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Interactive comment on "Estimation of turbulent heat flux over leads using satellite thermal images" *by* Meng Qu et al.

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Response to Reviewer' Comments:

The authors would very much like to thank you for your time and constructive comments. We have considered each comment carefully and incorporated practically all of them. Please find attached a revised version of our manuscript, in which we marked major modifications in red. Response to each comment are as follows:

"The authors present a study build upon widely used space borne thermal-infrared data from MODIS and Landsat-8 in combination with ECMWF ERA-Interim atmospheric reanalysis data to calculate turbulent heat fluxes. Based upon an almost perfectly collocated case study between the two sensors in the Beaufort Sea, the authors present a

thorough analysis of the sensors capabilities for the detection of lead sizes and widths as well as a comparison between two different methodologies to calculate the turbulent heat fluxes. Overall, the manuscript is mostly well written and a good extension to existing work in the field."

"General Comments:"

"Did the authors do anything about potentially present cloud cover? It looks to me that at least in some areas it could likely be a cloud artifact we are looking at."

Reply: Thanks for the question. For comparison, ice surface temperature (IST) map from MOD29 product is plotted in Fig.1. Potential cloud pixels are removed in MOD29 using cloud mask from MOD35 product, shown as "Nodata" in green color in Fig1 (b) and (C). As we can see, the pixels within leads marked as cloud are likely open water lead with fog or plume over the surface (Fett et al., 1997). To reserve potential lead areas, we applied the NSIDC algorithm (Hall et al. 2001) on thermal images from MODIS L1B product to calculate IST instead of using the MOD29 product. Since the area within Landsat-8 frame is mostly unobstructed by cloud, no cloud mask procedure was performed in our study.

In Page 3, Line 13 ∼19, we added: "Willmes and Heinamann (2015) used the MOD29 ice surface temperature (IST) product (Hall and Riggs, 2015) from the National Snow and Ice Data Center (NSIDC) to retrieve leads. The MOD29 product is filtered for cloud contamination using a cloud mask from MOD35. However, inspection of the corresponding MOD29 map of the study area revealed that the pixels within leads marked as clouds are likely open water with ocean fog or plume over the surface (Fett et al., 1997). Apart from that, the study area within the Landsat-8 frame is mostly unobstructed by clouds. To preserve potential lead areas, we applied the NSIDC algorithm (Hall et al. 2001) to thermal images from MODIS L1B to calculate IST instead of using the MOD29. Therefore, no cloud mask procedure was performed in our study."

Reference:

Fett, R. W., Englebretson, R. E., and Burk, S. D.: Techniques for analyzing lead condition in visible, infrared and microwave satellite imagery. Journal of Geophysical Research: Atmospheres, 102(D12), 13657-13671, 1997.

Hall, D. K. and G. Riggs.: MODIS/Terra Sea Ice Extent 5-Min L2 Swath 1km, Version 6. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: https://doi.org/10.5067/MODIS/MOD29.006. 2015.

Hall, D. K., Riggs, G. A., Salomonson, V. V., Barton, J. S., Casey, K., Chien, J. Y. L., ... and Tait, A. B.: Algorithm theoretical basis document (ATBD) for the MODIS snow and sea ice-mapping algorithms. Nasa Gsfc, 45, 2001.

"Specific Comments"

“P1, L20: Does ‘mainly due to its large area’ refer to the area of small leads? Is that linked to a likelihood of rather being ice free than bigger leads?”

Reply: Yes, the phrase ‘mainly due to its large area’ refers to the total area of small leads. However, as explained in the manuscript, within any remote sensing pixel, the radiometric signature of a narrow lead with open water may be identical to that of a wider lead with thin ice. Since the surface temperature of narrow leads from Landsat-8 are mostly below the freezing point (Figure 2), we are not sure whether the temperature signature is caused by subpixel open water lead or just lead covered with thin ice.

Page 8, line 23, we write: “However, within any optical, thermal or microwave image, the radiometric signature of a narrow lead with open water may be identical to that of a wider lead with thin ice.”

“P2, L44-45: Are Landsat-8 thermal bands really referred to as the ‘split-window’ bands?”

Reply: Yes. Although radiance measured by Landsat-8 Thermal Infrared Sensor (TIRS) suffers from stray light, it can observe ocean surface using two narrow thermal bands centered around 11μm and 12μm, more like the channel 4 & 5 on AVHRR

and band 31 & 32 on MODIS rather than the high gain and low gain mode available for ETM+ channel 6 aboard Landsat-7. Such design is referred to as ‘split-window’ channels or bands in literatures about AVHRR and MODIS, so we consider to use it here.

“P3, L15: Could the authors elaborate on their decision to not use the NSIDC MOD29 sea-ice surface temperature product directly but instead calculate it themselves using their parameters? Was it due to the applied cloud mask?”

Reply: Yes, it is all about the cloud mask. As explained above, the NSIDC MOD29 IST product filtered for cloud contamination using cloud mask from MOD35 product, tends to mark open water leads as cloud in the presence of ocean fog or plume (see the Fig. 1 above), thus we avoid MOD29 for this special purpose.

In Page 3, Line 13 $\sim$19, we added: “Willmes and Heinamann (2015) used the MOD29 ice surface temperature (IST) product (Hall and Riggs, 2015) from the National Snow and Ice Data Center (NSIDC) to retrieve leads. The MOD29 product is filtered for cloud contamination using a cloud mask from MOD35. However, inspection of the corresponding MOD29 map of the study area revealed that the pixels within leads marked as clouds are likely open water with ocean fog or plume over the surface (Fett et al., 1997). Apart from that, the study area within the Landsat-8 frame is mostly unobstructed by clouds. To preserve potential lead areas, we applied the NSIDC algorithm (Hall et al. 2001) to thermal images from MODIS L1B to calculate IST instead of using the MOD29. Therefore, no cloud mask procedure was performed in our study.”

“P6, L17: Could the authors discuss where this difference might originate from? From what I read this might simply be the difference between an optimized for sea-ice temperature scheme in comparison to a multi-purpose one?”

Reply: The difference in IST maps retrieved from MODIS and Landsat-8 TIRS, might result from, as suggested, the algorithms, the thermal radiance measured by the two different sensors, as well as any calibration procedure. As for the difference in algorithms, apart from their application range, we can find that sensor viewing angles are considered in Key's equation for IST retrieval from AVHRR and MODIS (mainly due to their wide swath), but not in the equation for TIRS. However, their difference has little impact on temperature anomaly and lead detection. A comprehensive comparison of IST retrieved from MODIS and TIRS is not the main goal of this study.

Page 8, Line 1 $\sim$ 2, we added: "About 23% of the difference (in turbulent heat flux estimated using bulk formulae) can be explained by IST bias between MODIS and TIRS, but most of the difference comes from small leads."

"P6, L21: I think I missed how exactly these iterative thresholds were calculated or estimated in the first place? In way to match the resulting lead sizes/distributions between the sensors? Iteratively implies for me that there is some kind of number/goal to reach."

Reply: Thanks for pointing this out. Several image-based threshold selection techniques for a binary lead segmentation were compared in Willmes and Heinemann (2015), and an iterative threshold selection method (Ridler and Calvard, 1978) was recommended for extracting leads from temperature anomaly map. Assuming an initial threshold using the mean (m0) of the whole image, the iterative threshold selection method proposed by Ridler and Calvard (1978) seeks for a threshold, mi, which is the mean of two averages mA and mB from two clusters divided by mi: target A and background B. In our study, this iterative process was performed in an IDL procedure.

Page 4, Line 33 $\sim$ 34, we added the following explanations: "Assuming an initial threshold using the mean temperature anomaly (m0) of the whole image, the iterative method seeks a threshold mi which is the mean of averages mA and mB from two clusters divided by mi: Leads (A) and pack ice (B)."

Ridler, T. W., and Calvard, S.: Picture thresholding using an iterative selection method. IEEE trans syst Man Cybern, 8(8),630-632, 1978.

"P6, L25-26: Is this difference or rather the larger number for MODIS really simply just

due to mixed pixels? Later on the authors discuss frequently how much of the total area comes from small leads, which MODIS cannot detect at all. From reading the manuscript, I would rather expect it to be different as there should not be any leads in MODIS that Landsat-8 cannot detect, but surely as the authors also stated, the other way around. Could clouds be a factor here?"

Reply: Thanks for the question. Although the 1km resolution is the finest for MODIS thermal (and AVHRR), potential and subpixel lead can be detected by MODIS at this scale (Lindsay and Rothrock, 1995). The observed lead fractions are composite of thresholds and contrast in surface temperature of leads compared to the surrounding ice, i.e. temperature anomaly Δt. Mixed pixels at MODIS scale might be the main reason for the difference, but the threshold should also be considered. When high thresholds (2nd and 3rd Std) were applied, lead fraction extracted from MODIS drops quickly below that from TIRS (Table 4), this is consistent with result from Key et al. (1994). About cloud contamination, as explained above, the Landsat-8 image area is mostly unobstructed by cloud. Difference in lead fraction caused by cloud is negligible here.

Page7, Line 24 $\sim$ 26, we added: "Although, the 1km resolution is the finest for MODIS thermal, the 1km wide lead category at MODIS scale should provide a reasonable guess of potential small leads or subpixel leads at MODIS scale (Lindsay and Rothrock, 1995)."

Page8, Line 33 $\sim$ 34, we added: "The obtained lead fractions are a composite of thresholds and contrast in surface temperature of leads compared to the surrounding ice, i.e., temperature anomaly Δt."

Page8, Line 38 $\sim$ 40, we added: "The difference in lead fractions from the two sensors mainly resulted from mixed pixels at MODIS scale, but the threshold should also be considered. When high thresholds (2nd and 3rd Std) are applied, the lead fraction extracted from MODIS drops quickly below that from TIRS (Table 4), and this is consistent with results from Key et al. (1994).”

Reference:

Key, J., Maslanik, J. A., and Ellefsen, E.: The effects of sensor field-of-view on the geometrical characteristics of sea ice leads and implications for large-area heat flux estimates. Remote sensing of environment, 48(3), 347-357, 1994.

Lindsay, R. W., and Rothrock, D. A.: Arctic sea ice leads from advanced very high resolution radiometer images. Journal of Geophysical Research: Oceans, 100(C3), 4533-4544, 1995.

“P6, L30: Is the choice of lead-width thresholds arbitrary or is there a reference for that from another study?”

Reply: Thanks for raising this question. We do have some consideration when making these categories. According to Andreas and Cash (1999) model, turbulent heat flux over lead are stable for lead more than a few hundred meters wide. Therefore, for lead with width less than 1km, turbulent heat fluxes estimated from fetch-limited model and bulk formulae are expected to differ more than larger leads. While lead more than 5km or 10km wide is very large and rare in Arctic winter, but can be observed in marginal ice zone, indicating the beginning of summer ice retreat. The choice of 5km break point is partly due to the fact that lead at this scale can be easily observed by passive microwave sensors like AMSR-E/2, and coupled in climate models using bulk formulae. In comparison, we can see how much leads and turbulent heat flux from lead were missed if we used passive microwave data and bulk formulae alone.

Page 4, Line 38 $\sim$ 39, we added: “Using width samples crossed by transects, Lindsay and Rothrock (1995) found mean lead width between 2 and 3 km in the Arctic winter; larger means are found in peripheral seas.”

“P8, L16: Iterative thresholds are mentioned again but I think I still have not read an explanation yet.”

Reply: As explained above, a description was added; hope this time it is clear.

Page4, Line31$\sim$32, we added: “Assuming an initial threshold using the mean temperature anomaly (m0) of the whole image, the iterative method seeks a threshold mi which is the mean of averages mA and mB from two clusters divided by mi: Leads (A) and pack ice (B).”

Ridler, T. W., and Calvard, S.: Picture thresholding using an iterative selection method. IEEE trans syst Man Cybern, 8(8),630-632, 1978.

“P9, L19-20: Technically, MODIS cannot detect any leads in thermal infrared with a width below 1km? You compare numbers from below 1km width with numbers from exactly 1km. I think that should be highlighted better or rephrased.”

Reply: Thanks for raising this question. Yes, MODIS cannot directly detect leads with a width below 1km. But during our image processing, we found that the proportion of lead in a MODIS pixel will influence the finally classification of that pixel. In other words, subpixel leads might be detected at 1km using MODIS thermal images. In the revision, we include the 1km to the first category.

Page 9, Line 19$\sim$23, we added: “In comparison with Landsat-8 TIRS and panchromatic images, we find that the lead map generated from the MODIS IST data neglects very small leads, but overestimates the width of other leads approximately 1 km wide. Overall, the 1 km wide lead category at MODIS scale should provide a reasonable guess of potential small or subpixel leads. The small leads retrieved using TIRS provide a valuable reference for the capacity of MODIS to detect narrow leads.”

Page 10, Line 18$\sim$22, we modified the conclusion as: “Within the studied area, the total length of leads is 10,150.3 km from TIRS, including 8502.2 km (83.76%) from small leads with width less than 1 km. This is in contrast to the total length of 2746.4 km from MODIS, where the narrow leads (1 km wide) only account for 1050.0 km (38.23%). The total length of leads is underestimated by 72.9% in the MODIS data.

For the area of leads, small leads (width $\leq$ 1km) account for 34.54% of the total lead area from TIRS, but only 13.00% of the total lead area from MODIS."

"Technical Corrections"

"P1, L11: I think that should be 'scales'"

Corrected.

"P1, L20: 'flux over leads'"

Corrected.

"P1, L23: 'exposed to the atmosphere'"

Corrected.

"P7, L6-7: I suggest to rephrase this sentence(s): Table 2 reveals that the total heat flux over leads calculated using TIRS IST is 6.59[: : :] over the total area of [: : :]km2. This is 42.33% larger [: : :]"

Corrected.

"P7, L14: Suggest to use 'difference' instead of 'increase'."

Corrected.

"P7, L18/19: 'leads' and 'widths'. To my understanding, there are probably quite some more cases of that throughout the manuscript. The authors should double-check that."

Corrected and checked.

"P7, L33-35: I find this last sentence hard to comprehend. Please rephrase."

Deleted.

"P7, L38: 'twice as' large?"

Corrected

"P8, L8: 'to extract lead signatures from the background'"

Corrected.

"P8, L24: Second Key reference is not capitalized."

Corrected.

Please also note the supplement to this comment:
https://www.the-cryosphere-discuss.net/tc-2018-262/tc-2018-262-AC1-supplement.pdf

Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-262, 2019.

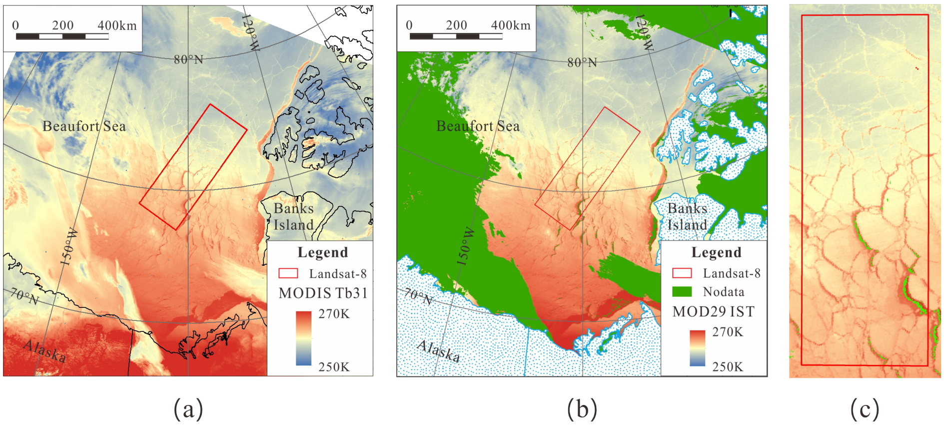

Fig. 1. Comparison of MODIS L1B thermal image (a) and MOD29 IST product (b), detail of Landsat-8 frame area in (b) are shown in (c).

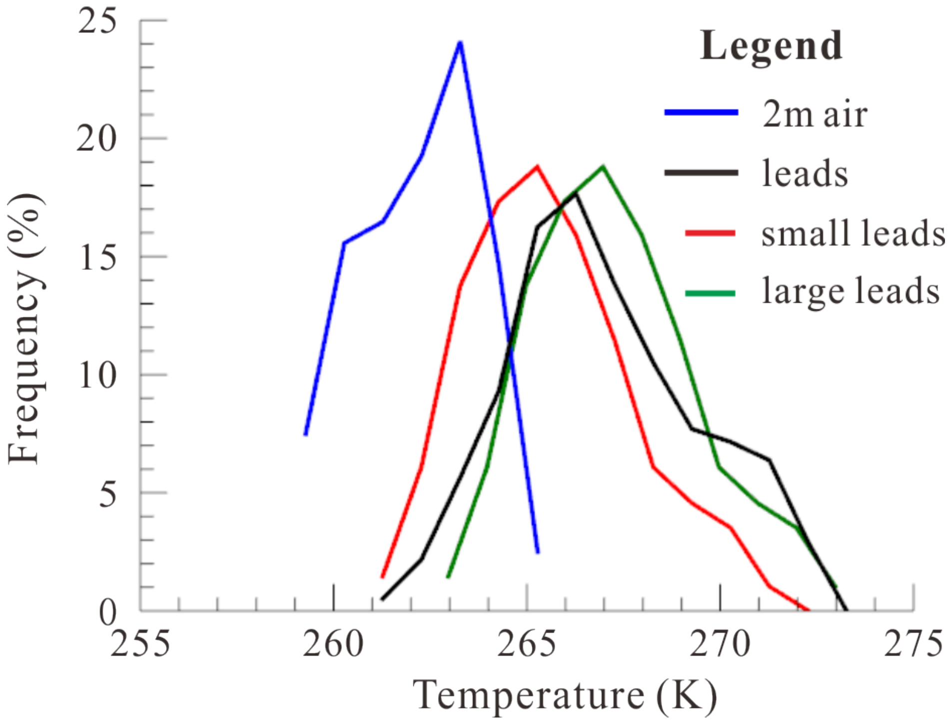

Fig. 2. Same as Figure 12 in the manuscrit, distribution of 2 m air temperature over leads and surface temperature of all leads, small leads with width <1km, and larger leads with width >5km.