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The Cryosphere Discussions

Interactive comment on "Permafrost and surface energy balance of a polygonal tundra site in northern Siberia – Part 1: Spring to fall" *by* M. Langer et al.

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We thank the reviewer for the critical remarks and suggestions on our manuscript. In the following we carefully consider all comments of the reviewer which are marked in bold. Changes in the manuscript are marked in italic.

General Comments: Langer et al. are presenting a descriptive analysis of the spring, summer, and fall energy balance at a polygonal tundra site in Northern Siberia. While the data is arguably of better quality than earlier work that relied on the Bowen Ratio techniques, much of the analysis is rather routine. The

results indicate that many of the conclusions of previous work are robust, despite different geographical locations (and techniques). Still, the authors are not highlighting classical papers (Ohmura's for example). I am currently not seeing a new contribution to the field but rather a confirmation of previous investigations.

Besides many routine observations and analyses the authors are convinced that this study also includes new aspects of the surface energy balance and addresses important aspects for modeling the energy turnover of the polygonal tundra. The new insights can be summarized as follows:

- the temporal evolution of the energy balance at a polygonal tundra site including the shoulder seasons (snow melt and freezing back). In particular, the new findings concern the triggering factors of the snow melt and the timing of the freeze-back which both has been found to be strongly related to advection of warm air masses (cloud cover).
- the spatial variability of the energy balance components including the sensible and latent heat fluxes. The study demonstrates that the partition of the turbulent fluxes at the polygonal tundra is determined by the micro-structures of the surface. A more precise evaluation of these spatial differences has been added to the revised version of the manuscript.
- The impact of small water bodies on the net radiation, which is increased by these landscape features. This is of particular importance since small ponds are frequent landscape features in the polygonal tundra, but they are difficult to identify with e.g. remote sensing.

In the revised version of the manuscript we now address important energy balance studies which indeed have not been account for in the previous version (Please also see comments of the first reviewer).

Text added to the introduction:

Several energy balance studies are already available for the North American Arctic (e.g., Ohmura, 1982, 1984; Eaton et al., 2001), and more are contained in the comprehensive reviews by Eugster et al. (2000) and Lynch et al. (1999). For the European Arctic, including Svalbard, energy-balance studies are published by Lloyd et al. (2001) and Westermann et al. (2009). However, Siberian sites are not included and generally few published studies are available for the Siberian tundra (Kodama et al., 2007; Boike et al., 2008).

Section 5.4 added to Discussion:

Only few studies on the surface energy balance exist for arctic regions, most of which only cover short periods or do not include all components of the energy balance. The most comprehensive summary for a number of sites in the Arctic and Subarctic (except Siberia) is given by Eugster et al. (2000). In addition, studies on the surface energy balance have been published for Alaska (Ohmura, 1982; Harazono et al., 1998; Mendez et al., 1998; Lynch et al., 1999; Vourlitis and Oechel, 1999; Chapin et al., 2000), Greenland (Soegaard et al., 2001), Svalbard (Harding and Lloyd, 1998; Westermann et al., 2009) and Siberia (Boike et al., 1998; Kodama et al., 2007). Since most of these studies only provide flux values for the summer season (July - August), a meaningful comparison is only possible for this time. Here, we use the averages of the summer period in 2007.

The Bowen ratio of around 0.35-0.5 observed in this study for polygonal tundra in Siberia demonstrates the high evapotranspiration rates of a typical wet land and is well within the given range from other arctic wetland locations. The total evapotranspiration rate of 1.4 $\mathrm{mm\,d^{-1}}$ *falls between the lower ranges reported from Svalbard (*$\approx 1\,\mathrm{mm\,d^{-1}}$*) (Lloyd et al., 2001; Westermann et al., 2009) and higher values for wetland sites in Greenland (1.5* $\mathrm{mm\,d^{-1}}$*) and Alaska (1.5 to 2.3* $\mathrm{mm\,d^{-1}}$*).*

With a fraction of 20% of the net radiation, the ground heat flux observed at the study *site is among the largest values reported for Alaskan, Greenland and Svalbard sites (Eugster et al., 2000; Westermann et al., 2009), while ground heat fluxes from other Siberian sites reported by Kodama et al. (2007) and Boike et al. (1998) fall in the same range. The main reasons for this are most likely similarly cold permafrost temperatures and a similarly large annual temperature amplitude due to the continental climate conditions.*

While the available dataset provides the opportunity to assess the spatial variability of the surface energy balance, the authors are focusing on the temporal variations at the stationary site. I would like to see the manuscript having an increased attention to the geographical differences/similarities in the energy fluxes even though the eddy covariance measurements represent a mosaic of the polygonal ground surface.

We extended the discussion section which now includes an paragraph setting the results in relation to energy balance studies performed at other geographical location of the arctic tundra. Furthermore, this study aims to present an overview of the magnitudes, as well as the temporal and spatial variabilities of the surface energy balance components. Thereby, the seasonality is in the main focus of this study. In addition, we have expanded on the aspect of spatial heterogeneity which includes Fig. 9 and the following paragraph in the results section:
Assuming that the dependencies between the net radiation and the differences in the turbulent heat fluxes displayed in Fig. 8 (which have been evaluated for a period of one week) can be generalized the entire summer period, we can calculate the average differences between both measurement locations for the entire summer period from the distribution of the net radiation (see histogram in Fig. 8). For the summer period 2008, the calculated average sensible heat flux is $7 \pm 7\,\mathrm{Wm^{-2}}$ *higher at the mobile station, while the average latent heat flux is* $8 \pm 10\,\mathrm{Wm^{-2}}$ *lower. Based on these results, we calculate the heat flux contributions of wet and dry surfaces using fractional*

unmixing. The average latent heat flux Q_{E} at location I (stationary station) and II (mobile station) can be evaluated as

$$Q_{\mathrm{E}}^{\mathrm{I}} = f_{\mathrm{dry}}^{\mathrm{I}} Q_{\mathrm{E,dry}} + f_{\mathrm{wet}}^{\mathrm{I}} Q_{\mathrm{E,wet}} \,, \tag{1}$$

$$Q_{\mathrm{E}}^{\mathrm{II}} = f_{\mathrm{dry}}^{\mathrm{II}} Q_{\mathrm{E,dry}} + f_{\mathrm{wet}}^{\mathrm{II}} Q_{\mathrm{E,wet}} \,. \tag{2}$$

Hereby, $Q_{\mathrm{E,dry}}$ is the average latent heat flux originating from dry surfaces, $Q_{\mathrm{E,wet}}$ is the average latent heat flux originating from wet surfaces and ponds, and f_{dry} and f_{wet} are the fractions of dry and wet (including pond) surfaces in the average flux source area at location I and II, respectively. According to the footprint analysis, the stationary location features $f_{\mathrm{dry}}^{\mathrm{I}} \approx 0.6$ and $f_{\mathrm{wet}}^{\mathrm{I}} \approx 0.4$, while the mobile location consists of $f_{\mathrm{dry}}^{\mathrm{II}} \approx 0.8$ and $f_{\mathrm{wet}}^{\mathrm{II}} \approx 0.2$. Note that performing this procedure for average fluxes and average footprint areas is a good approximation, as the fractions of wet and dry areas within the footprints do not vary strongly ($\pm 5\%$) over time. The calculated fluxes reveal that dry and wet surfaces are distinctly different sources for sensible and latent heat fluxes (Fig. 9): at dry surfaces, about the same amount of energy is attributed to sensible and latent heat fluxes (Bowen ratio $Q_{\mathrm{H}}/Q_{\mathrm{E}}$ of 1.29), while the wet surfaces feature a strong dominance of the latent heat flux (Bowen ratio 0.02) with an almost negligible contribution of the sensible heat flux. The latter is in good agreement with the small difference, that is usually observed between the surface and air temperatures for the wet areas. With declining net radiation in the fall period, almost no differences in sensible and latent heat fluxes are measured between the locations of the stationary and the mobile system.

Specific Comments: The manuscript is generally well organized apart from sections under "results" that includes portions suited for the discussion. I find several sentences awkward to read (see "technical corrections"). It would also help me as a reader if the authors avoided long paragraphs. Some sections

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are confusing. For example, the authors are discussing their second paper (winter energy balance) in the abstract and introduction. Also, the labeling of the sub-periods of the snowmelt period is extremely confusing. I find the language somewhat "wordy". In particular, I am not a fan of value laden phrases such as "essential".

As suggested by the reviewer, we removed awkward sentences and shortened the paragraphs, where possible. We removed the references to the second paper in the abstract and the introduction. We also revised our wording (see also reply to reviewer I).

The authors are describing the landscape as heterogeneous at the scales of meters. If the data is there, why not focus on the spatial (and temporal) variability in the partitioning of ground heat flux into its latent and sensible components for example? More efforts in data mining of the results from the mobile towers and how they compare to the stationary site could result in some new findings. One mobile tower has 79% dry area. Why not focus on that one?

In the revised version of the manuscript we provide a new Figure (Fig. 9), extended results (Sect. 4.2) and discussions (Sect. 5.3) on the spatial variabilities (Please see above).

I appreciate their efforts to produce a continuous description of the surface energy fluxes by modeling any missing data. In particular, I find the total evaporation rates (summer and snowmelt) of interest. On the other hand, I would appreciate if it was clear what sections are measured data and modeled in the continuous time series.

We now provide an overview of the available dataset in the methods section (Fig. 2).

In many places it seems like the authors could strengthen their interpretations with their own data.

We revised many parts of the discussions (Sect. 5) and the entire conclusions (Sect. 6). We removed statements which are too general and replaced them with specific statements related to our measurements and results. (Please also see comment of the first reviewer)

The authors invested in an extended description of the errors in the measurements and calculations, but I am missing a presentation of the the absolute errors when results are presented.

Due to the critical remarks of this and the first reviewer this paragraph has been revised. We now provided an extended error discussion in Sect. 5.1.

The scientific methods are clearly outlined with the exception that I am missing a clear description of how the ablation was monitored.

We added a sentence concerning the monitoring of the snow ablation to the methods section:
The snow-free area is roughly estimated by means of visual inspection of daily photographs taken automatically from a 2 m *mast at the measurement site.*

I would also appreciate a reference to the corrections applied when the

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fluxes were calculated. It is not fair to the reader to assume a familiarity with the "TK2" program.

The concerning paragraph has been completely revised:
The turbulent fluxes are calculated for 30 minute intervals with the 'QA/QC' software package 'TK2' (Mauder and Foken, 2004; Mauder et al., 2007), which includes standard corrections and quality tests. Besides the aforementioned correction of the buoyancy flux, processing the data involves an adjustment of the horizontal and vertical wind speed components using the planar fit correction (Wilczak et al., 2001), and an adjustment due to the displacement between anemometer and gas analyzer (Moore, 1986). The applied quality assessment follows the scheme of Foken et al. (2004) based on tests for stationarity of the turbulence characteristic. The stationarity criterion is considered to be sufficiently fulfilled (quality flags 1 and 2) if the average covariance inferred from 5 minute sub-intervals do not deviate by more than 30% from the covariance value over the entire 30 minute interval (Foken et al., 2004).

As the study is located at sites that are at least temporarily flooded, I am missing a description and a discussion of the heat storage component in the standing water column. Harazono et al. (1998) showed that a substantial portion of the diurnal surface energy exchange can be located to the energy dynamics of the shallow water column.

During the measurement period the study site only features a short period during and after snow melt when standing water affects the measurement site. Based on the daily photographs this period is determined to last 10 to 14 days. During this time, it is nearly impossible to infer energy balance storage in the transient layer of melting snow and ponding water with the available measurements. However a statement on this has been added to the results in Sect. 4.1.1:
During and shortly after the snow melt, the polygonal centers are temporally flooded,

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when the frozen soils impedes water drainage. This period lasts from 10 to 14 days, and the standing water column features a depth of a few millimeters to centimeters.

I am missing a profile figure describing the soil thermal regime ("permafrost" is nonetheless part of the title...)

According to the reviews on the companion paper (Langer et al., 2010b), we changed the focus and the title of the study to:
"The surface energy balance of a polygonal tundra site in northern Siberia – Part 1: Spring to fall"
Therefore, we like not to include an additional figure of the temperature profile as this would further expand the scope of this study.

What is typical wind direction? See impact of wind direction on the energy balance at a coastal location in the work by Rouse et al. 1987.

We extended Sect. 4.1.2 accordingly:
The wind speed appears to be associated with a diurnal pattern (Fig. 6), which indicates enhanced turbulent heat exchange during the day and lowered turbulence during the night. No dependence on the wind direction during day time was detected. The wind directions show a slight dominance in NW and SSE direction in 2007, while a slight dominance in NW and ESE direction is observed in 2008. For both years, we measure a distinct influence of the wind direction on the air temperature which is on average 6C colder during north winds. However, an corresponding influence of the wind direction is found neither on $Q_{\mathrm{H}}/Q_{\mathrm{net}}$ *nor on* $Q_{\mathrm{E}}/Q_{\mathrm{net}}$.

Technical corrections and specific comments: P. 902 Apart from being used in every other sentence, the word "essentially" does not provide any additional

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information. I suggest removing it.

Done. The wording of the entire manuscript has been revised.

L 2-4: Awkward sentence. Too busy.

The sentence has been removed in the revised version.

L. 5: Annual surface energy balance? The title focuses on the spring and summer. I am confused. The paper I am asked to review only includes the April to Sep. Please remove the "annual" and winter analyzes to avoid confusion.

Done. Sentence changed to:
The study was performed during half-year periods from April to September in each of 2007 and 2008.

L. 9: Missing a comma before "and". Please check the rest of the manuscript.

We revised the entire manuscript.

L. 10: Unclear. Dominant factor of the magnitude of the absolute fluxes?

Sentence changed to:
Short-wave radiation is the dominant factor controlling the magnitude of all the other components of the surface energy balance during the entire observation period.

L. 13-14: The second part of that sentence is unclear. Expand the second part, i.e. divide the present sentence into two sentences.

Sentence changed to:
The ground heat flux is mainly consumed by active layer thawing. About 60% of the energy storage in the ground is attributed to the phase change of soil water.

L. 17-19: Statistically significant? If not, remove "significant". Are the measurements flux measurements? If so, please say so.

Done. The word "significantly" has been removed.

L. 19: Remove "at different locations". It is obvious.

Done.

L. 20-21: Wordy. A suggestion: "However, spatial differences in the partition between sensible and latent heat flux only exist during conditions of high radiative forcing, which only occur occasionally."

Suggestion has been adopted.

L. 24: Remove "fundamentally" (same issue as I have with "essential").

Done.

L 24: I wouldn't call 1997 "recent".

Changed "recent" to "numerous".

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P. 903 L. 1: Affected by what? Remove "processes" (it makes is unnecessarily awkward to read).

Sentence changed to:
There is observational evidence that the turnover of energy and water have already been affected in the Arctic, again involving the thermal state of permafrost (Serreze et al., 2000; Hinzman et al., 2005).

L. 12-14. Awkward sentence.

The sentence has been removed in the revised version.

P. 904 L. 3: Annual? This paper is about the spring and summer.

Sentence changed to:
In this study we present data on the surface energy balance of a typical tundra landscape in northern Siberia collected between April and September during each of 2007 and 2008.

L. 5: Define is lowcentered or high-centered polygonal tundra.

A more precise definition is now given in the description of the study site:
The measurement site is located on the elevated terrace of the island, which is mainly characterized by low, centered polygons.

L. 8: Annual? If you have a Part 2 study that represents the winter, you can always mention that at the end of the introduction. L15: Annual? See comment above. L 19: Define landscape scale (100's meters?)

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This section of the introduction has been completely changed in the revised version of the manuscript:
In this study we present data on the surface energy balance of a typical tundra landscape in northern Siberia collected between April and September during each of 2007 and 2008. This article comprises the first part of a long-term energy balance study over the entire annual cycle of two consecutive years. The study aims to (i) compile the surface energy balance at a polygonal tundra site during the summer half year period, (ii) determine the seasonal and spatial variability of each energy-balance component which gives insight in the driving processes of the coupled permafrost-snow-atmosphere system, and (iii) identify the dominant factors that determine the energy partitioning and subsurface heat budget (active layer dynamics, permafrost temperatures).

P. 905 L. 1-2: Maximum air temp in September? Does not seem correct.

To clarify the sentence has changed to:
The snow-free period lasts until the end of September, and maximum air temperatures exceeding 20 ℃ are typically reached during July.

L. 9-11: Does this belong to the site description? Isn't this result?

Moved from the study site description to the result.

L. 12: Say low-centered polygons.

Definition added. Please compare comment above.

L. 15: Are they inundated (or saturated) throughout the summer or only after snowmelt? Please clarify.

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The following paragraph concerning the water level has been added:
During the entire study period, the water table is close to the surface, so that the soils at the depressed polygonal centers are usually water-saturated while the elevated rims are comparatively dry. During the snow melt, when water drainage is impeded by the frozen soils, the lowered centers are temporally flooded.

L. 24. Provide units.
Done. Explanatory sentence added:
The energy fluxes are given in $\mathrm{Wm^{-2}}$ *in the following.*

P. 906 L. 6-8. Unnecessary to provide eq. 2 if you will be using eq. 3.

Due to the variety of applied senors (pyranometers, pyrgoemeters, infrared surface temperature sensors and standalone albedo measurements) both equations are used for calculating net radiation. Therefore, we believe that it is appropriate to provide the basic form in Eq. 2 and the modified form, now presented in more detail by Eq. 3 and Eq. 4. Based on remarks by the first reviewer (see reply to the first reviewer), we modified the concerned paragraph in Sect. 3.1 to:
In addition to the net radiation sensors, measurements of the upwelling thermal radiation (CG1, Kipp & Zonen, Netherlands) are available at the standard climate tower (Fig. 1), while spatial differences are measured with distributed infrared surface temperature sensors (IRTS-P, Apogee Instruments, USA). The infrared sensors are mounted on small tripods about 0.8 m *above the surface and are directed at different tundra soils. According to instrument specifications, the IRTS-P sensors measure over a spectral range of 7-14* µm *and deliver brightness temperatures with accuracies of about* $\pm 0.5\,\mathrm{C}$ *(Bugbee et al., 1998). The true surface temperature* T_{surf} *and upwelling thermal radiation* $Q_{\mathrm{L}\uparrow}$ *are calculated similar to the approach described by Langer et al. (2010a) which accounts for the surface emissivity* ϵ *and the back scattered fraction of*

down welling thermal radiation (Eq. refdown welling thermal radiation). In accordance with Langer et al. (2010a) we assume emissivities of 0.98 for wet, and 0.96 for dry tundra surfaces. For averaging periods longer than a week the expected error on the true surface temperature is smaller than $\pm 1\,\mathrm{C}$ *(Langer et al., 2010a). This relates to an error in* $Q_{\mathrm{L}\uparrow}$ *of about* $\pm 5\,\mathrm{W m^{-2}}$ *in the relevant temperature range from -10 to 30*$\,\mathrm{C}$*.*
This might also justify the usage of all equations involved.

P. 907 L. 17: "We assume emissivities ϵ of 0.98 for wet and 0.96 for dry tundra surfaces (Langer et al., 2010a)." This assumption can drastically affect the spatial comparisons. A discussion/assessment of this assumption is preferred later in the paper.

We clarified the potential temperature error (please see above).

L. 21: Define solar noon. Is it a time period or a specific hour?

Paragraph has been specified:
The measurements are performed under clear-sky conditions over a period of 3 to 4 hours around solar noon. Based on these time series, average albedo values for wet and dry surfaces are inferred using incoming short-wave radiation, as measured by the CNR1 sensor. Following the accuracies of the sensors given in the manuals, the uncertainty for the calculated albedo value should be on the order of 10%

P. 908 L. 23: "For Bowen ratios of approximately 0.5 and average air temperatures of T_{air} 300 K, the offset is on the order of 15%..." This uncertainty should be included when the results are presented.

The uncertainty is now included in the extended discussion on the measurement

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errors and the energy balance closure (see Sect. 5.1)

L. 17-24: Separate the analyses into the data that is not missing the vapor flux and data that is.

In accordance with the used seasonal periods, the data analysis is already separated into sections when water vapor fluxes are available or not. Periods which are affected by missing measurements of the latent heat flux are now highlighted in Fig. 2 and also in Tab. 2.

P. 910 L. 22: Written weirdly. "Ground heat flux is essential for permafrost"??

Sentence removed in the revised manuscript.

P. 911 L. 16: Evaluate (no "d").

Done.

L. 17: The reference is incorrectly formatted. A parenthesis is missing?

Corrected.

L. 26: Use same units (Celsius or Kelvin) throughout the manuscript.

Temperature units are now all in degree Celsius.

P 913 L. 16-17: "With an almost identical snow depth, a similar snow-water equivalent is assumed for 2007." If no density was measured in 2007, write so.

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Paragraph changed to:
The latent heat content of the snow cover E_{melt} is calculated from the average snow-water equivalent (SWE) at the study site. The SWE is inferred from spatially distributed measurements of snow density using a core-tube immediately before the onset of snow melt in 2008. The the average snow density is evaluated by taking five cores at 20 different measurement locations. For the year 2007, for which snow-water equivalent measurements are not available, a similar density as in 2008 is assumed.

L. 21-25: It is unclear to me what definitions you are using. Please clarify what defines the three periods.

Paragraph changed to:
The time span considered in this study consists of two intervals, each from April to September, in 2007 and 2008. The energy balances of both periods are depicted in Fig. 3 with averaging intervals of 20 days. For the description of the seasonal energy balance characteristics, we separate the observation period into three subsections according to seasonal climatic conditions. The spring section is characterized by the presence of snow cover, up to the end of the melt period, the summer section features air temperatures well above the freezing point, and the fall section is defined by the beginning of refreezing and occasional snow fall.

P 914 L. 4: May is misspelled.

Corrected.

L. 7-9: Basic. Remove sentence.

Sentence removed.

L. 10-13: The method of SWE measurements was never explained earlier. Please do. How may samples, how many locations etc.

Please compare changes above.

L. 14: Write "mid-May".

Done.

L. 20-21: The naming is confusing when it is used later on. Give neutral names such as 1 and 2 or A and B.

We like to leave the names of the sub-periods as chosen (pre-melt, melt), since they exactly describe the difference between the periods. To reduce confusion we changed the wording in the concerning paragraph and added a separation to Fig. 4 and we payed more attention to consistent usage of the period names in Sect. 4.1.1.

L. 23: Unclear what the range -40 to 50Wm-2 actually represent. The diurnal amplitude?

Changed "diurnal cycle" to "diurnal amplitude".

P 915 L. 1: Unclear what you mean with "surface radiation budget".

Changed "surface radiation budget" to "net radiation" in the entire manuscript.

L. 13: Do you mean a total of 12 mm? If so, clarify.

Concerning sentence changed to:

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This heat flux corresponds to a total energy turnover of 30 $\mathrm{MJm^{-2}}$ *or a total amount of evaporated water of 12* mm*. As the snow water equivalent of 2008 amounts to approximately 57* mm*, about 20% of the snow cover sublimate or evaporate during the last days of the spring period.*

L. 18: Define the duration of the observation period (dates in parenthesis).

Done.

L. 14-16: "As the snow water equivalent of 2008 amounts to approximately 57mm, about 20% of the snow cover sublimate or evaporate during the last spring days. " I think this finding is worth to highlight in the abstract.

The finding on the snow cover evolution is now mentioned in the abstract as follows:
The thin snow cover melts within a few days, during which the equivalent of about 20% of the snow water evaporates or sublimates.

P 917 L. 14-15: I assume you mean a B below 1.

The reviewer is right, the Bowen ratio is meant to be below 1. We changed the Sentence to:
For both years, the average Bowen ratio, $Q_{\mathrm{H}}/Q_{\mathrm{E}}$*, is below one, indicating high rates of evapotranspiration.*

L. 16: This seems like a low number, especially since the area is continuously saturated.

Please note that the give amount of evaporated water only concerns the summer section when data are available (42 days in 2007 and 64 days in 2008). To clarify this limitation we changed the paragraph to:
During the summertime periods, the evaporated water amounts to about 70 mm *in 2007 (12 July - 23 August) and about 100* mm *in 2008 (7 July - 8 July; 29 July - 30 August). It is worth noting that the amount of evaporated water roughly equals the precipitation measured in the corresponding periods (Tab. 2). However, the inter-annual comparison is not meaningful, due to the different length of the observation periods.*

L. 20: What is the model?

Sentence changed to:
An inter-annual comparison of turbulent heat fluxes is feasible using modeled latent heat fluxes (Appendix. D) to fill gaps in the measured time series (Fig. 2).

L. 21: Boring usage of space. Instead, reference the figures in parentheses and tell the reader what the take-home message is. In general, try to follow that same style throughout the manuscript.

Sentence removed. Please see comment on L.20

L. 24-25. Awkward sentence.

We clarified our intention by changing the paragraph to:
Inter-annual differences in the turbulent heat fluxes occur during the early and mid summer period (Fig. 3). During this time, the net radiation in 2008 is depressed, most likely due to increased cloudiness. In accordance with the net radiation, lower sensible heat fluxes are observed in 2008. In contrast, the latent heat fluxes are slightly higher

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during early summer 2008, which may be attributed to the higher precipitation (Fig. 3).

P 918 L. 8-10: Awkward sentence. Need to be cut into several sentences.

Sentence changed to:
The fall period is characterized by steadily decreasing air and surface temperatures. This period is further characterized by the onset of freezing and occasional snow fall, but a continuous snow cover does not form yet.

L. 25-17: Why don't use the measured short-wave radiation when discussing cloudiness?

As indicated in Tab. 2 (now also depicted in Fig. 2), measurements of the four component sensor are not available during the fall period 2007. Therefore, the interpretation of radiation measurements with respect to cloudiness can only be based on measurements obtained by the net radiation sensor. During the day the incoming short wave radiation is attenuated, while the downwelling thermal radiation is enhanced by clouds. However, during the nights (in fall) the net radiation is only determined by thermal radiation which simplifies the identification of cloudy conditions.

P 919 L. 4: Why discussing in net short-wave and not net all wave?

The reviewer is right and the latent heat flux should be better discussed in the context of net radiation. Paragraph changed to:
In both years the latent heat flux exceeds the net radiation. Hence, the required energy for evapotranspiration must be delivered partly by the other energy balance components. According to the heat flux directions, this can only be assigned to the sensible heat flux.

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L. 27-28: A circular statement. Awkward as written

We clarified our intention and changed the corresponding paragraph to:
During nights with clear-sky conditions, the differences in surface temperature are inverted, with increased surface temperatures and thus increased outgoing long-wave radiation at the wet locations. During overcast periods, the spatial differences in surface temperature largely vanish. As such cloudy conditions are frequent and the day and night differences of the surface temperature under clear-sky conditions cancel at least partly, the spatial differences of the surface temperature are reduced to below 1 C for longer averaging periods, resulting in differences in the average net long-wave radiation of less than 5 $\mathrm{W m^{-2}}$*. Thus, we conclude that the spatial differences of the average net radiation between wet and dry surfaces are smaller than 10* $\mathrm{W m^{-2}}$ *during the summer period.*

P 920 Would be neat to tie in the snow depths with the energy balance discussion. For example, how does the net radiation change with a thinning snow cover?

As demonstrated in Fig. 4 and also stated in the results (Sect. 4.1.1) the net radiation steadily increases with retreating snow cover. This is mainly attributed to the decreasing albedo due to the melt out of the polygonal rims. Since point measurements of the albedo are not available during this period, it is not possible to separate this effect from the effect of a thin snow cover. We added the following statement to the results of the spring period:
This rapid change in the net radiation is related to a gradual change of the surface albedo, which has a value 0.8 before and 0.2 after snow melt. The gradual change in the surface albedo is attributed to the successive melt out of the elevated polygonal rims.

I want to see extended results on the spatial variability in fluxes. Currently, there is only only 1 page about spatial variations. When do these differences occur/not occur?

The section on spatial variabilities has been extended in the results (Sect. 4.2) and the discussion (Sect. 5.3) sections. In addition, we provide a new figure (Fig. 9).

L. 18: Data quality assessment should go before any other results. It is results too.

According to the critical remarks of the first reviewer, the entire discussion on the data quality has been changed (see Sect. 5.1). We now given an overview of the potential error sources and discuss the potential impacts on the results. However, with quantitative information on many error sources not available, the error assessment must be made a qualitative manner. Therefore, we prefer to leave the error assessment as a part of the discussion on the results.

L. What about heat storage in ponding water?

As decribed above, ponding water only occurs during a short period during and after snowmelt, during which it is impossible to tell the actual effect of the ponding water from our data. However, we chose the spring and summer periods accordingly, so that no ponding water is present at the beginning of the spring period, while it has disappeared at the end. Therefore, the energy stored in the ponding water is released through the other components of the energy balance, which we account for.

P 921 L. 20: Nowhere did I see the results highlighting the importance of the thermal state of permafrost.

We changed "thermal state of permafrost" to "strong soil temperature gradient" which is discussed later in the concerned section (Sect. 5.2)

P. 922 L. 2: Remove “out”.

Done.

L. 27-29: Contradictory statements. L. 28 “surface cooling”, L 29 “ground heat flux only marginally affected”, L 1-3 (P. 923) “surface temp not affected..”

Paragraph changed to:
During the summer months, the net radiation is reduced for cloud-covered skies, which in turn leads to surface cooling. According to our measurements, this mainly affects the magnitude of turbulent heat fluxes. While the surface temperature is lower under cloudy conditions, this only marginally decreases the strong temperature gradient in the soil, so that the impact of clouds on the ground heat flux is minor. Hence, the thawing dynamics of the active layer is only marginally affected by changed cloudiness.

P. 924 L. 22: “Albedo differences in spring are not likely: : :” Can’t you show that with your data?

Short-wave component measurements are not available during spring 2007, so that we can only guess that albedo differences of the entirely snow covered landscape are very small. However, the reviewer is right that our argumentation is too speculative so that we changed the statement to:
While both differences in the surface temperatures (and thus $L_{\uparrow}$) and in the albedo could explain the observed differences, our data do not allow to separate these two factors here. Nevertheless, it is important that the radiation budget of small water bodies, which occur frequently in polygonal tundra landscapes, may be distinctly

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different from the surrounding tundra surfaces.

L. 26: Why the reference? Isn't that what you are presenting here?

The reference has been removed.

P. 925 L. 12: I would not call eddy cov measurements micro-scale as they represent a mosaic of surface conditions, which are tied to the polygonal features.

We clarified our intention by changing the paragraph to:
Spatial differences of the turbulent fluxes are verified by using a second eddy covariance system with a different flux source area. The measurements reveal differences in sensible and latent heat fluxes according to variations in the fractions of dry and wet surfaces in the footprint areas (Fig. 8).

L. 19-22: Just because the long-term average is similar does not allow you to make that broad of a conclusion. I believe you were constrained in your analysis by a) that your two footprints were too similar and b) that the uncertainty in the calculated fluxes too large.

According to the extended discussion on spatial differences we also changed this paragraph (Sect. 5.3) The critical points mentioned by the reviewer are now not longer included. (Please see above)

P 926 L. 1-3: Repetition of comprehensive.

Sentence removed in the revised version.

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Wording changed to: "In this study we present a surface energy balance study of at wet polygonal tundra landscape from April to September in 2007 and 2008 considering seasonal and spatial variations. This extensive study improves the understanding of the energy exchange processes at soil-atmosphere interface of a typical permafrost landscape."

According to the comments this and the first reviewer the paragraph has been changed to:
In this study, we present long-term measurements of all components the surface energy balance at a polygonal tundra landscape in northern Siberia for two spring, summer and fall seasons (April to September). Furthermore, the study includes rarely available data on the spatial variablity of the surface energy balance from the point scale to a few hundred meters. In a companion paper (Langer et al., 2010b), a similar data set is presented for the winter season, so that the entire annual cycle of the surface energy balance can be documented.
In the following, we briefly summarize the key findings on the surface energy balance from spring to fall:

L. 9-13: The connection between cloud cover and soil freeze-up is interesting.

In accordance with the reviewer, we believe that further investigation on the shoulder seasons especially on this subject would be of great value. However, a more detailed analysis would also require more detailed measurements of the down welling radiation which was not sampled during the study.

L. 22-: You said earlier that there was no difference in the larger scale surface energy balance measurements among the two sites. ? I am confused.

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This statement is not related to the findings of the two eddy covariance measurement sites, but to the differences in net radiation observed at the polygonal pond. To clarify the intention of this statement we changed it to:
The deviation of net radiation between water bodies and tundra soils is at maximum immediately before and after melting ice cover on the pond in spring. Depending on the frequency of occurrence, small water bodies can decrease the summer time surface albedo.

Table 2. Provide ratios (sensible/net rad), to aid the comparison.

Done.

Figure 4. What explains the high night time ground heat fluxes and also high night time latent heat fluxes? It does not match with the measured net radiation.

The high night time ground heat flux could be explained by the fact that the ground heat flux is only measured at wet locations, while the net radiation and the turbulent heat fluxes are spatial averages which also include dry surface areas. Such inconsistencies occur during summer nights with clear sky conditions. During such periods the ground heat flux at the wet locations is measured to stay positive while it is very likely that it is negative at the dry soils. A paragraph concerning the error induced by spatial measurement inconsistencies has been added to the discussion in Sect. 5.1 (please see above).

Figure 5. How large percentage of the presented results is based upon modeled values?

The percentage of modeled latent heat fluxes in the concerning diagram is 68% in 2007 and 8% in 2008. This information is now included in the figure caption (Fig. 3).

Figure 5. Confusing; the direction of the sign for net radiation has suddenly changed since Figure 4.

We changed the sign of Q_{net} with respect to illustration. We wanted to display the magnitude of all energy balance components within one figure, which is easier when the net radiation is displayed in opposite direction. To reduce confusion, we now added a second y-axis for Q_{net}.

Figure 6. Define the labels in the figure caption.

Done.

Figure 7. Did you only compare to one mobile tower? Why not present results from all three locations?

The main focus of this study is the seasonal evolution of the energy balance. We agree with the reviewer that the spatial variability is an important aspect which deserves more attention. However, in order not to leave the scope of this study, we restrict the discussion to an exemplary situation where the difference in the footprint areas is at a maximum.

Figure 7. Clarify what E and H stands for.
Figure 7. The labeling of the y-axis is confusing.

We changed the labels and added a definition to the figure caption:
Differences of sensible (ΔQ_{H}) *and latent heat fluxes* (ΔQ_{E}) *as measured between the*

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stationary station and the second location of the mobile eddy system. The histogram depicts the distribution of net radiation values over the entire summer period.

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