lowlands (Brabets et al. 2000) so for the majority of the basin the issues related to high mountains are not an impediment, and more so due to the fact we filtered and excluded glacier pixels (which tend to be higher elevations) from the analysis. We added the phrase *"and validated"* to the first sentence in the third paragraph of the Data and Methods section: *"SSM/I data and the technique for detecting snowmelt timing has been previously established and validated in the upper YRB using 37GHz vertically polarized data."*

2) The definition of the variables is not clear. A diagram showing the temporal evolution of the brightness temperature and the corresponding snowpack properties would help. You also need to be more precise in the text. For example, the following phrase gives the impression that the end of the melt-refreeze period corresponds to the snow-off date. It corresponds to the date when the snowpack is isothermal. [Page 717, lines 5-9] The timing of this high diurnal variation period of melt-refreeze affects the progression of meltwater through a basin, corresponding to the snow off date"

The sentence referenced was changed to read: *"The timing of this high diurnal variation period of melt-refreeze (when the snow is fully saturated and the snowpack isothermal) affects the progression of meltwater through a basin, as its timing is closely followed by the snow off date (which is usually a few days to weeks later dependent on maximum snow accumulation), freshet timing, and peak snowmelt runoff, and is closely linked to green-up and growing season start (Cayan et al., 2001; Schwartz et al., 2006; Wang et al., 2011)."*

In order to make the variables more clear and to be more precise about the melt-refreeze period we added a figure showing the relation of the different datasets and variables over a year for a representative pixel that encompasses Fairbanks, for which there is consistent ground data available (streamflow, temperature, precipitation, and snow depth). In the middle of the third paragraph of the Data and 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)."

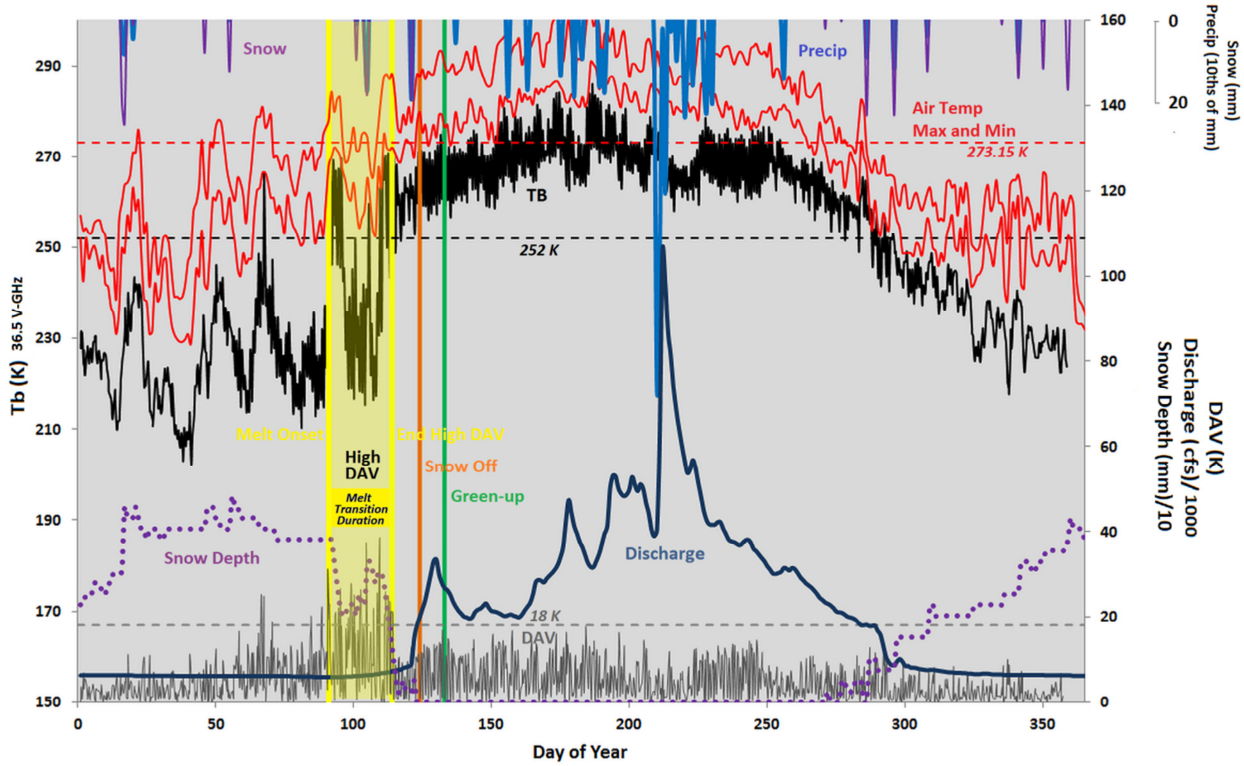

Figure 2. Illustration of the relation of melt timing variables and processes. Brightness temperatures (T_b) and diurnal amplitude variation (DAV)(from AMSR-E 36.5 V-GHz) in 2008 for the Fairbanks pixel (see label F in overview map Figure 1) in the Tanana River sub-basin of the Yukon River. T_b and diurnal 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).

3) The methodology was not presented for the power spectrum analysis e.g. what windowing was used, what method was used to identify significant frequencies. It would be instructive to show an example plot of the computed power spectrum with the associated confidence intervals.

The discrete Fourier transform of the data was done using standard IDL routines; the code and two example plots (one with confidence intervals) are provided below (Figure C and D) but since this level of detail would be extraneous in the paper we did not amend the paper to include these details. Additionally, we decided to remove the power spectrum analysis from the final paper due to the limited confidence such a short dataset confers with this type of analysis.

IDL program to transform time series of melt timing to frequency domain and determine peak periods

*****y is an array with the time series of melt onset date for a given basin/elevation class
dft=fft(y) ;fft transforms time series to frequency domain
mag=abs(dft) ;the magnitude is the absolute value of the discrete fourier transformation
pwr=mag^2 ;power spectra
n_positive_modes=n/2 ;positive Fourier modes (n is the number of elements)
frequency=findgen(n_positive_modes)*(1.0/23) ;frequency vector of the positive modes. The fundamental frequency is (1.0/23) which is 1.0/period where period is n* sampling interval (# of years)
frequency_nodc=frequency[1:n_positive_modes-1]
pwr_nodc=2.0*pwr[1:n_positive_modes-1]
p=plot(frequency_nodc,pwr_nodc,/xlog,/ylog,xtitle='Frequency($years^{-1}$)',ytitle='Spectral Density',view_title='Power Spectrum of MOD 1988-2010') ;plotting spectral density
peak=max(pwr_nodc,i_peak) ;peak frequency
frequency_nodc_peak=frequency_nodc[i_peak] ;locate the peak
peak_period=1/frequency_nodc_peak ;inverse of peak frequency gives the period of the cycle
;arrays to hold the results
peakarray[j]=peak ;array that holds the peak
freqpeakarray[j]=frequency_nodc_peak ;array that holds the frequency at which the peak occurred
period[j]=peak_period ; array that holds the peak period
CI_low=df/chisqr_cvf(0.975,df)*pwr_nodc ;low confidence interval
CI_high=df/chisqr_cvf(0.025,df)*pwr_nodc ;high confidence interval

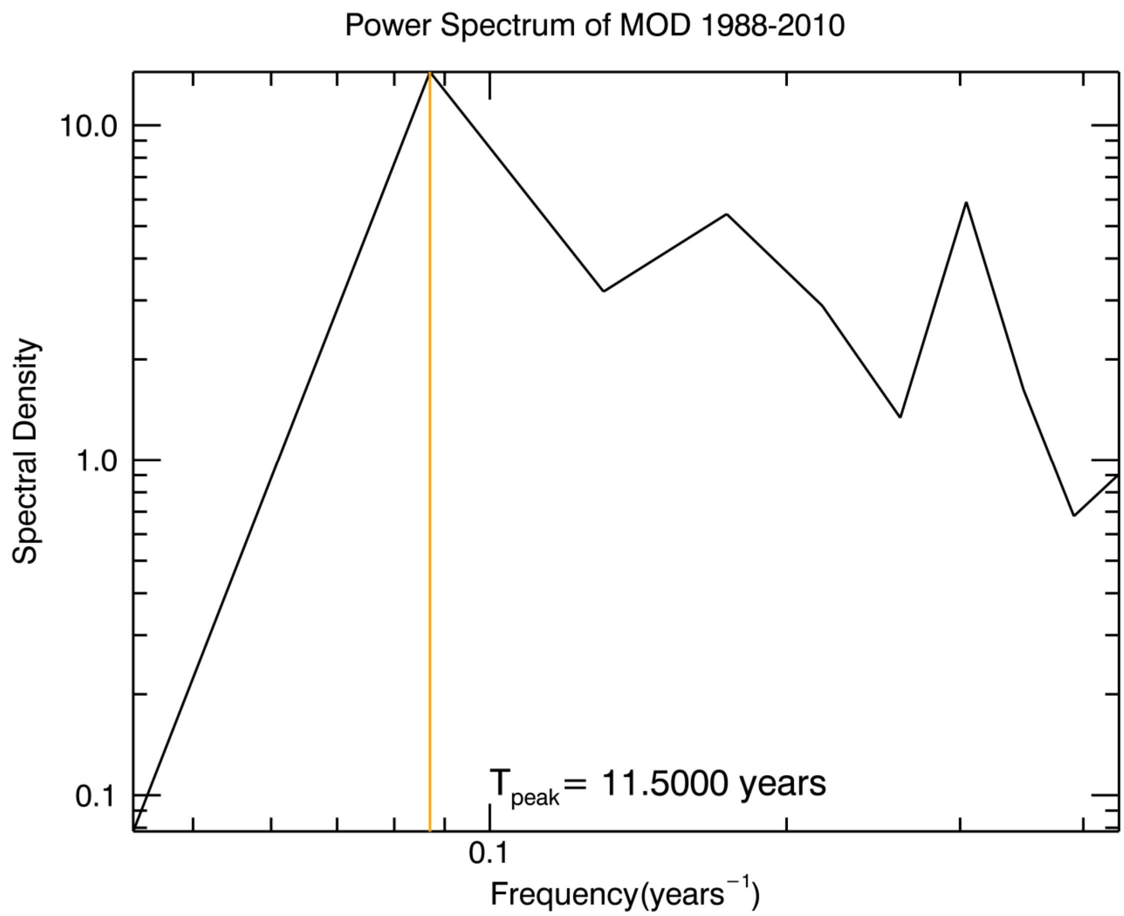

Figure C. Example of the spectral density from the power spectrum analysis for melt onset averaged for the Chandalar basin for the years 1988-2010.

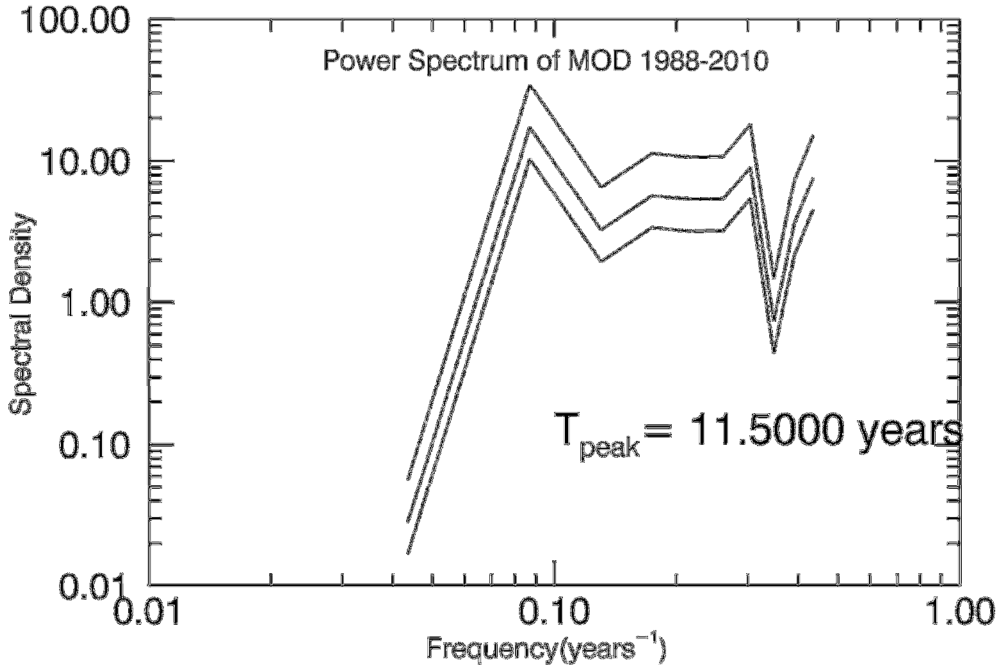

Figure D. Example of power spectrum results with confidence intervals for average melt onset of one basin and elevation class (Upper Yukon Sub-basin for 801-100 m elevation class).

4) There is no justification provided for the selection of 7-years for the moving trend analysis. I do not find this to be very useful as it amounts to a verbal description of a filtered time series. This is the first time I have ever encountered the term "sub-trend". It might be more interesting to look for break-points using statistical tests for homogeneity but even then your time series is rather short for trend analysis. You could get around this shortcoming by placing it in a longer context using downscaled climate station or reanalysis data.

Several other windows (3 years, 5 years, and 10 years) were explored. The same sub-trend patterns were seen. 7-years was observed to be the least noisy and was used for the analysis. The purpose of this time interval approach was to have a smaller moving window through the time series in order to explore the dataset's sub-trends, which we feel is adequate for this analysis. We clarified this in the Results section after the sentence, "*To get a sense of the sub-trends affecting the longer term trends, a 7 year moving interval window was used for analysis where each column is the trend for the 7 year time period starting with each year from 1988 to 2003.*"
By adding, *"Other interval windows (10, 5, and 3) were also considered and showed similar results; 7 years was chosen as the least noisy."*

5) Fig 1: I had to zoom this 500% to read anything. The plot titles are confusing as they are placed along the x-axis. What does the black colour mean? It is not shown in any legend. I think the results would be easier to understand if you provided contour maps of the gridded output (it would also get rid of the need to identify all the sub-basins).

As mentioned in the Figure caption, the black color indicates there is no data for that basin and elevation. We added this to the legend key. The contour map suggestion is a good one but we feel that the current visualization works best for showing the trend, its significance, and r-squared. To address the zoom and plot title issues we have redone the figure, separating it into three separate (and larger) figures. Please see the revised submission for the changes. An example of the new size and caption for one of the three panels from the original figure is shown below (the other two figures show the moving window trend intervals, and the varying trend intervals but the figure set-up and size is similar to this one).

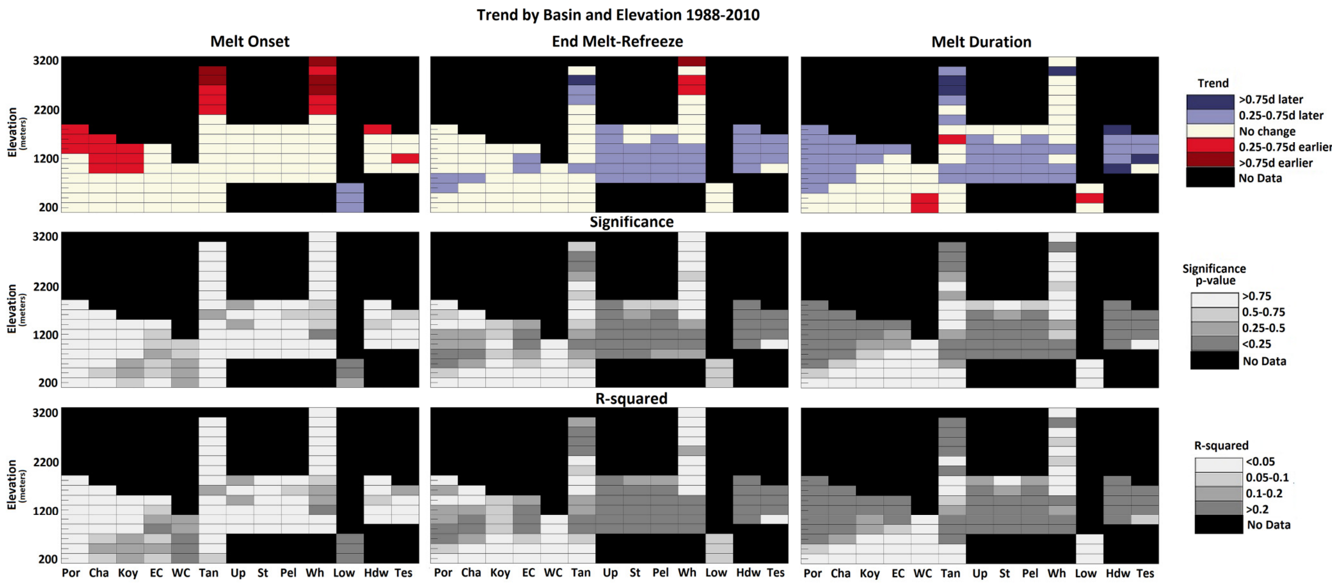

Figure 3. Spatial and temporal trends (each basin (x-axis) and elevation class (y-axis)) for melt onset (left column), end melt-refreeze (center column), and melt duration (right column). In each column, top plots are the direction and magnitude of trend (red is earlier melt and blue is later melt timing). Middle plots are the significance of the trends - p-value of student's t-test (darker is more significant). Bottom plots are the R2 values (darker is higher R2). Black indicates no data for that basin and elevation. Basins are arranged from highest to lowest latitude (left to right). Labels for basins are as follows: Por=Porcupine, Cha=Chandalar, Koy=Koyukuk, EC=East Central, WC=West Central, Tan=Tanana, Up=Upper, St=Stewart, Pel=Pelly, Wh=White, Low=Lower, Hdw=Yukon Headwaters, Tes=Teslin.

6) Fig 2a is too small and does not readily convey information on the absolute elevation ranges over the basin**.** Figs 2b and c. I suspect the differences in peak cycle are probably noise, given the relatively short period of data, the lack of information on the method for determining significant frequencies, and no clear physical explanations for the differences in frequencies. If the authors really want to make a contribution to understanding the elevation response of snow to climate variability and change there is a large volume of literature they should consult, none of which is cited in this paper e.g. Beniston, Hantel, Phil Mote, Stewart, Rangwala

I'm also unclear how useful this information is. The frequency analysis was not identified as a key objective in the introduction and there are no examples given in the text outlining what this information contributes to. Over northwestern NA one might expect to see PNA and PDO signals in melt-related variables based on previous work. However, my experience with frequency domain analysis of snow cover is that the results are dominated by decadal and multi-decadal variability with few robust relationships between snow cover and atmospheric teleconnections.

Our intent in this paper was not to contribute to understanding the elevation response of snow to climate variability, rather to look at trends and variability in melt timing across a wide spatial domain and investigate the signals within these trends for which we were utilizing the power spectrum analysis. Thus, the power spectrum/frequency analysis was not a key objective rather a means to investigate the dataset. We feel that the solar cycle frequency that is found as a peak period in many of the basins for melt onset is not noise, but a consistent, clear signal that we would expect given the dependency of melt intensity on solar radiation. The 5-7 year peak periods seen in the end of melt/refreeze period is also a consistent signal across the majority of the YRB, which suggests to us this is not entirely noise (although we grant there may be some noise in the dataset). This provides us with an understanding that the timing of these (melt onset and end of melt-refreeze) are dominantly influenced by different processes, with melt onset influenced by solar radiation, and consequentially, elevation; and end of melt-refreeze, or snow saturation, by a complexity of factors probably including weather, precipitation, and circulation patterns (affected by ENSO). We agree with the reviewer that PNA and PDO would also be atmospheric circulation pattern signals that we would see affecting melt timing, but the brevity of our dataset precludes the discrimination of these longer cycles.

We have decided to remove Figure 2 and the power spectrum analysis due to the brevity of the dataset, though 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:

"In this study, 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 (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 the research presented here 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."

We also moved Fig. 2a to Figure 1 as an overview map and digital elevation model of the basin and made it larger and clearer.

Further we have added several of the references mentioned by the reviewer: Rangwala and Miller 2012; Mote 2003; Beniston et al. 1997; Regonda et al. 2004; Takala et al. 2011.

We added several sentences to the text discussing this literature and elevation dependencies, including adding this as the second paragraph in the Discussions and Conclusions:

"The spatial variability of the melt timing trends may reflect variations from incoming solar radiation or differential warming rates dependent on elevation. Several high elevation climate records have shown temperature changes (especially seasonal warming rates) greater than the global average, suggesting future climate change may be more apparent in these areas (Beniston et al., 1997). Others suggest the 0°C isotherm locates the areas of strongest warming rates possibly a result of snow/ice albedo feedbacks (Pepin and Lundquist, 2008; Rangwala and Miller, 2012). While an "elevation-dependent" climate response is observed and modeled in many studies, there is large variability both spatially and temporally due to the complexity of mountain systems (Rangwala and Miller, 2012). The prevalence of snow in high elevations may have a buffering effect on changes while lower elevation's snow variability may suggest climate change susceptibility (Rice et al., 2011), both factors that can influence the melt timing trends presented here. In addition, atmospheric circulation patterns and increasing fractions of precipitation falling as rain instead of snow may be factors affecting the trends in melt timing."

This sentence at the end of the Results section:

"Additionally, trends in SWE were found to be elevation dependent (suggesting temperature as the dominating factor) (Mote, 2003), and hydroclimatological variables were found to exhibit elevation gradients in a majority of studies (Regonda et al., 2004; Rangwala and Miller, 2012)."

This sentence at the end of the Introduction section:

"Further evidence of elevation dependency is seen in the earlier shifts in the timing of peak streamflow that vary by elevation in the western United States with the strongest trends at elevations less than 2500m (Regonda et al., 2004) and in the declining trends in April 1st snow water equivalent (SWE) in the Pacific Northwest that are elevation dependent (Mote, 2003)."

7) Fig 3. This also looks like noise again, how robust and useful is this information?

The correlations are significant (p<0.001) over 0.6, significant over 0.5 (p=0.015), and significant for 0.41 (p~0.05), from a two-tailed correlation significance test for degree of freedom of 21). A line was added to the plots to indicate significance and melt-refreeze and melt transition duration plots added. We feel this information is useful for investigating the importance of solar activity's influence on snowmelt processes.

References

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.

Beniston, M., Diaz, H.F., and Bradley, R.S.: Climatic change at high elevation sites: an overview, Climatic Change, 36, 233-251, 1997.

Brabets, T.P., Wang, B., and Meade, R.H.: Environmental and hydrologic overview of the Yukon River Basin, Alaska and Canada, USGS Water-Resources Investigations Report 99-4204, Anchorage, Alaska, 2000.

Cayan, D.R., Kammerdiener, S.A., Dettinger, M.D., Caprio, J.M., and Peterson, D.H.: Changes in the onset of spring in the western United States, Bulletin of the American Meteorological Society, 82, 399-415, 2001.

Fu, C., James, A.L., and Wachowiak, M.P.: Analyzing the combined influence of solar activity and El Nino on streamflow across southern Canada, Water Resources Research, 48, W05507, 2012.

Mote, P.W.: Trends in snow water equivalent in the Pacific Northwest and their climatic causes, Geophysical Research Letters, 30, 12, 1601, 2003.

Pepin, N.C. and Lundquist, J.D.: Temperature trends at high elevations: Patterns across the globe, Geophysical Research Letters, 35, L14701, 2008.

Ramage, J.M., McKenney, R.A., Thorson, B., Maltais, P., and Kopczynski, S.E.: Relationship between passive microwave-derived snowmelt and surface-measured discharge, Wheaton River, Yukon, Hydrological Processes, 20, 689-704, 2006.

Rangwala, I. and Miller, J.R.: Climate change in mountains: a review of elevation-dependent warming and its possible causes, Climatic Change, 2012, doi: 10.1007/s10584-012-0419-3.

Regonda, S.K., Rajagopalan, B., Clark, M., and Pitlick, J.: Seasonal cycle shifts in hydroclimatology over the western United States, Journal of Climate, 18, 372-384, 2004.

Rice, R., Bales, R.C., Painter, T.H., and Dozier, J.: Snow water equivalent along elevation gradients in the Merced & Tuolumne River basins, Sierra Nevada, Water Resour. Res., 47, W08515, 2011.

Schwartz, M.D., Ahas, R., and Aasa, A.: Onset of spring starting earlier across the North Hemisphere, Global Change Biology, 12, 343-351, 2006.

Takala, M., Luojus, K., Pulliainen, J., Derksen, C., Lemmetyinen, J., Karna, J-P., Koskinen, J., and Bojkov, B.: Estimating northern hemisphere snow water equivalent for climate research through assimilation of space-borne radiometer data and ground-based measurements, Remote Sensing of the Environment, 115, 3517-3529, 2011.

Tedesco, M., Brodzik, M., Armstrong, R., Savoie, M., and Ramage, J.: Pan arctic terrestrial snowmelt trends from spaceborne passive microwave data and correlation with the AO, Geophys. Res. Lett., 36, L21402, 2009.

Wang, L., Wolken, G.J., Sharp, M.J., Howell, S.E.L., Derksen, C., Brown, R.D., Markus, T., and Cole, J.: Integrated pan-Arctic melt onset detection from satellite active and passive microwave measurements, 2000-2009, J. of Geophysical Research, 116, D22103, 2011.