Summary:
Many thanks to each of the reviewers for their thoughtful comments on this work. We have attempted to address each concern as completely as possible given the time constraints for the manuscript revision. We acknowledge that many of the data sources are not ideal for this type of experiment, however, Antarctica is a region that is poorly-instrumented and we have used the most appropriate data sources available. The information gained by surface melt magnitude retrieval is important as surface melt can be a primary mechanism for ice shelf collapse and is currently a phenomenon that is poorly understood. Microwave-based assessments of surface melt provide only binary melt/no melt information, whereas our approach will give a surface melt magnitude. Even if the melt magnitude is poorly constrained, it still provides valuable information about the ice shelf that is not otherwise available.

The reviewers asked us to examine the melt magnitude retrieval model's sensitivity to precipitation grain size, differing uncertainties in downwelling solar radiation, and sensitivity to changes in albedo. We have found that SNTHERM89 is relatively insensitive to precipitation grain size (a doubling of grain size results in a less than 0.01% liquid water fraction decrease). Using an uncertainty of 20 W/m^2 for the radiation uncertainty results in a 22% change in liquid water fraction. As this is a smaller uncertainty that the previously reported uncertainties for +/- 5% changes in solar radiation, and reviewer #2 has suggested that reported downwelling solar radiation values from NCEP/NCAR reanalysis may vary by as much as 100 W/m^2 we have chosen to maintain the original reported uncertainty values, which represent an average uncertainty in radiation of approximately 35 W/m^2. Even a doubling of reported liquid water fractions (such as would be obtained with a 5% uncertainty of downwelling solar radiation) at low values such as seen in this study area would correspond to a difference from 0.5% LWF to 1% LWF. This would still discriminate between low surface melt events (such as were mapped in this study) versus more significant melt events in the 10% LWF range such as were observed by Lampkin and Peng (2008).

Sensitivity to changes in albedo appears to be the most significant previously unaccounted-for uncertainty. This is linked to uncertainty in downwelling shortwave radiation as well as reflected shortwave radiation. Decreases in albedo exponentially affect liquid water fraction, with changes in albedo of 10% causing a three-fold increase in the liquid water fraction modeled by SNTHERM. This provides a high-upper-end uncertainty bound on albedo. Uncertainty in albedo is likely to be much smaller than this, however, because the ice surface is typically not contaminated by significant amounts of particulate matter. More realistic changes in albedo on the order of 1% would affect liquid water fraction by a much smaller amount, on the order of 10% (meaning a 0.5% LWF value would vary between 0.45% and 0.55%). Again, while in absolute numbers this seems like a large amount, it still allows for the determination of LWF values with a degree of certainty that can discriminate between low (0-2%) LWF events versus larger (5-10%) LWF events.

The primary remaining issues for the reviewers appear to be the lack of ground-based validation, and poorly constrained radiation inputs to SNTHERM89. We have attempted to control for these issued with a broad suite of sensitivity analyses and comparisons to other methods of detecting surface melt, specifically XPGR. While the end result is an admittedly poorly-constrained estimate of surface liquid water fraction, there is still information that is not currently obtainable through any other assessment of surface melt conditions. While this is an empirically-based study, the physical relationship between shortwave IR reflectance, grain size and surface melt has been extensively studied and has already been used as a proxy for surface liquid water fraction over Greenland (Lampkin and Peng, 2008). The addition of surface temperature as a portion of the melt magnitude retrieval model is twofold in that it helps account for 1) the non-linear response of grain size to conditions other than surface melting; and 2) helps ensure that melt is actually occurring because a low surface temperature will reduce the retrieved LWF value.

The relationship between melt magnitude retrieval presented here corresponds well with passive microwave assessments of surface melt over the same time period. When no surface melt is detected by XPGR, liquid water fractions are generally less than 0.5%. During times when surface melt is present in the XPGR, higher liquid water fractions are retrieved. These correspond well both spatially and temporally between both assessments of surface melt conditions.

Reviewer #1:

1. Section 5: In words is explained how the calibration is performed, and a flowchart is given. Indeed a similar method has been used for Greenland (Lampkin and Peng, 2008), but given the poor quality of elements of the data, just this description is not enough. Include a full, clear and conclusive discussion and evaluation of the model results and the subsequent regression. Now the reader has to trust you that it works.

   Objective: To further clarify the methodology used in this study
   Solution: A section has been included describing the methodology in greater detail, including the elements of data that differ from Lampkin and Peng (2008).

2. Section 6: The Antarctic Summer is short, so it contains only a few 8-day intervals with melt. If you really want to show that this method works, extend the analysis over several years.

   Objective: There are few composite periods in which melt has occurred, so there is a need to expand the study period over multiple years.

Solution: We are in the process of refining our technique using an addition melt season later in the MODIS record that will be incorporated into a forthcoming manuscript detailing an Artificial Neural Network calibration of MODIS imagery to retrieving surface melt magnitude on Antarctic Ice Shelves. Including another season within this analysis was not possible due to the time constraint on the revisions for this manuscript.

3. Figure 7: Mean LWF_{eff} for certain XPGR Melt Duration is not very informative. Provide probability distributions of LWF_{eff} for each XPGR melt duration. Then more insight is given about the prediction performance. For example, for most no-melt days XPGR observations, one expects a LWF of zero.

   Objective: More information is necessary regarding the XPGR comparison.
   Solution: This information will be added to the final manuscript as a replacement for Figure 7.

4. Figures 8, 9, 10: Why do all the sensitivity tests not extend over the whole analysis period?

   Objective: To get a reasonable sensitivity of SNTHERM to various meteorological forcings over the study period
   Solution: When meteorological inputs to SNTHERM89 are modified, they may cause output results that are not physically reasonable. In cases where too much solar radiation was used as an input into SNTHERM89, SNTHERM89 was unable to process the large amounts of liquid water that were generated in the model, causing the model to fail. Therefore sensitivity results are unavailable after large pulses of liquid water have been generated by SNTHERM89. However, we have been able to present SNTHERM89 output prior to the generation of large melt pulses, which indicated the sensitivity of SNTHERM89 to each forcing parameter.

5. Section 7: Please Explain how the Relative Uncertainties (Table 2) are determined and what they mean. If it is indeed a 2.8% uncertainty on the estimated LWF_{eff} values, thus 0.01% to 0.02% LWF's then it is too low to be realistic.

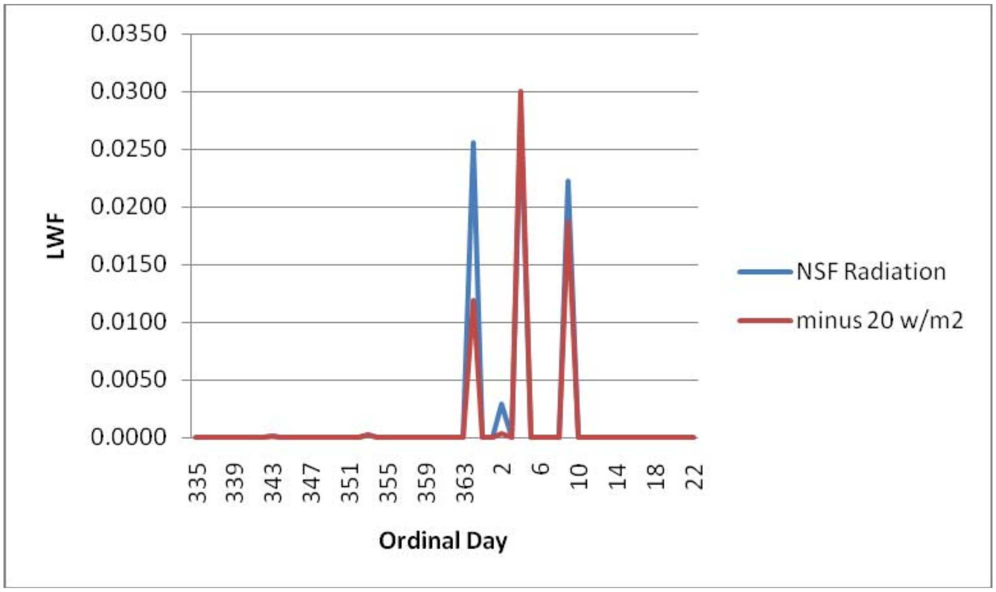
   Objective: To provide a clearer explanation of the errors associated with the SNTHERM89 forcing as well as instrumental error from various sources.
   Response: The 2.8% value was unclear; this refers to a LWF uncertainty of 2.8%, so a reported LWF of 1% could range from 0% to 3.8%.

6. Section 7: Section 4.3 section is not very clear about the method to get a reasonable SW estimate. I conclude from it that there is significant uncertainty related to it. Please clarify section 4.3 and add the results of sensitivity tests for SW radiation, including albedo, in section 7.

   Objective: Shortwave radiation over the entire solar spectrum was not available for the study period. An approximation of this measurement was essential for the forcing of SNTHERM89.
   Solution: Downwelling shortwave radiation was determined by doubling the measured amounts from the NSF UV/Vis radiation measurements that are measured for wavelengths of 290-600nm. Data from the NSF UV/Vis project does not account for all of the downwelling shortwave radiation over the entire spectrum. As a first-order approximation, a factor of 2 was applied to the measured radiation over the 290-600nm wavelengths. This accounts for the radiation that is downwelling in the wavelengths longer than 600nm that were not measured by the NSF radiation monitoring network. The albedo from NCEP/NCAR is calculated as follows: (reflected solar out)/(downwelling solar in), and it is applied as a scale factor to the NSF UV-Vis radiation to provide the missing “reflected solar out” component that is not measured at the NSF study site, but is necessary as an input to SNTHERM89. In addition, we have performed another sensitivity analysis to see the effects of changing the albedo by 10% on the SNTHERM89 output. This has been added as another figure to the final manuscript. Section 4.3 has been edited as suggested, and sensitivity tests for albedo have also been added to the analysis.

7. I would assume that the uncertainty on downwelling LW radiation is more than 5%, many models have 20 W/m^2 biases. Figure 9 shows that for 5% deviations the LWF changes a factor of 2. Surprisingly this gives a relative error of 1.4%. More importantly and once again, please explain how this error estimate is obtained.

   Objective: To characterize the otherwise-unbounded uncertainty in downwelling shortwave radiation
   Response: Uncertainties of 5% in downwelling solar radiation represent as much as a 35 W/m^2 bias. Sensitivity tests using a fixed value of 20 W/m^2 have been performed in addition to the 5% sensitivity test. A reduction in solar radiation by 20 W/m^2 results in a 22% reduction in LWF amounts. This sensitivity is lower than the previous reported sensitivity for 5% fluctuations in incoming solar radiation; therefore the original sensitivity test is presented in the final manuscript. Results of the 20 W/m^2 sensitivity test are presented below:



8. Section 8/Figures 11 and 12: I don't see the added value of the discussion of the meteorological conditions for melt. If you want to investigate why melt events occur on the Ross Ice Shelf, you need more than only wind fields that are only on 2.5 degree resolution.

   Objective: To indicate the physical processes that are responsible for surface melt conditions, explaining ties to future work and as justification for the broader impacts of this study without detracting from the main purpose of this paper, which is to describe a method of surface melt magnitude retrieval
   Response: The original submission contained more information on meteorological conditions of the Ross Ice Shelf, but was shortened to provide more of a focus on the melt magnitude retrieval. This is not intended to be an exhaustive study of the meteorological conditions that affect surface melting, but rather insight into future work that will more thoroughly examine the relationship between synoptic and mesoscale meteorological forcing and local surface melt conditions.

Reviewer #2:
For absolute melt amount from MODIS to be calibrated in a useful way (AND to determine whether calibration is possible at all) requires accurate determination of actual melt at the surface and liquid water content in the subsurface snow layers. To do that requires an accurate determination of all components of the surface energy budget (net shortwave radiation, net longwave radiation, turbulent fluxes of sensible and latent heat, subsurface heat flux). Because melting in Antarctica is usually weak and short-lived (around noon in summer only), i.e.

associated with small energy fluxes (~10-50 W m-2), these terms must be determined with high accuracy, better than ~5-10 W m-2, to be able to determine their sum and hence melt energy and rate.

Objective: You have brought up some valid points about the necessity to resolve several energy flux parameters with a high degree of accuracy and precision, which are certainly key limitations in the calibration technique we have outlined.
Solution: While not all of the forcing inputs used in our study are of ideal quality, they provide the best available data for a region that is poorly-instrumented. What we have attempted to do, in order to compensate for poor data quality, is to provide an honest assessment of the uncertainties caused by each of the inputs into our model, as it is our view that an assessment of surface melt magnitude with high uncertainty is more useful than no assessment of surface melt magnitude at all.

Moreover, they must be determined at high temporal resolution (hourly) to capture the short-lived melt events. In addition, surface temperature must be known in order to ascertain that melting really takes place.

Objective: Validation that surface melt has occurred
Solution: Surface temperature (2m) at the reference locations is known via AWS output, and surface skin temperature is accurate to within 1 degree C from the MODIS imagery. Validation for surface melting was via XPGR, a standard surface melt indicator that had been in use for 15 years.

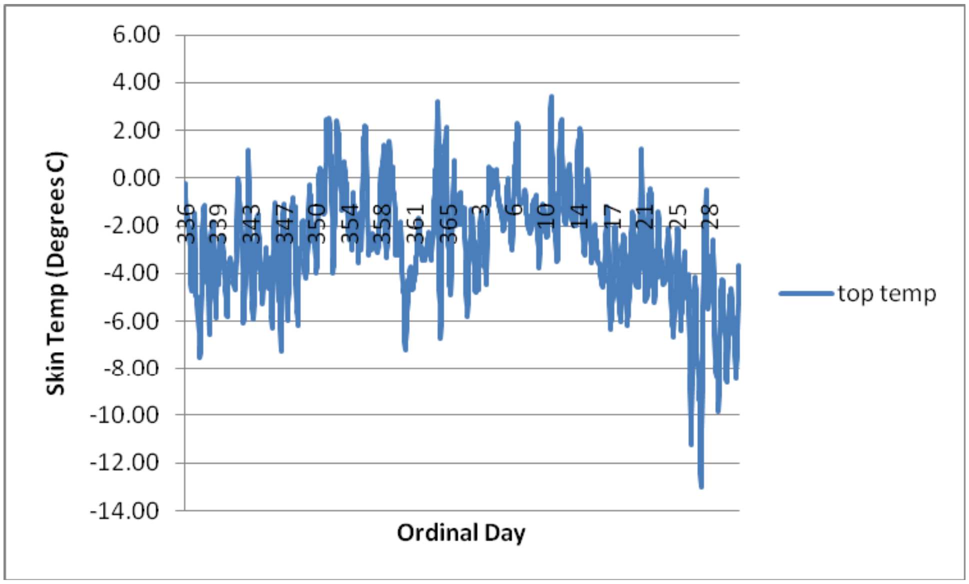
Finally, penetration of meltwater in the snowpack and subsequent refreezing takes place in Antarctica, which also influences the liquid water content and must be taken into account. This requires assumptions about the initial temperature of the snowpack (needed to initialize the 1D snow model), the retention capacity of the snow, i.e. the open pore space.

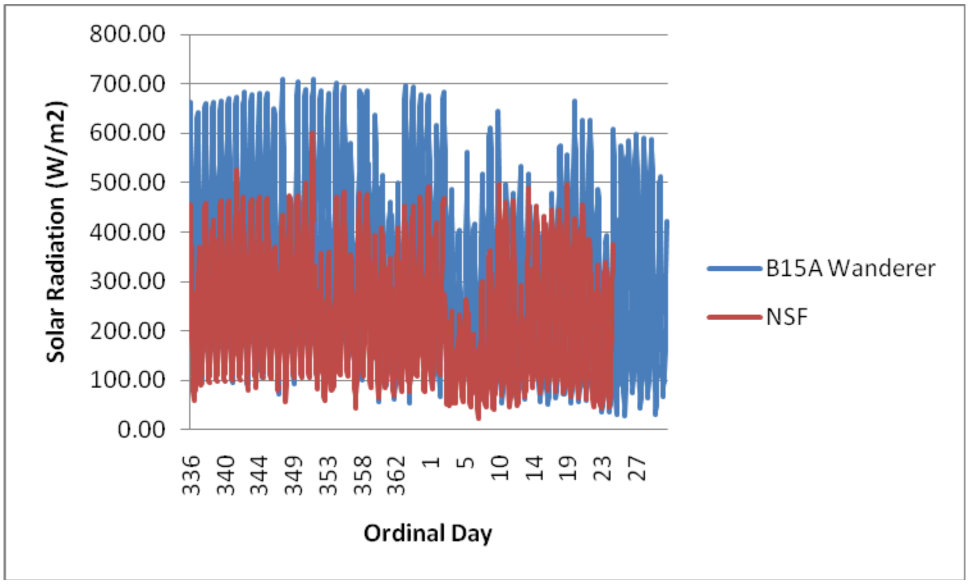
Objective: Characterize the penetration of meltwater and the characteristics of the snowpack at depth
Solution: Snowpack characteristics are well-resolved by the SNTHERM model as determined by sensitivity testing in Lampkin and Peng (2007) and this manuscript. When several stratigraphic conditions are used, they converge to a stable solution forced by meteorological data after approximately two to three days. SNTHERM is also able to resolve the infiltration of liquid water into the snowpack, which should allow for a minimum of bias on that front.

Unfortunately, the authors do not have the disposition over snowpack characteristics, nor do they have sufficiently accurate radiation measurements. The problem of reliable input data is exemplified by the large errors in the NCEP/NCAR reanalysis shortwave downwelling radiation, which differs from nearby observations by a factor of two, representing an uncertainty of > 100 W m-2, far larger than the above-mentioned precision. This precludes any accurate assessment of surface energy exchange and melt rate.

Objective: Radiation measurements provide the single most important source of uncertainty for this project. Uncertainties in the measurements are high, and small changes in incoming radiation can result in large changes in liquid water fraction. In addition, snowpack characteristics can affect the amount of liquid water in the upper portions of the firn.

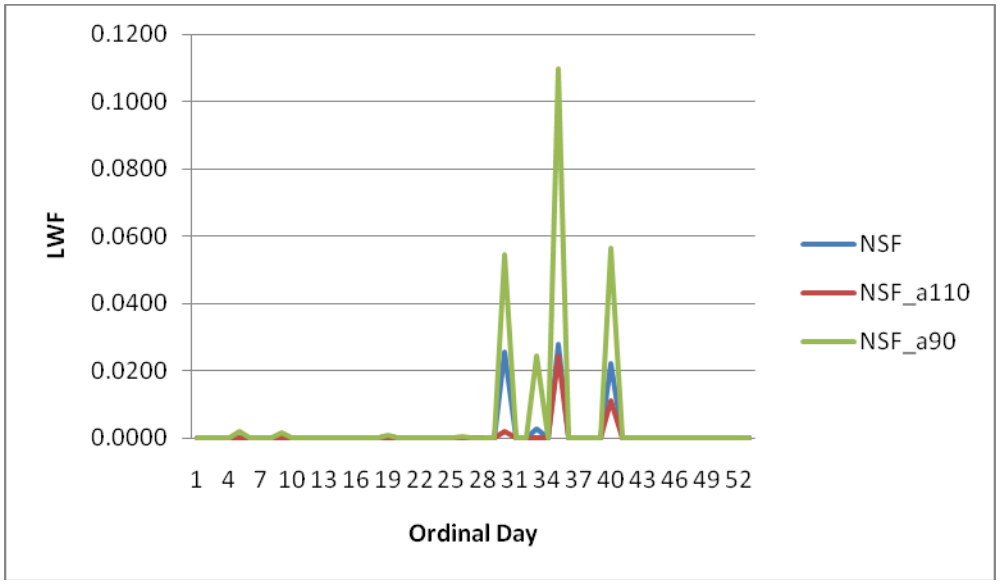
Response: As mentioned above, snowpack characteristics in the upper levels of the firn tend to converge to similar solutions as a result of meteorological forcing within 72 hours of initialization. Again, while there are large errors in NCEP/NCAR reanalysis shortwave radiation, we have provided bounds on the uncertainties as a result of radiation forcing. In addition, we have compared the NSF UV-Vis radiation dataset with another on-the-ground dataset from B15A-Wanderer iceberg station. While pyranometers were not installed on B15A during our 2002-03 study season, the 2004-05 summer season has been used for comparison between the radiation used in this study and another measured radiation dataset. While B15A is significantly further from the reference stations than McMurdo, it is much closer than the Neumayer and Sonya stations that are on the other side of the continent. We can validate that surface melt is occurring (via XPGR) only on days when the temperature is at or above 0c, and we can also compare the downwelling solar radiation measurements between the NSF site (measured 290-600nm multiplied by a factor of 2 to account for the "unmeasured" portion) versus that measured over the total solar spectrum at B15A.





At least as important is an accurate assessment of surface albedo, which determines how much of the downwelling radiation is absorbed and can be used to heat the surface to the melting point or, when melting has started, how much shortwave radiative energy is used for melting. For instance, assuming an albedo of 0.75 or 0.85 makes a 67% difference in absorbed solar radiation, usually the most important source of melting energy. Albedo is used from NCEP/NCAR, but it's value is not mentioned nor how it is determined in that model.

Objective: To characterize the uncertainty in surface liquid water fraction contributed by uncertainty in albedo
Response: The albedo from NCEP/NCAR is calculated as follows: (reflected solar out) / (downwelling solar in), and it is applied as a scale factor to the NSF UV-Vis radiation to provide the missing "reflected solar out" component that is not measured at the NSF study site, but is necessary as an input to SNTHERM89. In addition, we have performed another sensitivity analysis to see the effects of changing the albedo by 10% on the SNTHERM89 output. Changes in albedo are also an important consideration in the error for this study and have been factored into the error analysis. The graph below has also been added to the final manuscript as Figure 11.



The authors use AWS data, and average them to 6-hourly values. I do not see how this can be used to calculate the highly-nonlinear stability corrections for the turbulent fluxes, which requires a much higher temporal resolution. This may sound as second order effect, but it is not: on the Brunt ice shelf, it has been shown that sublimation is an important heat loss for the surface preventing or limiting melt (King, J. C., S. A. Argentini, and P. S. Anderson, 2006: Contrasts between the summertime surface energy balance and boundary layer structure at Dome C and Halley stations, Antarctica, J. Geophys. Res., 111, D02105, doi:10.1029/2005JD006130). This likely is also the case for Ross ice shelf, where sublimation has been demonstrated to be important in the surface energy budget (Stearns, C. R. and G. A. Weidner, 1993: Sensible and Latent Heat Flux in Antarctica, Antarctic Research Series 61, 109-138). So, before the satellite data can be usefully linked to surface melt rate, the latter must be calculated with a certain degree of precision.

Objective: To accurately model phenomena such as sublimation and turbulent fluxes that are occurring that have an effect on surface liquid water fraction.
Solution: The effects of sublimation on heat loss do have the potential to effect changes in surface melt conditions. However, again, we feel that the uncertainty introduced by the effects of processes such as this do not completely negate the utility of this method. We recognize that this study would benefit from increased temporal resolution for meteorological inputs and do not negate the importance of high-resolution measurements in determining the effects of turbulent fluxes on the liquid water content. Higher-resolution data is available for later seasons from the B-15A wanderer station; however, radiation data at anything shorter than 6-hour intervals is unavailable for this study season and location.

This requires a dedicated surface experiment, or the use of existing high-quality meteorological data, including radiation measurements, such as from Neumayer or Syowa stations (both

Baseline Surface Radiation Network stations). Only then can a convincing case be made that MODIS data can be used to assess melt rate.

Objective: Validation of the retrieval model through dedicated surface experiments and high-quality meteorological data.
Solution: Surface melt is minimal surrounding the Neumayer and Syowa stations, making the validation at these locations implausible. Current resources do not permit the undertaking of a ground-based experiment over Ross at this time, however further validation can be accomplished using data from B15A.

Reviewer #3:

Please see annotated manuscript for grammatical changes; these have all been changed as suggested.

To my humble opinion, the paper could have been submitted as a letter. All the information that the authors provide regarding, for example, the XPGR and other topics is way too much for a paper. It goes without saying that it is important to provide background but there is too much discussion on topics that are ultimately not implying the validity of the method. This distracts the reader from the main paper's topic. Also, some sections of the first part of the paper are very sloppy and the style is not effective.

Response: The background section has been shortened and revised to streamline the paper and improve the writing style.

I am not fully convinced that this approach can really provide valuable information against that derived with microwave data. Also, in terms of spatial resolution, QUIKSCAT data processed at BYU at 2.25 km can be used for wet/dry snow maps with a spatial resolution higher than that used in the study (4 km).

Response: This method is not meant to replace microwave assessments of surface melting, but rather augment them with some indication (albeit poorly constrained) of the magnitude of surface melting that has occurred. Both Passive Microwave and QuikSCAT remain limited to describing melt in a binary fashion, with no capability of describing melt magnitude. QuikSCAT data has been processed at 2.225 km^2; however MODIS data over both land areas and oceans has been processed at 1km^2. This was the basis for the 1km^2 melt retrieval over Greenland (Lampkin and Peng, 2008). There is no physically-based reason that this imagery cannot be processed at 1 km^2 over ice shelves, so theoretically it will be possible in the future to retrieve surface melt magnitude at this resolution should the MODIS data be processed at the highest available resolution.

There is another issue and very important: there is no evidence of a direct validation of some of the results (e.g., grain size on the surface, LWC along the vertical profile, etc.). As long as I understand the inherent difficulties connected with this phase of the work, this is still a major drawback of the whole paper. There is no mention of this in the conclusions. I strongly suggest the author to highlight the fact that the LWCeff is not validated and that the results discussed regard the output of a model.

Objective: Validation of the model results
Solution: Mention of this fact has been added to the conclusions section of the final draft. Complete direct validation has not been applied to the results of this study; however, other means of validation have been undertaken, namely comparison to XPGR and a suite of sensitivity analyses to correspond with uncertainties at various points in the study.

The overall methodology has some ‘obscure’ points, such as the variability of grain size due to factors different from melting and the fact that the method is based on empirical relationship. Other more elegant methods could and should be applied, such as classification methods or neural network approaches that aim at generalizing the relationships among the different inputs and outputs. I do not recommend the publication of the paper as long as the above mentioned issues are not addressed.

Objective: To account for variability of grain size due to factors other than surface melt and accounting for the non-linearity of the response of shortwave infrared reflectance and surface temperature to surface melt conditions
Solution: Forthcoming work will address the non-linear response of SW IR reflectance and surface temperatures to LWF by employing an artificial neural network rather than a linear model. This will be accomplished over all West Antarctic Ice Sheets and will include reference points at both Larsen and Limbert AWS stations, increasing the LWF range over which this model is applicable.

Page 1072
- Line 2. How is it clear that surface temperature over Antarctica are increasing? The above mentioned papers refer to different periods and most of the warming occurs in winter and fall, not in summer. The author should include more details of the mentioned papers (specifying the years over which the trends are estimated) and should also specify how they can relate the more melting that they claim (whose trends are not statistically significant over the satellite era) is related to the above mentioned trends of surface temperatures

Response: The Steig et al. (2009) paper does show statistically significant warming in all seasons over Ross Ice Shelf with the exception of summer. Larsen Ice Shelf does experience statistically significant warming during the summer months, and it is our hope to expand the analysis over this area with forthcoming research.

Page 1077
- Line 20. What is the criterion for the cloud mask ?

Response: The MODIS cloud mask identifies a clear-sky confidence interval of high confident clear, probably clear, undecided, and cloudy. High confident clear and probably clear pixels are used in this study.

Page 1081
- Line 14. Why was a 0.5 diameter used. What is the sensitivity of the method to the initial grain size values ?

Objective: Determine the sensitivity of the method to initial grain size values.
Solution: A 0.5mm diameter seemed appropriate for snow particles at the surface, and SNTHERM is relatively insensitive to precipitation grain size. A sensitivity test was performed to address this issue using 1mm grain size for precipitation, with no statistically significant difference between the two initialization values. Results are presented below (differences in average LWF are less than 0.1% LWF):