Author Response to Anonymous Referee #3

1) The authors have conducted an interesting study using satellite passive microwave data to examine snow melt in the Yukon basin. They identify melt onset, the end of the melt/refreeze interval and the duration between onset and interval end. They seek trends, frequencies and periodicities within sub basins. While a useful contribution to the literature there are weaknesses to the manuscript that warrant attention. These are discussed below.

We appreciate the reviewer's comments and have tried to address the weaknesses as discussed below.

2) A better introductory discussion of what is meant by melt-refreeze is needed. It must be made clear that this is not the end of melt. Rather it marks a point at which the snowpack no longer freezes (most likely at night). Just how far into the melt season does this occur? How does this vary by latitude and altitude within the basin? This could be examined by comparing the cessation date with runoff. Also, it should be further discussed whether a longer duration of the melt onset to end of melt/refreeze is a function of an earlier onset and/or a later end of melt/refreeze.

The reviewer is correct that the end of melt-refreeze is not the end of melt, rather it is the end of a melt transition period where the snowpack goes from melting and refreezing at night to actively melting until snow clearance. It is at this point that the snowpack is isothermal and saturated. The longer duration of this melt transition duration is both a function of earlier onset and later end of melt-refreeze. To amend the paper to better clarify what is meant by melt-refreeze we have added the following lines:

In the Data and Methods section at the end of the third paragraph 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)."

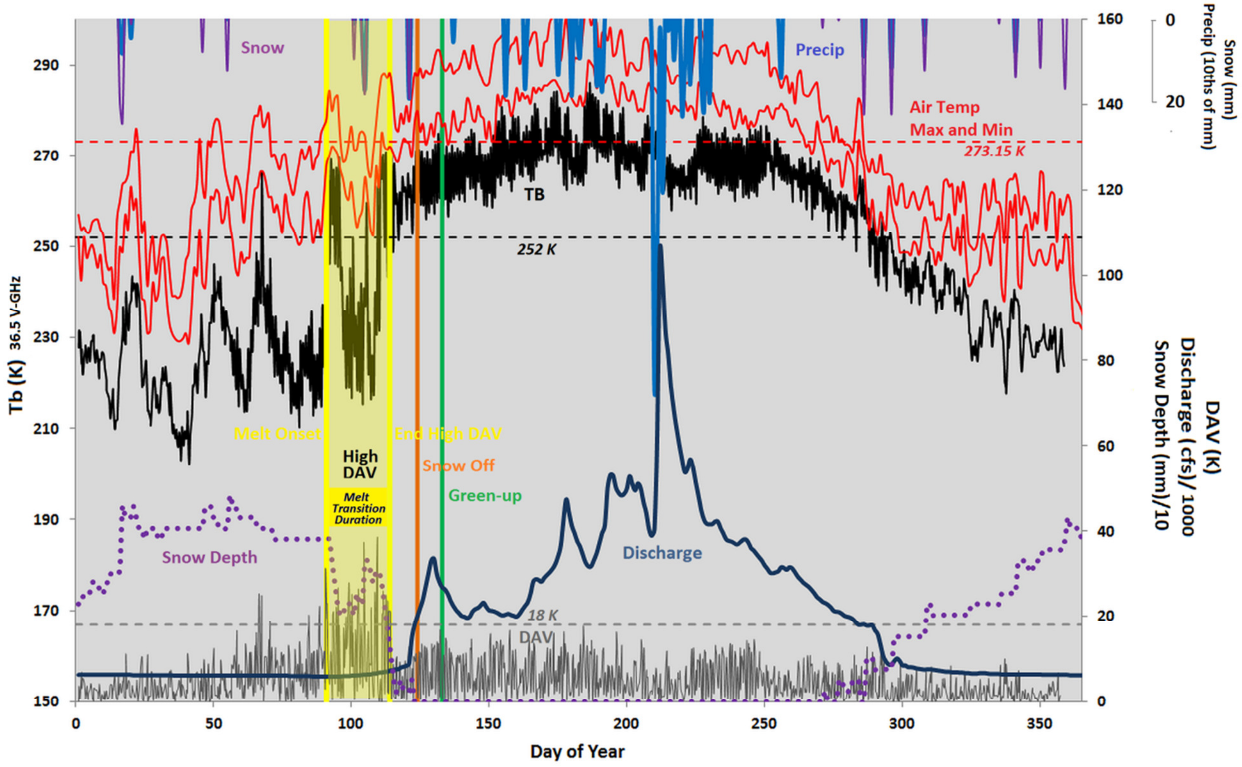

Figure 2. Illustration of the relation of melt timing variables and processes. Brightness temperatures (T_b) and diurnal amplitude variation (DAV)(from AMSR-E 36.5 V-GHz) in 2008 for the Fairbanks pixel (see label F in overview map Figure 1) in the Tanana River sub-basin. T_b and diurnal amplitude variation (DAV) thresholds - snowpack is melting when T_b>252K and |DAV|>18K (Apgar et al. 2006) - determine dates of melt onset and end melt-refreeze (end of high DAV), defined as where thresholds are met for more than three of five consecutive days and early melt events (thresholds met before onset for short duration). Analysis of SSM/I is the same but with slightly different thresholds (246K and 10K). 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).”

At the end of the first paragraph in the Results section after the sentence, *“Longer melt duration trends are significant and occur throughout the YRB with the exception of no change in the lowest elevations.”* We added: *“Melt duration is a function of both earlier melt onset and later melt/refreeze, depending on the sub-basin and elevation class.”*

3) I have serious concerns regarding the power spectrum results. To state a possible relationship to an 11 year solar cycle with only 23 years of data is highly suspect. I would refrain from such a mention or at least couch it in the frame that I have suggested.

The reviewer brings up a good point and we have decided to remove the analysis due to the brevity of the time series. We feel that the removal does not significantly detract from the main purpose (trend analysis and exploration of variability of melt timing variables in a large river basin) and conclusions (latitude and elevation strongly relate to melt timing and there are significant trends in melt transition duration).

4) A question from a review familiar with microwave-snow studies but not a practitioner. Would using a multi-channel approach provide any additional evaluative assistance?

The reviewer brings up a great question regarding multi-channel approaches. We focus on the 37 GHz vertically polarized channel due to its high sensitive to surface wetness. This is most useful for determining the melt-refreeze period from the diurnal amplitude variations (DAV). DAV calculated for the other channels have more noise and are less sensitive to melt as can be seen in Figure E below. For the purposes of distinguishing the DAV the single channel approach has worked well and we do not feel including multiple channels will add significantly to the evaluation.

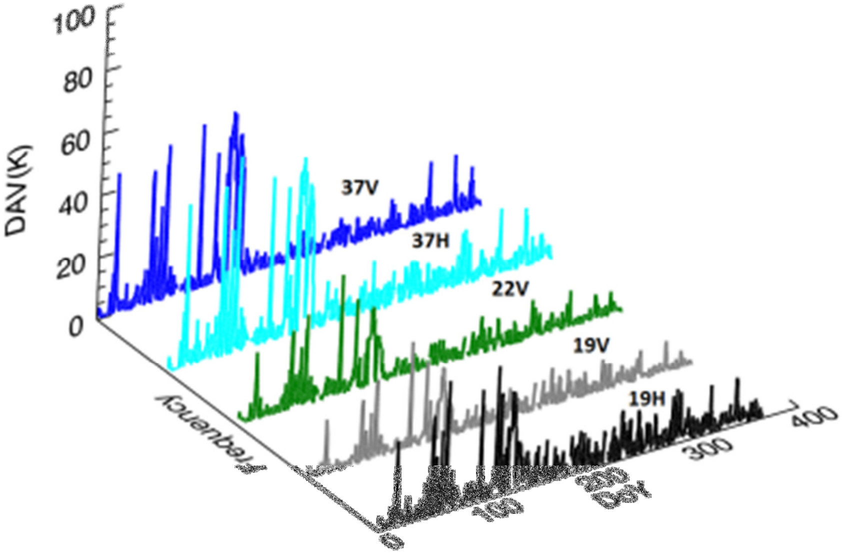

Figure E. Diurnal Amplitude Variations (absolute values) calculated from multiple brightness temperature channels for a pixel in the Yukon River Basin for 2009.

5) Also might corrections with changes in instrumentation have an impact on the timing of the threshold exceedences? Couldn't this impact dates by a fair bit at times?

We discuss the potential correction for transition between sensors quite a bit in the text of the paper (second paragraph in the Data and Methods section). Given the amount of error that may be introduced in any such correction/adjustment and based on a manual inspection of the time series for several pixels (see Figure F below for an illustration), we decided not to correct for transitions. In addition we are averaging the timing parameters over basins and elevation bands so we reason errors from instrumentation will be minimal, although we acknowledge the potential for some biases. Others have used a similar approach, making no adjustments when combining SSM/I data (Takala et al. 2011). Further, the DAV part of the analysis should be insensitive to sensor change as the methodology subtracts out any bias.

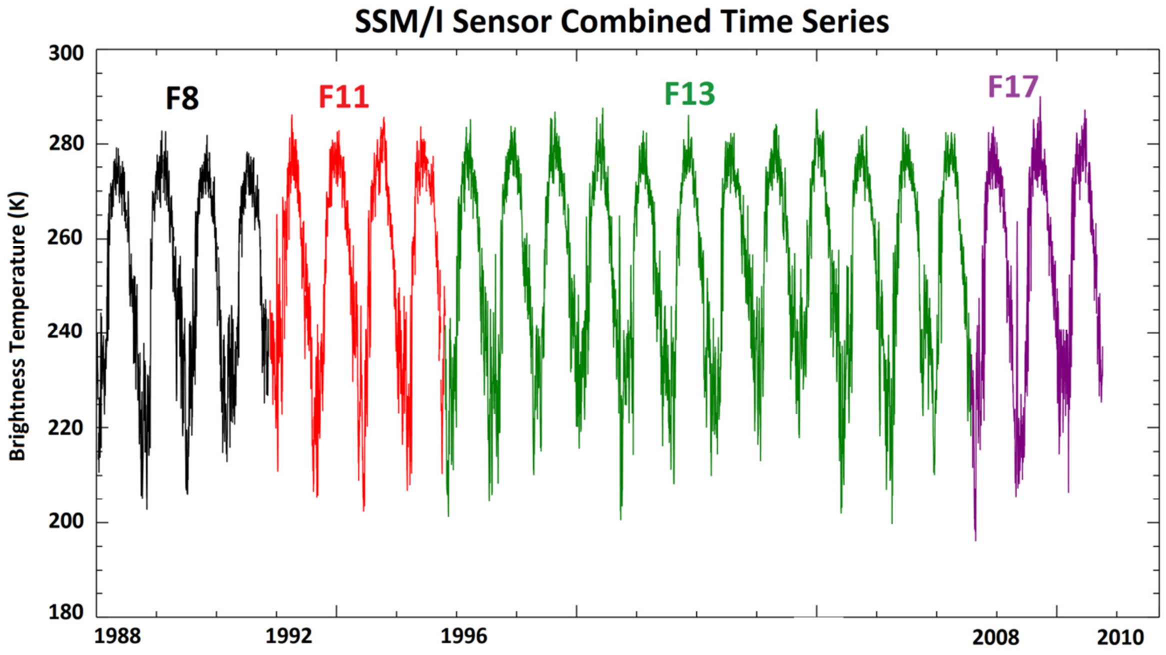

Figure F. Combined time series for one pixel in the Yukon River Basin of SSM/I brightness temperatures with the different sensors denoted with different colors. We acknowledge the potential bias/error from sensor transition but reason the effects are minimal and have not adjusted the time series.

6) How are basins in Alaska most sensitive to winter increases in temperature (as suggested with the Nijssen et al reference on page 717, line 2)? Clearly, unless you are discussing potential increases in snowfall in this region associated with warmer temperatures there isn't a good reason for this. This is certainly the least important of the comments I've made.

We state *"Projections for the middle of the 21st century include: increases in average air temperatures of 3° C for the Arctic by 2040, increases in precipitation in mid to high latitudes leading to overall deeper arctic snow cover, and increases in snowmelt and runoff for cold regions (Adam et al., 2009). The snowpack integrates effects of changes over several months, resulting in the strongest shifts to the hydrological cycle predicted for the early spring melt period; especially since snowmelt dominated basins are the most sensitive to temperature increases in the winter (Nijssen et al., 2001)."*

We emphasize snowmelt dominated basins as most sensitive since changes to snowpack accumulation and melt onset timing will affect the hydrology in early spring. Stone et al. (2002) found earlier melt in Alaska which is attributed to diminished snowfall and warmer temperatures in spring. This reference was added to the paper to better support the previous statements. After the fifth sentence in the Introduction we added:
"Some shifts are already being identified with spring snowmelt in northern Alaska advancing since the 1960s due to warmer temperatures and diminished snowfall, of importance to the surface radiation budget due to the resulting changes in albedo (Stone et al., 2002)."

In addition we added this after the Nijssen reference:
"For instance, Regonda et al. (2004) found shifts (advancing) in the timing of streamflow for snowmelt-dominated basins in the western United States over 50 years, as well as a decrease in snow water equivalent and increase in the fraction of precipitation as rain instead of snow. These trends reflect increases in spring temperatures and increases in winter temperatures and precipitation leading to diminished snowpack (Mote, 2003)."

References

Adam, J.C., Hamlet, A.F., and Lettenmaier, D.P.: Implications of global climate change for snowmelt hydrology in the twenty-first century, Hydrological Processes, 23, 962-972, 2009.

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.

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

Nijssen, B., O'Donnell, G.M., Hamlet, A.F., and Lettenmaier, D.P.: Hydrologic sensitivity of global rivers to climate change, Climatic Change, 30, 143-175, 2001.

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.

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.

Stone, R.S., Dutton, E.G., Harris, J.M., and Longenecker, D.: Earlier spring snowmelt in northern Alaska as an indicator of climate change, Journal of Geophysical Research, 107, D10, 4089, 2002.

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.