Anonymous Referee #2

Received and published: 14 March 2018

Review of paper tc-2018-27 Tikhonov et al. "Theoretical study of ice cover phenology at large freshwater lakes based on SMOS data"

We thank Referee #2 for carefully reading our manuscript and the comments. We attempted to provide answers to all his/her questions and make necessary corrections. The answers are below in red.

General

The study deals with investigating L-band passive microwave emissions over freshwater lakes from a theoretical perspective, employing a forward model to simulate brightness temperatures which are then compared to observations from the SMOS mission.

The subject is interesting as relatively few studies have focused on modeling the passive microwave signatures from lakes. There are none that I am aware of that focus specifically on L-band. Although at present the coarse spatial resolution of spaceborne passive microwave sensors at L-band ultimately constrains their applicability to a limited number of large lakes, the study is still relevant given the specific advantages of this frequency compared to higher bands. In this way, this study also has the potential of bringing new information to the ongoing discussion of an operational follow-on sensor to the SMOS and SMAP exploratory missions.

From a general viewpoint the study is well written, clear and easy to follow. However, insufficient detail is given on key factors regarding the model simulations; I am left wondering if some kind of tuning of the forward model has been done. If so this is fine but clear details should be given so other groups may seek to replicate the results. Furthermore, comparisons of model results to observational data are very qualitative, e.g. no numbers (bias, RMSE etc.) are given. These factors weaken the broader conclusions that can be drawn from this study.

See answers to the comments below.

An additional aspect that I feel the authors omit is employing the full potential of SMOS data by analyzing data from different incidence angles. This may have relevance especially concerning conclusions made about sensitivity to dry snow (see major comments below).

See answers to the comments below.

Last, the references should be expanded to acknowledge more modeling work done for lakes at other microwave bands and studies related to SMOS and the cryosphere. Authors now refer mainly to their own work (with the exception of papers by Kang et al., which are extensively cited). In light of the above the potential of the paper is not really achieved. I give several recommendations below to help make this happen; I would recommend the authors should carefully address these comments before publication.

See answers to the comments below.

Major comments

1. Introduction, line 23: Add appropriate reference to the SMOS mission, e.g. Kerr et al., 2010.

An appropriate reference (Kerr et al, 2010) is added.

2. Introduction, throughout: The authors should refer more broadly to recent publications on applying L-band for the cryosphere. Studies on L-band signatures from the Antarctica (Macelloni et al.,), sea ice (Kaleschke et al.) and snow cover (Schwank et al.) have been published in recent years.

As suggested, we've broadened the review of the literature on cryosphere studies in L-band in "Introduction". Among them are investigations of brightness temperature of Antarctica ice sheet (Macelloni et al., 2013, 2014); analysis of snow brightness temperature dependence on its wetness, density and ground permittivity (Schwank et al., 2015; Naderpour et al., 2017; Schwank and Naderpour, 2018a, 2018b); snow thickness retrieval over thick Arctic sea ice (Maaß et al., 2013); investigation of brightness temperature variations of Arctic sea ice (Heygster et al., 2009; Richter et al., 2018); retrieval of Arctic sea ice thickness (Huntemann et al., 2014; Kaleschke et al., 2012, 2016; Richter et al., 2017; Tian-Kunze et al., 2014; Zhou et al., 2018).

3. Although not dealing with lakes as such, the study by Schwank et al. (2015) should be of particular relevance as they also present a model for snow cover at L-band which should at least be cited. I assume the model could also be easily applicable for lake ice. Similarly, there are some other works looking at lake ice signatures at AMSR frequencies beyond Kang et al., which could be added (see e.g. Kontu et al., 2014).

As suggested, we've added a short review of various models of radiative properties of snow, ice and other Earth covers. The most widely used are HUT (Helsinki University of Technology) (Pulliainen et al., 1999; Lemmetyinen et al., 2010) and MEMLS (Microwave Emission Model of Layered Snowpacks) (Matzler, Wiesmann, 1999; Wiesmann, Matzler, 1999). HUT was successfully used for analysis of brightness temperature of snow- and ice-covered lakes and wetlands derived from aerial and satellite microwave radiometry data (Gunn et al., 2011; Kontu et al., 2014). Modified versions of MEMLS were used for detailed analysis of L-band emission of freezing ground covered with snow as well as wet snow cover (Schwank et al., 2014; Schwank et al., 2015; Schwank and Naderpour, 2018a, 2018b).

Also, we've added references (Du et al., 2017; Gunn et al., 2011; Kontu et al., 2014) to works on lake ice signatures at AMSR frequencies.

4. Section 2.1: The authors use only an incidence angle of 42.5 degrees from the L1C data (actually a collection of snapshots from 40 to 45 degrees). Why was this angle chosen over others (available from nadir to 70 degrees)?

The seasonal dependencies of brightness temperature at large freezing lakes discussed in our manuscript were in fact revealed incidentally as a by-product of another research. It had no connection with freshwater lakes and required no less than twice a day measuring of upwelling microwave radiation at a fixed viewing angle over a widest possible area. Indeed, the SMOS data contains measurements at various viewing angles. However, the imaging pattern is such that the maximum number of measurements falls into the 40-45 degrees range (Kerr et al, 2010). At the other angles, the resulting data time series have significant amount of gaps. From this perspective, the algorithms of streamline processing of L1C products were developed and optimized so as to obtain as complete as possible time series of the data. Investigation of seasonal variations of brightness temperature at freezing lakes is undoubtedly of great interest. However, it requires certain amount of calculations and will be performed as a separate task.

5. Related to the above: Incidentally, SMOS incidence angels close to 41 degrees were noted by Schwank et al. (2015) to be insensitive to dry snow (whereas observations at other incidence angles were found to be sensitive to the presence of dry snow). Close to 41 degrees sensitivity to dry snow cover disappears at V-polarization, due to the opposing effects of impedance matching and refraction. Perhaps this is the cause the authors see no change in observed or modeled Tb with dry snow cover, as stated on p12, section 4? This should be discussed. Looking at other incidence angles beyond 42.5 degrees might shed some light here.

In our work, we attempt to explain seasonal brightness temperature variations observed at a viewing angle of 42.5 degrees at large freezing freshwater lakes. The reason for choosing this angle is given above. Referee #2 is quite right: recently, there have appeared a considerable number of works dedicated to Earth cover investigation in L-band. They regard Antarctica (Macelloni et al., 2013, 2014), snow cover (Maaß et al., 2013; Naderpour et al., 2017; Schwank et al., 2015; Schwank and Naderpour, 2018a, 2018b), and sea ice (Huntemann et al., 2014; Kaleschke et al., 2012, 2016; Richter et al., 2017; Tian-Kunze et al., 2014; Zhou et al., 2018; Richter et al., 2018). We have revealed the phenomenon of dramatic and fast change in L-band brightness temperature at freshwater lakes that was not discussed in literature before. The aim of this work is to provide an explanation of the phenomenon, which is, in our view, successfully achieved. Investigation of brightness temperature angular dependencies for snow on freshwater ice is a separate big task that could be addressed in future.

6. Section 3 is quite long, I suggest to divide into subsections. Section 3.1 could present the model and relevant equations, while section 3.2 could present the simulation setup (use of data etc) specific for this study (i.e. starting from p8, line 18).

As suggested, we’ve divided Section 3 into two subsections. The model is described in Section 3.1, its modification in Section 3.2.

7. Related to the above: p10 lines 10-17: This does not really deal with results, but should be moved from section 4 to section 3.

This part is moved to Section 3.2.

8. Section 3, section 4 and Table 3: Judging from figure 5 an almost perfect match of model vs. observations is achieved but it is not perfectly clear if e.g., tuning of model input parameters (given in Table 1) was required to achieve this. For TR1 no tuning is possible from what I see, but what about volumetric wetness for ice in TR2 and snow and ice in TR3? A range is given in Table 3, but it is not clear if these were defined individually for each lake? If no tuning was required, the authors could also highlight this.

We've added the following explanatory paragraph at the end of Section 3.2:

"In the modeling, we used mean seasonal values of snow density, ice grain diameter, volumetric wetness of snow, ice porosity and size of air bubbles in ice. These characteristics were taken from various sources (Kuz'min, 1957; Gray and Male, 1986; Kotlyakov, 2000; Kozlov, 2000; Cuffey and Paterson, 2010; Barry and Gan, 2011; Singh et al., 2011). It was assumed that in the transitional period (from TR2 to TR3), a gradual increase in lake ice porosity, as well as snow and ice wetness took place. These parameters are listed in Table 3. They were almost the same for all the lakes."

9. P10 lines 5-7: Dry snow and ice are transparent at L-band yes, but they still affect the emitted brightness temperature from the surface beneath though impedance matching and a change in the refraction angle. See Schwank et al., 2015. I imagine these results are also applicable to the water-ice-snow system.

We quite agree with Referee #2 in that ice and snow cover influence lake brightness temperature, that is why we put "almost completely transparent" not "completely transparent". This issue is highlighted in Section 4 when discussing TR2. At the chosen viewing angle (see answers to Comments 4 and 5 for the choice reasoning), snow is transparent, while ice adds to the radiation emitted by the water surface.

10. P12, line 19-20: Again, the insensitivity to snow may be due to the choice of incidence angle (although at H-pol, something could perhaps be seen). I suggest the authors analyze the response vs. incidence angle e.g. for one lake comparing simulations with the TR1, TR2 and TR3 setting against SMOS observations (e.g., the average Tb for those periods at different incidence angles).

As already mentioned in the answers to Comments 4 and 5, this work is intended to explain the revealed phenomenon of dramatic and fast seasonal change in brightness temperature of large freshwater lakes. Investigation of brightness temperature angular dependencies for snow on freshwater ice is a separate big task that could be addressed in future.

11. Section 5: The conclusions section is too short. The authors should provide a more complete assessment of their study, including the main results.

As suggested, we've expanded "Conclusions" to provide a more complete assessment of our study and detailed description of the results.

Minor/Editorial

1. P8, lines 8 and 19, maybe elsewhere: I think the convention is to write "wavelength" as one word (not wave length). Furthermore on line 19, wavelength is not a synonym to frequency, as it is now implied by the parenthesis. Please rephrase.

Corrected.

2. P9, line 17: "Note that for both media: : :" Sentence seems incomplete.

Corrected.

3. P12, line 13: "most wet". Unclear what is meant. Almost wet? Mostly wet?

Corrected.

4. P12 lime 14: Typo: capitalized ‘M’ in ‘cm’

Corrected.

5. P13, line 7: “even in the cold season”

Corrected.

We would like to thank again Referee #2 for his/her time and effort, comments and suggestions that helped improve our manuscript.

Sincerely,
Vasiliy Tikhonov and Co-author

References

Barry, R. G., and Gan, T. Y.: The Global Cryosphere. Past, Present, and Future, University Press, Cambridge, 2011.

Cuffey, K. M., and Paterson, W. S. B.: The Physics of Glaciers, Elsevier, Burlington, 2010.

Du, J., Kimball, J. S., Duguay, C., Kim, Y., and Watts, J. D.: Satellite microwave assessment of Northern Hemisphere lake ice phenology from 2002 to 2015, The Cryosphere, 11, 47–63, https://doi.org/10.5194/tc-11-47-2017, 2017.

Gray, D. M., and Male, D. H. (Eds.): Handbook of Snow, Pergamon Press, Toronto, 1986.

Gunn, G. E., Duguay, C. R., Derksen, C., Lemmetyinen, J., and Toose, P.: Evaluation of the HUT modified snow emission model over lake ice using airborne passive microwave measurements, Remote Sens. Environ., 115, 1, 233-244, https://doi.org/10.1016/j.rse.2010.09.001, 2011.

Heygster, G., Hendricks, S., Kaleschke, L., Maass, N., Mills, P., Stammer, D., Tonboe, R. T., and Haas, C.: L-Band Radiometry for Sea-Ice Applications, Final Report for ESA ESTEC Contract 21130/08/NL/EL, Institute of Environmental Physics, University of Bremen November 2009, http://www.iup.uni-bremen.de/iuppage/psa/documents/smos_final.pdf.

Huntemann, M., Heygster, G., Kaleschke, L., Krumpen, T., Mäkynen, M., and Drusch, M.: Empirical sea ice thickness retrieval during the freeze-up period from SMOS high incident angle observations, The Cryosphere, 8, 439–451, https://doi.org/10.5194/tc-8-439-2014, 2014.

Kaleschke, L., Tian-Kunze, X., Maaß, N., Mäkynen, M., and Drusch, M.: Sea ice thickness retrieval from SMOS brightness temperatures during the Arctic freeze-up period, Geophys. Res. Lett., 39, L05501, https://doi.org/10.1029/2012GL050916, 2012.

Kaleschke, L., Tian-Kunze, X., Maaß, N., Beitsch, A., Wernecke, A., Miernecki, M., Müller, G., Fock, B. H., Gierisch, A. M. U., Schlünzen, K. H., Pohlmann, T., Dobrynin, M., Hendricks, S., Asseng, J., Gerdes, R., Jochmann, P., Reimer, N., Holfort, J., Melsheimer, C., Heygster, G., Spreen, G., Gerland, S., King, J., Skou, N., Søbjærg, S. S., Haas, C., Richter, F., Casal, T.: SMOS sea ice product: Operational application and validation in the Barents Sea marginal ice zone, Remote Sens. Environ., 180, 264-273, http://dx.doi.org/10.1016/j.rse.2016.03.009, 2016.

Kerr, Y. H., Waldteufel, P., Wigneron, J.-P., Delwart, S., Cabot, F., Boutin, J., Escorihuela, M. J., Font, J., Reul, N., Gruhier, C., Juglea, S. E., Drinkwater, M. R., Hahne, A., Martin-Neira, M., and Mecklenburg, S.: The SMOS Mission: New Tool for Monitoring Key Elements of the Global Water Cycle, P. IEEE, 98, 5, 666–687, https://doi.org/10.1109/JPROC.2010.2043032, 2010.

Kontu, A., Lemmetyinen, J., Pulliainen, J., Seppanen, J., and Hallikainen, M.: Observation and Modeling of the Microwave Brightness Temperature of Snow-Covered Frozen Lakes and Wetlands, IEEE T. Geosci. Remote, 52, 6, 3275-3288, https://doi.org/10.1109/TGRS.2013.2272077, 2014.

Kotlyakov, V. V.: Selected works in six books, Book 1, Glaciology of Antarctica, Nauka, Moscow, 2000. (In Russian).

Kozlov, D. B.: Ice of freshwater reservoirs and streams, MGU, Moscow, 2000. (In Russian).

Kuz'min, P. P.: The physical properties of snow cover, Gidrometeoizdat, Leningrad, 1957. (In Russian).

Lemmetyinen, J., Pulliainen, J., Rees, A., Kontu, A., Qiu, Y., and Derksen, C.: Multiple-Layer Adaptation of HUT Snow Emission Model: Comparison With Experimental Data, IEEE T. Geosci. Remote, 48, 7, 2781-2794, https://doi.org/10.1109/TGRS.2010.2041357, 2010.

Maaß, N., Kaleschke, L., Tian-Kunze, X., and Drusch, M.: Snow thickness retrieval over thick Arctic sea ice using SMOS satellite data, The Cryosphere, 7, 1971–1989, https://doi.org/10.5194/tc-7-1971-2013, 2013.

Macelloni, G., Brogioni, M., Pettinato, S., Zasso, R., Crepaz, A., Zaccaria, J., Padovan, B., and Drinkwater, M. R.: Ground-Based L-Band Emission Measurements at Dome-C Antarctica: The DOMEX-2 Experiment, IEEE T. Geosci. Remote, 51, 9, 4718-4730, https://doi.org/10.1109/TGRS.2013.2277921, 2013.

Macelloni, G., Brogioni, M., Aksoy, M., Johnson, J. T., Jezek, K. C., and Drinkwater, M. R.: Understanding SMOS data in Antarctica, in: IEEE International Geoscience and Remote Sensing Symposium (IGARSS), 3606-3609, 2014, https://doi.org/10.1109/IGARSS.2014.6947263.

Matzler, C., Wiesmann, A.: Extension of the Microwave Emission Model of Layered Snowpacks to Coarse-Grained Snow, Remote Sens. Environ., 70, 3, 317–325, https://doi.org/10.1016/S0034-4257(99)00047-4, 1999.

Naderpour, R., Schwank, M., and Mätzler, C.: Davos-Laret Remote Sensing Field Laboratory: 2016/2017 Winter Season L-Band Measurements Data-Processing and Analysis, Remote Sens-Basel, 9, 11, 1185, 2017, https://doi.org/10.3390/rs9111185.

Pulliainen, J. T., Grandell, J., and Hallikainen, M. T.: HUT snow emission model and its applicability to snow water equivalent retrieval, IEEE T. Geosci. Remote, 37, 3, 1378-1390, https://doi.org/10.1109/36.763302, 1999.

Richter, F., Hendricks, S., Kaleschke, L., Tian-Kunze, X., King, J., and Haas C.: A weekly Arctic sea-ice thickness data record from merged CryoSat-2 and SMOS satellite data, The Cryosphere, 11, 1607–1623, https://doi.org/10.5194/tc-11-1607-2017, 2017.

Richter, F., Drusch, M., Kaleschke, L., Maaß, N., Tian-Kunze, X., and Mecklenburg, S.: Arctic sea ice signatures: L-band brightness temperature sensitivity comparison using two radiation transfer models, The Cryosphere, 12, 921–933, https://doi.org/10.5194/tc-12-921-2018, 2018.

Schwank, M., Rautiainen, K., Mätzler, C., Stähli, M., Lemmetyinen, J., Pulliainen, J., Vehviläinen, J., Kontu, A., Ikonen, J., Ménard, C. B., Drusch, M., Wiesmann, A., and Wegmüller, U.: Model for microwave emission of a snow-covered ground with focus on L band, Remote Sens. Environ., 154, 180-191, https://doi.org/10.1016/j.rse.2014.08.029, 2014.

Schwank, M., Mätzler, C., Wiesmann, A., Wegmüller, U., Pulliainen, J., Lemmetyinen, J., Rautiainen, K., Derksen, C., Toose, P., and Drusch, M.: Snow Density and Ground Permittivity Retrieved from L-Band Radiometry: A Synthetic Analysis, IEEE J. Sel. Top. Appl., 8, 8, 1-14, 2015, https://doi.org/10.1109/JSTARS.2015.2422998.

Schwank, M., and Naderpour, R.: Snow Density and Ground Permittivity Retrieved from L-Band Radiometry: Melting Effects, Remote Sens-Basel, 10, 2, 354, 2018a, https://doi.org/10.3390/rs10020354.

Schwank, M., and Naderpour, R.: Snow Wetness Retrieved from L-Band Radiometry, Remote Sens-Basel, 10, 3, 359, 2018b, https://doi.org/10.3390/rs10030359.

Singh, V. P., Singh, P., and Haritashya, U. K.: Encyclopedia of Snow, Ice and Glaciers, Springer, Dordrecht, 2011.

Tian-Kunze, X., Kaleschke, L., Maaß, N., Mäkynen, M., Serra, N., Drusch, M., and Krumpen, T. SMOS-derived thin sea ice thickness: algorithm baseline, product specifications and initial verification, The Cryosphere, 8, 997–1018, https://doi.org/10.5194/tc-8-997-2014, 2014.

Wiesmann, A., Matzler, C.: Microwave emission model of layered snowpacks, Remote Sens. Environ., 70, 3, 307–316, https://doi.org/10.1016/S0034-4257(99)00046-2, 1999.

Zhou, L., Xu, S., Liu, J., and Wang, B.: On the retrieval of sea ice thickness and snow depth using concurrent laser altimetry and L-band remote sensing data, The Cryosphere, 12, 993–1012, https://doi.org/10.5194/tc-12-993-2018, 2018.