

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

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Received and published: 19 April 2019

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:

“A review on “Estimation of turbulent heat flux over leads using satellite thermal images” The focus of the paper is the estimation of turbulent sensible and latent heat fluxes over leads using high-resolution satellite thermal images. The heat transfer over leads play important role in the heat budget of the atmospheric and oceanic boundary layers and affects many processes in the Arctic climate system. However, there is a

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large uncertainty in the estimates of turbulent heat flux over leads due several reasons: i) the insufficient resolution of satellite images used in models, ii) sparseness of in situ observations and iii) uncertainties in parametrizations of turbulent heat transfer over inhomogeneous sea ice surface. The paper provides new estimates of such uncertainties using satellite images of various resolution and shows the necessity to use high-resolution images and also more adequate parametrizations. To some extent, the paper follows the line of the Marcq and Weiss (2012) paper, but uses realistic surface and air temperatures, as well as wind speed for their case study and also using different satellite data. Therefore, the study adds to the current knowledge and provides revised estimates of the heat flux calculation uncertainties and thus is relevant and valuable. However, the quality of the paper is low and has to be strongly improved. It concerns the choice and description of methods, the analysis of results and language. The paper cannot be accepted in its current state. I suggest major revision with resubmission.”

“Major comments”

“1.The two methods are used for the turbulent heat flux estimates: the traditional bulk formulae and the fetch-dependent model proposed by Andreas and Cash (1999).

The bulk formulae and their application have to be described in more detail.

First of all, it is potential temperature that has to be used in the formula for the sensible heat flux.

Second, the heat transfer coefficients depend on height, surface roughness lengths for momentum and heat (z_{0m} and z_{0t}) and stability. Which height, which values for the roughness lengths and, finally, which universal stability functions are used?

The authors say that they use the air temperature at 2m height, but wind speed at 10m height from the reanalysis data. Since these heights differ from each other, the bulk formulae cannot be used in their classical form.

The authors need to describe in detail how they solve the bulk equations. Do they

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use z/L or the bulk Richardson number as a stratification parameter in the stability functions?"

Reply: Thanks for your questions and advices. As suggested, the bulk formulae are now modified in Page 5, Line13 ~ 17.

Page 5, Line 24 ~ 25, we added: "Csh and Cle are transfer coefficients for sensible heat and latent heat, calculated using equations from Oberhuber (1988) and Goosse et al. (2000) (see Appendix B)."

In our study, 2m air temperature from ERA-interim Reanalysis datasets was used as potential temperature T_r in the formulae;

A constant turbulent heat coefficient of 1.44×10^{-3} from Nihashi and Ohshima (2001) was used in our previous experiment, which might not be appropriated for Arctic leads. As suggested, we have modified the experiments using equations (Appendix B) from Oberhuber (1988), Goose et al. (2000), and Marcq and Weiss (2012) to solve the coefficients for the bulk formulae. Most part of the parameterization originates from Large and Pond (1981, 1982):

Page 11, Line 2 ~ 18, we added Appendix B:"Equations used for turbulent heat flux estimation using bulk formulae (Large and Pond, 1981, 1982; Oberhuber, 1988; Goosse et al, 2000; Marcq and Weiss, 2012)"

Since the wind speed and air temperature from ERA-interim are at different height, in our previous manuscript, a power law equation was used to calculate u_r using 10m wind magnitude u_{10} from ERA-interim:

$$u_r/u_{10} = (r/10)^a$$

where a is the wind shear exponent. An empirical value of $a = 1/7$ was used. In our modified experiments, a log law equation based on principles of boundary layer flow, was used (Ray et al., 2006):

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Page 5, line 26~29, we added: Since the wind speed and air temperature from ERA-interim are at different heights, a wind profile equation was used (Ray et al., 2006):

$$u_{10}/u_r = (\ln 10 - \ln Z_0)/(\ln r - \ln Z_0) \quad (9)$$

where u_{10} and u_r are wind speed at 10m and 2m height, and Z_0 is the surface roughness length.”

As a result, the mean wind speed at 2m height over leads, rises from ~ 5 m/s (using power law) to ~ 7 m/s (using log law). Estimated turbulent heat flux also increases in response.

Assuming an initial value for friction velocity u^* , the equations (B1) \sim (B13) and Eq. (9) are solve iteratively. As shown in Eq. (B13), the equations use z/L as a stratification parameter, comparing to the bulk Richardson number used in Andreas and Cash (1999).

Reference:

Nihashi S, Ohshima K I.: Relationship between ice decay and solar heating through open water in the Antarctic sea ice zone. *Journal of Geophysical Research: Oceans*, 106: 16767-16782. 2001.

Oberhuber, J. M.: An atlas based on the 'Coads' data set: The budgets of heat, buoyancy and turbulent kinetic energy at the surface of global ocean. 1988.

Goosse, H., Campin, J. M., Deleersnijder, E., Fichefet, T., Mathieu, P. P., Maqueda, M. M., and Tartinville, B.: Description of the CLIO model version 3.0. Institut d'Astronomie et de Géophysique Georges Lemaitre, Catholic University of Louvain, Belgium. 2001.

Marcq, S., and Weiss, J.: Influence of sea ice lead-width distribution on turbulent heat transfer between the ocean and the atmosphere. *The Cryosphere*, 6, 143-156, 2012.

Large, W. G., and Pond, S.: Open ocean momentum flux measurements in moderate to strong winds. *Journal of physical oceanography*, 11(3), 324-336. 1981.

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Large, W. G., and Pond, S.: Sensible and latent heat flux measurements over the ocean. *Journal of physical Oceanography*, 12(5), 464-482. 1982.

Ray, M. L., Rogers, A. L., and McGowan, J. G.: Analysis of wind shear models and trends in different terrains. University of Massachusetts, Department of Mechanical and Industrial Engineering, Renewable Energy Research Laboratory. 2006.

“2. Concerning the fetch-dependent model. In lines 5-10 at page 5, the authors claim that the heat transfer over large leads is less efficient because the temperature (and humidity) difference between the lead surface and air is decreasing with fetch. This mechanism is present in the Renfrew and King (2000) model for heat fluxes over polynya (Renfrew, I.A. & King, J.C. *Boundary-Layer Meteorology* (2000) 94: 335. <https://doi.org/10.1023/A:1002492412097>) and in the model of Chechin and Lüpkes for cold-air outbreaks over the marginal sea-ice zone (Chechin, D. and Lüpkes, C. (2017), *Boundary-Layer Meteorology*, 162:91-116 , pp. 1-26 . doi: 10.1007/s10546-016-0193-2). The authors should refer to these papers. However, in the basis of the Andreas and Cash model there is a different physical mechanism of how fetch affects turbulent heat transfer. Andreas and Cash suggest that the thicker the thermal boundary layer is, the closer the conditions are to the free-convective limit. They claim that in the free-convective limit the heat transfer is less efficient than in the forced convection. I suggest, that the authors review the existing physical interpretations of the effect of fetch, e.g. by Andreas and Cash, by Alam and Curry (1997), which are different. Also (!), in the Andreas and Murphy (1986) paper, different physics is described (e.g., the effect of a more rough sea ice, for example, and a different interpretation of the free convection contribution). Also, refer to the Esau 2007 paper (Amplification of turbulent exchange over wide Arctic leads: Large eddy simulation study, *J. Geophys. Res.*, 112, D08109, doi:10.1029/2006JD007225.)”

Reply: Thanks for these valuable suggestions, a brief review on recommended studies was added to our manuscript.

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Page 2, Line27 ~ 40, we added: “Models were developed for estimation of TIBL thickness and turbulent heat flux over coastal polynyas, leads, and ice edges (Alam and Curry, 1997; Andreas and Cash, 1999; Renfrew and King, 2000, Chechin and Lüpkes, 2017). Chechin and Lüpkes (2017) modeled boundary layer development downwind of the ice edge, potential temperature, and mix-layer height, and wind speed variation was analyzed as well. Renfrew and King (2000) modeled turbulent heat flux over large fetch (5–50 km wide, typical for coastal polynya) during cold-air outbreaks. The dependence of turbulent heat flux on lead width was estimated in several studies (Andreas and Murphy, 1986; Alam and Curry, 1997; Andreas and Cash, 1999). On the basis of the Monin–Obukhov similarity theory and the surface renewal theory, Alam and Curry (1997) estimated turbulent heat flux over leads using an intricate surface roughness model (Bourassa et al., 2001). Sensible heat flux across a single lead is integrated from fetch 0 to fetch X. Andreas and Murphy (1986) calculated transfer coefficient CN10 at 10 m height for turbulent heat in neutral stability, using the nondimensional fetch $-X/L$, where L is the Obukhov length. A maximum CN10 of 1.8×10^{-3} was found at small fetch, and the value decrease to 1.0×10^{-3} with increasing $-X/L$. Andreas and Cash (1999) computed lead-average turbulent heat flux using transfer coefficient C^* as a function of stability parameter $-h/L$, where h is the fetch-dependent height of the TIBL. For small fetch ($-h/L < 6$), turbulent heat is exchanged by mixed free and forced convection, resulting in a large C^* and higher heat flux.”

Page 5, Line38 ~ 40, we added: “Another mechanism is described in Esau (2007) for leads 1km~10km wide. Under weak wind condition (~ 2 m/s), convective overturning prevents cold breezes from penetrating into the lead area, reducing the average turbulent heat flux.”

“3. As already mentioned, there is another model which takes into account the dependency of heat flux on fetch over leads, namely, the Alam and Curry (1997) model. This model has different physics and more processes are taken into account. It is not clear why the authors prefer the Andreas and Cash model and do not consider the Alam and

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Curry model. This has to be explained.”

Reply: Thanks for pointing out the Alam and Curry (1997) model. In that model, turbulent heat flux across single lead is integrated from fetch 0 to fetch X, along the wind direction. Indeed, it is more theoretical and takes more factors into account. But in the large scale application, it is hardly applicable due to lack of high resolution meteorological data like 2m air temperature. Besides, the model assumes universal water surface within leads (with a complicated surface roughness model for open ocean), which is different from our case where narrow open water or thin ice dominate. Actually, we tried to apply the Alam and Curry (1997) model in the remote sensing setting, but failed due to lack of sea surface information (e.g. phase speed, wave age etc.). Thus, only the fetch-limited model of Andreas and Cash (1999) was selected in our experiment.

Page 6, Line 2 ~ 8, we added the explanations as follows: “However, the assumption of universal water surface in leads and the application of sea surface roughness model (Andreas and Murphy, 1986; Alam and Curry, 1997) are not applicable in our case, where open water and thin ice dominate. Since the signal of TIBL is absent in the coarse grid of 2 m air temperature from the ERA reanalysis dataset, the data might not be appropriate to demonstrate the Alam and Curry (1997) model, which relies on accurate measurement of meteorological parameters. Whereas the Andreas and Cash (1999) model is more sensitive to lead width than atmospheric conditions (Marcq and Weiss, 2012). Therefore, only the Andreas and Cash (1999) model was used in our experiment.”

“4. One of the results of the study is that the fetch-dependent model produces larger fluxes than the bulk formulae. However, the transfer coefficients in the bulk formulae depend strongly on the roughness length for momentum and heat (z_{0m} and z_{0t}) and therefore, the obtained result is only valid for specific values of z_{0m} and z_{0t} , which are not given in the paper (!). Using other values for z_{0m} and z_{0t} can produce completely different results. The Andreas and Cash model, as it is described in the paper, does not show an explicit dependency on the roughness length. However, implicitly,

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roughness is present in their model and the authors need to describe how the roughness length is present in the model of Andreas and Cash. What are the values for the roughness length in the Andreas and Cash model and how do they compare with the ones used in the bulk formulae? Note, that the Andreas and Cash model is a reformulation of the earlier Andreas and Murphy model. The latter is formulated in such a way that it is compatible with bulk formulae. Namely, they are suggesting to use a fetch-dependent “lead-averaged” neutral heat transfer coefficient. In other words, the Andreas and Murphy formulation would allow a more reasonable comparison with the standard bulk approach.”

Reply: Thanks for the question. For open water leads, Andreas and Murphy (1986) parameterize turbulent transfer coefficient at 10m as

$$CN_{10} = (1.0 + 0.8 \text{ EXP}(0.05(X/L)))/1000$$

where X is the fetch or lead width. However, the reference height of 10m might not be suitable for study narrow leads in pack ice, where the TIBL is generally shallower. On the base of Andreas and Murphy (1986), Andreas and Cash (1999) used bulk Richardson number R_{ib} to calculate Obukhov Length L i.e. Eq. (16) under the assumption that the ratio between roughness lengths for momentum and heat, i.e. Z_0 / Z_T , is about $\text{EXP}(2)$. In our case, this simplification result in a higher $|L|$ than that from Oberhuber (1988) and Goose et al. (2000). If the Obukhov length from Eq. (B8) and (B13) were used to calculate the coefficient C^* in Andreas and Cash (1999) model, and estimated turbulent heat flux will be smaller (Table 3), but still 15.53% larger than that from bulk formulae.

Page 9 line 25~31, we added: “In both the Andreas and Murphy (1986) and Andreas and Cash (1999) models, for reference height $r < 10$ m, the ratio between roughness lengths for momentum and heat, Z_0/Z_T , is assumed to be $\sim \text{EXP}(2)$ to calculate Obukhov length L using Richardson number R_{ib} (see Eq. (17)). The calculated Obukhov length L has absolute values about 67% higher than those using Eq. (B8) and

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(B13) from the bulk formulae (Oberhuber, 1988; Goosse et al., 2000). If Eq. (B8) and (B13) were used to solve Obukhov length and coefficient C^* in the Andreas and Cash (1999) model, estimated turbulent heat flux will be smaller (Table 3), but still 15.53% larger than that from the bulk formulae, with an even larger part of the difference from the small lead category (42.48%, compared to 32.96% in Section 4.3.2)."

Page 6, Line 27, we have Eq. (17)

$$L^{-1} = 8.0 \cdot (0.65/r + 0.079 - 0.0043r) \cdot Rib \quad (17)$$

Page 11, Line 11 and 18, we have Eq. (B8) and (B13)

$$T_0 = Tr \times (1 + 2.2 \times Tr \times qr \times 10^{-3}) \quad (B8)$$

$$r/L = 100r \times ((Ts - Tr) + 2.2 \times (T_0^2)(qs - qr) \times 10^{-3}) / (T_0 \times ur^2) \quad (B13)$$

Page 21, we updated Table 3: Estimated turbulent heat flux (W) for Landsat-8 TIRS using bulk formulae, the Andreas and Cash (1999) model, and modified Andreas and Cash model using Obukhov length from Eq. (B8) and (B13).

"5. Describe better the case study. Which date is it, what are the synoptic conditions over the study area? Was it a clear-sky case or clouds were present? Does it represent typical conditions in the Arctic? The presented surface and air temperature distributions suggest that this is either autumn or late spring. But one would expect that the effect of leads is strongest in winter."

Reply: Thanks for the question. The Landsat-8 and MODIS images used in our study were acquired on April 26, 2016. The study area is mostly unobstructed by cloud in this scene. According to the ERA-interim datasets, the study area is dominated by polar easterlies, with 10m wind speed range from 4.8 to 9.5 m/s. Air temperatures at 2m from the reanalysis data range from 257.3 ~ 263.8K. Temperature difference between surface and 2m air is about 5K. The Landsat-8 imagery is sparse in the Arctic ocean, especially in the winter polar night. These three successive scenes of thermal images can also provide valuable details of spatial distribution of spring leads.

Page 3, Line 6, we added: “acquired on April 26, 2016”

Page 20, we updated table 1: "Satellite images and other data used in this study."

“Minor comments”

–Page 1, lines 26-27, rephrase “The rate of turbulent heat transferred”, simply “Turbulent heat flux”

Corrected

–Page 1, line 36. “More intensive network” needs clarification. Also, “stronger influence of leads” - influence on what?

Corrected, “networks of more intensive lead with stronger local influence are expected”

– Page 2, line 14 - “heat flux transfer rate” - the efficiency of heat transfer?

Corrected, “Assuming higher heat transfer over narrow leads than wider leads”

– Page 2 line 16 – remove “More often than not”

Corrected

– Page 2, lines 20-25, explain better what is meant by “Fetch limited models” and how they are using the fetch-dependence of the internal boundary layer height. Otherwise, the logic is disrupted.

A review of models developed for estimation of internal boundary layer height and turbulent heat flux was added on page 2 Line 27 ~ 40.

– At least in the introduction the authors should cite the study by Tetzlaff et al. (2015) where the most recent observations of heat fluxes and the internal boundary layer height over leads are presented: Tetzlaff, A. , Lüpkes, C. and Hartmann, J. (2015), Aircraft based observations of atmospheric boundary layer modification over Arctic leads. Q.J.R. Meteorol. Soc., 141: 2839-2856. doi:10.1002/qj.2568

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Page2, Line 25 ~ 26, we added: “Convective plumes formed above leads may further complicate the process within the TIBL (Tetzlaff et al., 2015).”

– Page 3, line 10. The actual grid of the ERA-Interim reanalysis has horizontal spacing 0.75o and not 0.125o. The original ERA Interim data is interpolated on the 0.125o grid which does not increase the resolution.

Corrected Page3, Line 9, we write: “This dataset provides global coverage with a temporal resolution of 3 hours, 0.125° grid data is available for download (~10 km in study area, interpolated from original 0.75° grid).”

– Page 3, line 39. albedo anomaly

Corrected

– Page 4, Lines 8-9 rephrase “varying air condition”

Corrected, “air temperature variation”

– Page 4, Line 21. “limited used of lead width” - what does it mean??

Deleted

– Page 4, Line 29 “rate of turbulent heat change” - what does it mean?? Rephrase!

Corrected, “turbulent heat exchange”

– Page 4, Eq. 4 – use CH instead of Cs for the heat transfer coefficient

Corrected

– Page 4, Line 36 Ce is the bulk transfer coefficient for water vapor

Corrected

– Page 4, Line 37 “at the surface”, this is wrong. These values are at heights z0t and z0q, which are the roughness lengths for heat and moisture fluxes.

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Corrected.

– Page 4, Do the authors use the saturation specific humidity over ice or over water? Do they distinguish between the open water and thin ice in this respect?

Yes. Saturated specific humidity was used over lead surface for both open water and thin ice, but different sets of parameter were used to calculate saturated vapor pressure at the surface of open water and thin ice.

Page 5, Line 20~23, we write: “ e_0 represents the saturated vapor pressure at surface temperature T_s :

$$e_0 = e_0 \times 10^{(a t / (b + t))} \quad (8)$$

with e_0 represent saturate vapor pressure at 0 °C, approximately 6.11 hPa, t is temperature in Celsius, and a and b are coefficients (for water surface, $a = 7.5$, $b = 237.3$ K; for ice, $a = 9.5$, $b = 265.5$ K).”

– Page 5, Line 11. This is shown in figure 4, not in figure 3.

Corrected

– Page 5, Line 35, Not “in spite”, but “apart from a dependency on the width of a lead”

Corrected

– Page 5, line 36. Which simulation? What was used for this simulation - Bulk formulae, or the Andreas and Cash model? For the bulk model, such result is obvious and does not need to be shown. Andreas and Cash write that their model is, on the contrary, not very sensitive to wind speed.

The simulation, as well as Fig. 3 and 4, is based on Andreas and Cash (1999) parameterization. Although, they claim that their model “depends only weakly on surface level wind speed”. Our test shows that, for the narrowest lead from TIRS ($X=30$ m), turbulent heat flux, especially sensible heat, rises quickly with larger ΔT and stronger wind.

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– Page 6, Section name “Results” and not “Result”.

Corrected

– Page 6, line 35. How is the length of leads calculated?

Page 4, Line 43 ~ page 5, Line 2 we added: Since we assign lead width to every pixel across the lead, the length L_i for lead width X_i can be calculated as follow:

$$L_i = a_0 \times N_i / X_i \quad (4)$$

where a_0 is the pixel size, for TIRS, the value is 30 m, for MODIS, 1km; and N_i is pixel number for width $X_i = a_0 \times i$, ($i = 1, 2, 3, \dots$).

– Page 6, line 35. The Authors say that the MODIS resolution is 1000m. However, they introduce a class of small (which they call narrow in other places) leads with width less or equal 1km. Somehow, they found 13% of such leads in the MODIS image. They need to comment if 1km wide leads are resolved with 1km resolution.

Reply: The detectability of leads are composite of thresholds and contrast in surface temperature of leads compared to the surrounding ice, i.e. temperature anomaly Δt . Although the 1km resolution is the finest for MODIS thermal (and AVHRR), potential and subpixel lead can be detected at this scale (Lindsay and Rothrock, 1995). In the revised version, we now include 1km in the first category, and statistics in Table 2 are updated.

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

Page 9, Line19 ~ 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

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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.”

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.

– Page 7, line 4. The direction of fluxes from the ocean to the atmosphere is not consistent with the Eq. (4) and (5). The authors should modify the Equations to get the right sign and direction of fluxes.

Corrected.

– Page 7 line 12. In which range of width is the fetch-limited model valid? Why was it applied to Landsat only? There wide leads in Landsat as well. Write that Landsat better resolves leads, so that’s why it was applied to it.

Reply: Andreas and Cash (1999) fit C^* for $-h/L$ range from 0.05 to 20. Although high wind ($\sim 7\text{m/s}$) and low temperature difference ($\sim 5\text{K}$) in our case leading to large $|L|$ up to 40m, the C^* fitting still holds for lead width $X > 15\text{m}$ from TIRS. Since the turbulent heat flux saturate for lead width great than 1km, as depicted in Fig. 4, we think there is no need to apply the model with coarse leads from MODIS.

Please also note the supplement to this comment:

<https://www.the-cryosphere-discuss.net/tc-2018-262/tc-2018-262-AC2-supplement.pdf>

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

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